CONFERENCE PROCEEDINGS 1

Third International Conference on Managing Pavements

Volume 2

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Third International Conference on Managing Pavements

Volume 2

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Introduction

The road systems of the world represent a huge investment on the part of governments and taxpayers. There is widespread concern over the status of the road infrastructure, and despite indications of increased investment, it is clear that the funds available are not likely to meet all the needs in the long run. More than ever, wise investment decisions concerning the road system will be crucial to the future of highway transportation.

During recent years a number of pavement management systems and concepts have been developed to assist decision makers in making choices. However, their effectiveness and the extent of their use or implementation still require substantial improvement. In large part this is due to financial, technical, organizational, and political factors. Yet effective pavement management remains a key to the future of roadway systems.

Objectives

The objective of this conference is to enhance effectiveness and efficiency in managing pavements for roads, streets, airfields, and other paved areas. The conference provides an opportunity for executives, practitioners, and researchers to share and evaluate recent experiences with pavement management systems. It addresses the benefits of implementation, the effects of support for decision making, advances in the state of the art and in technology, and the need for future development.

Format

The conference, conducted over three and one-half days, includes formal paper presentations, workshops, and optional tutorials. The conference addresses the following themes:

- **Appropriate Systems:** Papers cover the development or enhancement of pavement management systems appropriate to the agency under consideration. Workshops have been designed to enable small groups of participants to evaluate and discuss the priority issues from their perspectives.
- **Implementation Issues:** National, state, provincial, municipal, and local developments and implementation issues are presented. Discussions include innovations in implementation and marketing of maintenance and rehabilitation programs to decision makers.
- **Institutional Issues:** Papers from several countries describe institutional issues at national, state, and local levels. An educator's perspective is also included. Workshops enable participants to identify ways of overcoming potential hurdles to implementation.

• **Managing Information:** A full range of techniques, and when and how to use them, is presented. An optional tutorial is offered for those who wish to gain first-hand experience.

• **Analytical Issues:** The latest experience with performance prediction, optimization of benefits from scarce resources, and user and agency cost modeling is covered in presentations and workshops. Two optional tutorials in predictive tools and optimization techniques are available.

• **New Frontiers:** Information about emerging issues that are likely to affect pavement management is provided.

Conference Proceedings

The proceedings of the Third International Conference on Managing Pavements is being published in three volumes. The initial two volumes, which will be distributed to all conference attendees, include papers presented at the conference, all of which underwent full TRB peer review. The third volume, to be prepared after the conference, contains additional papers presented at the plenary and workshop sessions, some of which may have been peer reviewed. The papers that have undergone review will be so identified. The third volume will be distributed to all conference attendees and to all who purchase the first two volumes.

APPROACHES TO DEVELOPING APPROPRIATE SYSTEMS

Considerations for Developing and Supporting Appropriate Pavement Management Software for End Users

Shirley A. Rodenborn, *Metropolitan Transportation Commission*
Roger E. Smith, *Texas Transportation Institute*

Developing the appropriate decision support software for pavement management is a difficult task that requires considerable knowledge, insight, and patience on the part of the systems analyst and programmers. The systems approach to developing software requires the systems analyst to determine what the ultimate user desires in the software and to develop a programming plan on the basis of those needs. However, in pavement management, many of the end users have never used a computer before and have no idea of what they want from it, let alone of what it can provide them. In addition, most end users are no more familiar with pavement management concepts than they are with computers. No matter how well the concepts are explained, the users do not understand what pavement management will do until they start using it. To make matters worse for the systems analyst, if the software is designed to provide everything the experts think should be included, it is too complex for the average ultimate user to understand and use. A number of things can be considered in the development of pavement management software to keep the problems manageable. First, a dynamic approach to software development must be followed. A simple software package should be developed in a modular form that will facilitate later modifications and allow addition of other modules. It should be prepared to facilitate exchange of data with other operating software in the agency and should provide adequate housekeeping features such as backing up data and removing extraneous files. Ease of use and training of the ultimate users must be considered from the beginning. Finally, the long-term support of the software must be considered.

The Metropolitan Transportation Commission (MTC) is the regional transportation planning agency for the San Francisco Bay Area. Its responsibilities include highways, public transit, and water transportation, as well as the entire transportation infrastructure.

In 1981 MTC began assisting several local public works directors in documenting local agency pavement maintenance and rehabilitation needs and shortfalls within the Bay Area. The goal of this project was to develop support for requests for additional revenues for pavement maintenance from locally elected officials.

In 1982 MTC released *Determining Maintenance Needs of County Roads and City Streets* (*1*), which showed that Bay Area cities and counties were deferring pavement maintenance projects at a rate of $100 million a year. The report also documented that Bay Area cities and counties had an existing street and road pavement maintenance and rehabilitation backlog of $300 million to $500 million. In 1982 this report was used in convincing the California state legislature to increase the state gas tax from 7 cents to 9 cents. Of the 2-cent increase, 1 cent went to cities and counties for use on local streets and roads.

During the next 2 years, MTC continued to work with a committee of local public works officials to help them evaluate and establish priorities for their road and street needs. A major recommendation from this study was for MTC to adopt and support a pavement management system (PMS) for local agencies in the San Francisco Bay Area.

In 1984 MTC began development of a PMS (2). Six local jurisdictions (three cities and three counties) formed an advisory group to assist MTC in the PMS development. ERES Consultants, Inc., was retained by MTC to assist with this effort. The six local jurisdictions were adamant about not wanting the system to be a "black box:" they wanted to keep it simple, and they wanted to know how it worked in all phases of operation.

From the first PMS in 1985 to the present time, the process has been interactive with the users. Quarterly meetings are held, and troubleshooting and consultation services are available. User feedback has been incorporated into succeeding versions of the system. Currently the PMS has been adopted by 62 Bay Area cities and counties and more than 100 other jurisdictions nationwide.

MTC Pavement Management System

Pavement Inventory

A brief discussion of the network-level system is provided to assist with discussion of the development of the several modules in the pavement management decision support software (PMDSS). A simple inventory was established, minimizing the data collected. The management sections were required to match the data collection sections, and it was recommended that they match areas of past maintenance activities. Each agency divides its streets and roads into these management sections at the same time it collects descriptive data (length, width, functional classification, surface type, etc.) that are entered into the microcomputer-based data base. A simplified walking survey is conducted, and approximately 10 percent of the total area of each section is inspected for seven distress types that are most commonly found in the Bay Area and that have an impact on pavement decisions. The inspection information is entered into the microcomputer data base. The program then extrapolates the distress across the section and assigns a pavement condition index (PCI) in which 100 is considered perfect, and 0 indicates total destruction.

Needs Analysis

With this information the agency can complete a needs analysis. The PCI is projected over a 5-year period twice in one run. One report shows the worst case (assuming no treatment is applied), and the other shows the best case (applying the agency's treatment policy assuming an unconstrained amount of funds). The scenario module allows the user to select the sections that should be given first priority for funding. It also allows the user to analyze the effects of various budget decisions and shows the impact of various levels of expenditure in terms of overall network PCI and amount of deferred maintenance. Tables and graphs derived from this data make excellent exhibits for presentation to decision-making bodies during budget discussions.

Additional Features

During the past 9 years, this system has been through several changes that take advantage of the advances in technology. A graphics module has been added, and the 5-year projection period has been expanded. A mapping module has been developed for jurisdictions that have digitized their network of streets and roads.

Considerations in Development of PMDSS

Developing the appropriate PMDSS is a difficult task that requires considerable knowledge, insight, and patience on the part of the systems analyst and programmers. The PMDSS is user-oriented, and the software must meet the needs of the user. After several exasperating tries at developing the software, it becomes apparent that the analysts and programmers cannot assume that anything is obvious to the user; nor can they assume the user will complete the next logical step. The system must be designed for a wide variety of end-user levels of expertise and made as foolproof as possible.

End Users

Most small to moderate-sized local agencies invest their pavement management experience in one or two people in the organization. Generally, pavement management is only one of several responsibilities for such people. The pavement management positions often are at relatively low pay levels, and people in those jobs may only stay for a limited time. When a promotion, transfer, or job change moves that person away from responsibility for pavement management, it may take several weeks or months before a replacement fills the position. The pavement management experience from the preceding pavement management activities is often lost, and frequently the new person must start over on much of the system. In some cases the new person must start pavement management implementation again from scratch. In other cases, that person may not place as much emphasis on pavement management as his or her predecessor did, and the system becomes dormant or lost.

This lack of continuity among end users highlighted the need to place strong emphasis on user-friendliness in the system design. Many end users have never used a computer before and have no idea of what they want from it, let alone what it can provide them. In addition, most end users are no more familiar with pavement management concepts than they are with computers. No matter how well the concepts are explained, the users will not understand what a pavement management system will do until they start using it.

Design Considerations

There is often controversy over what to include in the PMDSS. If the systems analyst includes everything the experts think should be in the PMDSS, the software is too complicated for the average user. On the other hand, if the PMDSS is designed to try to help novices avoid all the pitfalls they may encounter, the software operates too slowly and frustrates the average user. One possible solution is to have a three-level system: one for the expert, one for the beginner, and one for the average user. Unfortunately, this is not a very viable option. Getting one version working and thoroughly debugged requires a major expenditure of resources. Developing and maintaining three is beyond the resources of MTC. As a compromise, MTC's PMDSS includes a few of the more complex features and enough checks so that a beginner can successfully negotiate the system. This PMDSS, combined with a good training program for beginners and a hot-line support system for problems, provides a valuable tool for local agencies.

Menu System

The user interface is extremely important for reducing the perception of complexity. The menus that lead the user through the system must make sense to the user and adhere to the KISS (keep it simple, stupid) adage. The MTC-developed PMDSS uses a menu system that is easy to use because it is arranged logically to help walk the user through the process. The menu system was developed through constant feedback from the users. The more the end users are involved in designing a menu system the easier it is for them to use and understand it. Figure 1 shows a display of the MTC PMDSS main menu. This menu lists the modules so the users can step through the pavement management system in a logical sequence that matches their work with their own pavement management processes. The data are entered, edited and then the PCI is calculated in the Data Base Calculations module. The Select Report module section lists several reports that will give information at any step in the pavement management process. Next comes the Budget Need and Budget Scenario modules. Users have the option of adjusting the maintenance treatment and costs to reflect the needs of their individual jurisdictions in the Modify Treatment

PMS Main Menu

1. Enter Data
2. Edit Data
3. Data Base Calculations
4. Select Report
5. Budget Needs
6. Budget Scenarios and Long Term
7. Modify Treatment Criteria/Cost
8. Utilities
9. Exit to RBase
10. Exit to Operating System

FIGURE 1 **Main menu for MTC PMDSS.**

Criteria/Cost module. The Utilities module contains all the housekeeping features needed to maintain the data base.

At present the most user-friendly menu software is that used for Apple's Macintosh computers and for Microsoft's Windows used in the PC microcomputers. This approach uses symbols representing the application and then key words that describe the options available. When the key word is highlighted, a pull-down menu appears to guide the user through the process. This type of menu software needs fairly high-powered computers (386 or better). Unfortunately, small to moderate-sized local agencies generally do not have the computers necessary to run this kind of system.

Input at the design phase from the "correct" officials in the local agencies takes away the monolithic aspect of the approach. By "correct" officials is meant management representatives from the engineering, financial, and maintenance departments, the departments that contain the end users of the PMDSS. The more these officials are involved, the more backing the PMDSS will have in the agency. This backing is necessary for the PMDSS to succeed.

Data Base Selection

The backbone of a PMDSS is the data base manager. This is what stores, updates, and retrieves the pavement management data. The analyst must choose a data base manager that will maintain the integrity of the data but which is also flexible enough to allow the data to be exported out to routines written in programming languages that can perform speedy mathematical calculations needed for the financial and modeling modules.

For a pavement management system the data base manager should have interactive end-user tools with which users can construct simple applications quickly and easily without programming. MTC's PMDSS allows for a basic description of a section, but some users want to add signals, signs, trees, bus stops, and other features to their copy of the data base. Data base tools must be available so the user can easily make the PMDSS more adaptable to the needs of his or her particular jurisdiction.

The reports that come with a pavement management system cannot possibly satisfy all the needs of the local agencies using the system. Most data base managers have report capabilities that can be relatively simple to use. Features to look for in report writing are a quick reporting option, breakpoints or grouping options, headers, and footers. These features must be presented in a way the user can readily understand.

A relational data base is best suited for developing pavement management applications because all the lengthy descriptive data about a management section need only be stored once and related to the repeating data. A relational data base is a system composed of separate files (or tables) that together comprise a single data base. The separate tables are often in a one-to-many relationship; that is, detail records related to one table are stored in another table. For example, the PMDSS would have a management section description table containing detailed information about each management section, and the maintenance history table would contain many records for each management section. The tables are linked together by common field; in this example it would be the management section identification code. The relational method of storing data makes efficient use of disk space, in that lengthy information applying to many records (for example the beginning and end locations of a street) are stored only once.

Many data base managers use structured query language (SQL) for data access and manipulation, since that language was designed for use with relational data. Users do not need to learn SQL syntax to use SQL in most data base managers, because it comes with a "Query by Example" feature. Query by Example is a visually oriented method of specifying queries; conditions are given in a table like grid. This feature allows users to design their own queries. SQL is a straightforward language. Anyone with knowledge of programming can use it easily. This is good for maintenance and debugging and does not tie the data base to one programmer.

Several features should be available in the data base manager. It should be powerful, flexible, and easy to use both for the programmer and end user. It is essential that there be a powerful report writer feature (for complicated reports generated by the programmer) that is easy to use (for quick reports the end-user needs).

A highly desirable feature for many implementations is a data base manager that produces compiled code. This means that the end users do not have to buy the data base manager software, which saves them about $500 to $700. They cannot query the data base or make new reports if they are using a compiled version, however. Another drawback of some compilers is they might not allow the exporting of data.

Modular Development

Modular development of any software package makes implementing the whole system much easier. Developing software in small logical chunks facilitates debugging by isolating the area in which to search. It also makes it easier for the user to determine if the system is headed in the right direction. Using a data base to store, enter, edit, modify, and report data allows one programmer to work on that part of the module while another works on the mathematical calculation part of the module. Data base languages generally do not provide adequate support for complex mathematical functions, so a good import-export feature is necessary in the data base manager.

MTC developed the entering, editing, PCI calculation, and reports necessary for these features as the first module. Microrim's RBase data base manager was chosen because at the time (1984) it was one of the few relational data base managers available. The first PCI calculation program was written in Basic and subsequently rewritten in C. The C programming language takes advantage of the new architecture in the latest-model computers, making the calculations much faster. The second module was the Needs Analysis, which included Modifying Treatments and Costs Option. As each module was developed, the appropriate reports were also developed. It was very hard to obtain feedback on the reports needed by users until they actually began using that module. After using the module, users always needed reports a little different from those that the system produced. In fact the more the users use a system and the more they see what a computer-based pavement management system is capable of, the more they want it to do. Such dynamic modifications are easier with modular development.

Testing

As each module was developed it was sent out to selected users for testing. Feedback from users was invaluable in restructuring the menu system and reports. Testing gives better results when the users who are doing the testing range in expertise from naive to experienced (both in computers and pavement management), mirroring the range of end users. The more bugs found at the test level, the fewer headaches when the system is actually distributed.

Based on the lessons learned from the first version, MTC placed considerable data checks in the program. However, that still was not enough. For initial testing MTC used the first city that completed the condition survey and entered its data. This was naturally a smaller city with very good street conditions and few financial problems. It did not test certain limits of the program, and the production version was released with problems that would have been found if data from a larger jurisdiction with worse streets had been used.

Data Checking

No matter how many times the concept of "garbage in-garbage out" is discussed, the idea does not seem to sink in. After data are entered, the obvious thing to do is to check them. Even though the PMDSS contains a series of reports that will list data in various ways making it easy for the user to check the data, several users have refused to check the data. One approach being used is to encourage them to do so by placing a pop-up list of the reports available for listing the data immediately after the user exits the data module. The PMDSS could force them to choose one. This does not guarantee they will check the data, but it provides them all the tools to do so with a minimum of effort.

Most data base managers allow checking of individual fields. If the data base system allows pop-up menus in data entry, it can be used to provide a list of all the eligible values for a field and force the user to highlight the correct value and press enter. This is acceptable on a fast computer or for an end user who cannot type, but for a slow computer it is faster and less frustrating for the user to type in the commands (provided they can type). All reputable data base managers have a rules feature that will check individual field ranges. For example, the functional classification code field could require A, C, or R, and the user would not be allowed to enter anything else. Numerical ranges can be verified and street section codes can be checked for uniqueness; however, correct spelling of street names and beginning and end locations of streets cannot be checked automatically.

There are housekeeping functions that cannot be programmed to be done automatically. Backing up the data base periodically is the responsibility of the user. However, messages should appear at critical places, that is, where the data base is about to be altered, to warn the user that the data base should be backed up. When the data base is to be irrevocably changed, the user should have a chance to review the data or the action that will update the data base.

An example is the situation that occurs after the user enters maintenance treatments applied to a section. When a section is reconstructed, the PCI is reset to 100 in the MTC PMDSS. However, the MTC PMDSS does not update the data immediately. The system lists the data and gives the user the opportunity to review and edit them. After the user has, it is hoped, checked the data, he or she must start the updating process, receiving a warning about backing up the data base.

Some other things are impossible for the program to catch. MTC had a user who discovered that a program would go much faster if he hit the "ESCAPE" key on the computer. Of course, all that was happening was that the program was skipping the rest of the processing for that module. The only way to save the user from destroying his or her data base is education and training in the use of the computer and the pavement management system.

Training

MTC has quarterly user meetings during which one section is devoted to computer problems that users are having. A majority of the problems come from poor quality control of the data, and in the users' group the users give feedback to each other on how to handle this problem. Another section of the user meeting features one of the pavement management support staff demonstrating a section of the pavement management system. This is to help the new users and to refresh old users' knowledge.

MTC also offers at least three different courses each quarter. One course is on the basic operation of the pavement management system, with detailed explanations of all the modules. The user starts with an empty data base and is taught to enter, check, and edit the data. Then they run the PCI calculation, analyze the output for inaccurate results, modify the maintenance treatments and costs, run budget needs, and analyze results. The course also teaches users how to run a variety of scenarios, which results in all of the features being covered at least once.

The second course is based on RBase features. The course teaches simple data base manipulation commands using both SQL and Query by Example methods. The third course is an in-depth report writing course so the users can generate the reports they need without destroying their data bases. This is all hands-on training for the students, and the only negative feedback received after training sessions was that the training computers were too slow. Each course receives a detailed explanation of the data structure, whether they want it or not, so they can see how the files relate to each other.

Hot-Line Support

One of the main reasons that MTC's pavement management system has been so successful is the telephone support available for users. A pavement management system is not run very frequently, which stresses the need for a good menu system and some accessible help for users navigating through the PMDSS. In the beginning, the problems were about 50 percent minor programming bugs and 50 percent data entry mistakes. Now they are almost all data entry errors or misuse of the program.

Conclusion

A dynamic approach is important in developing a PMDSS because hardware, software, and pavement methods are always changing. The design of the PMDSS must be flexible, to take advantage of improving technologies. Modular development will make it easier to change and to maintain the PMDSS. It is important to choose a data base management system that is user-friendly and has strict data-checking capabilities.

It is important to remember that a system can be the best in the world but still useless unless it is supported and used continually. A good user interface, ongoing training, and management support will ensure its usefulness as a PMDSS.

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Strategy for Development and Implementation of Road Management Systems in the Southern Africa Development Community Region

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Reduced budgets and increased deterioration of roads in many of the Southern Africa Development Community (SADC) countries have led to increased demands for economic efficiency in the use of scarce public funds. The inability of current approaches to be able to allocate resources among all competing components of the road network in an optimal manner has led road agencies in the SADC region to consider a more comprehensive, systems approach to road management. Unfortunately, there is no common strategy for the development of such systems in the 10-country SADC grouping, which is important for a region wishing to harmonize its approaches to road management. Based on experiences gained from the development of a road management system (RMS) in Botswana, a strategy is formulated for the development of such a system for the SADC countries in a manner that is considered appropriate to the prevailing scarce financial and staff resources. The RMS framework is based on an integrated, modular approach in which a central or core database, containing common data elements, is linked to and interacts with a number of decision support subsystems such as pavement management, which can be operated to achieve various objectives. This approach allows application subsystems to be added separately and in a staged manner to suit the requirements and capabilities of the road agency. An implementation strategy is proposed to take account of various issues that are likely to affect the sustainability of the RMS. These issues include institutional, organizational, operational, staffing, and training, for which various recommendations are made.

Despite the substantial efforts that were made during the United Nations Transport and Communications Decade in Africa (UNTACDA), which was first proclaimed in 1977, poor economic performance has plagued the economies of many African countries, including the majority of those in the 10-country Southern Africa Development Community (SADC) grouping (see Figure 1). Existing transport systems in the majority of these countries are still far from adequate and continue to constitute major constraints on the overall economic integration and development in the region (*1*).

As indicated in Table 1, the physical, economic, and road network characteristics of the various SADC countries vary enormously. They range from low-income countries with low-density, lightly trafficked networks, which combine to place on the particular governments a high-kilometer cost burden per road user, to relatively high-income countries with high-density, heavily trafficked networks in which road user costs are very sensitive to road conditions. In all the countries, there is a scarcity of professional staff resources at all levels of the road agency's organization (*2*).

In view of the vital role that an efficient highway system plays in the economic development of any country, priority effort is now required to return and maintain national road networks in the SADC region in good condition. Indeed, African countries have once again been prompted to request the United Nations General Assembly to proclaim UNTACDA II for the period 1991

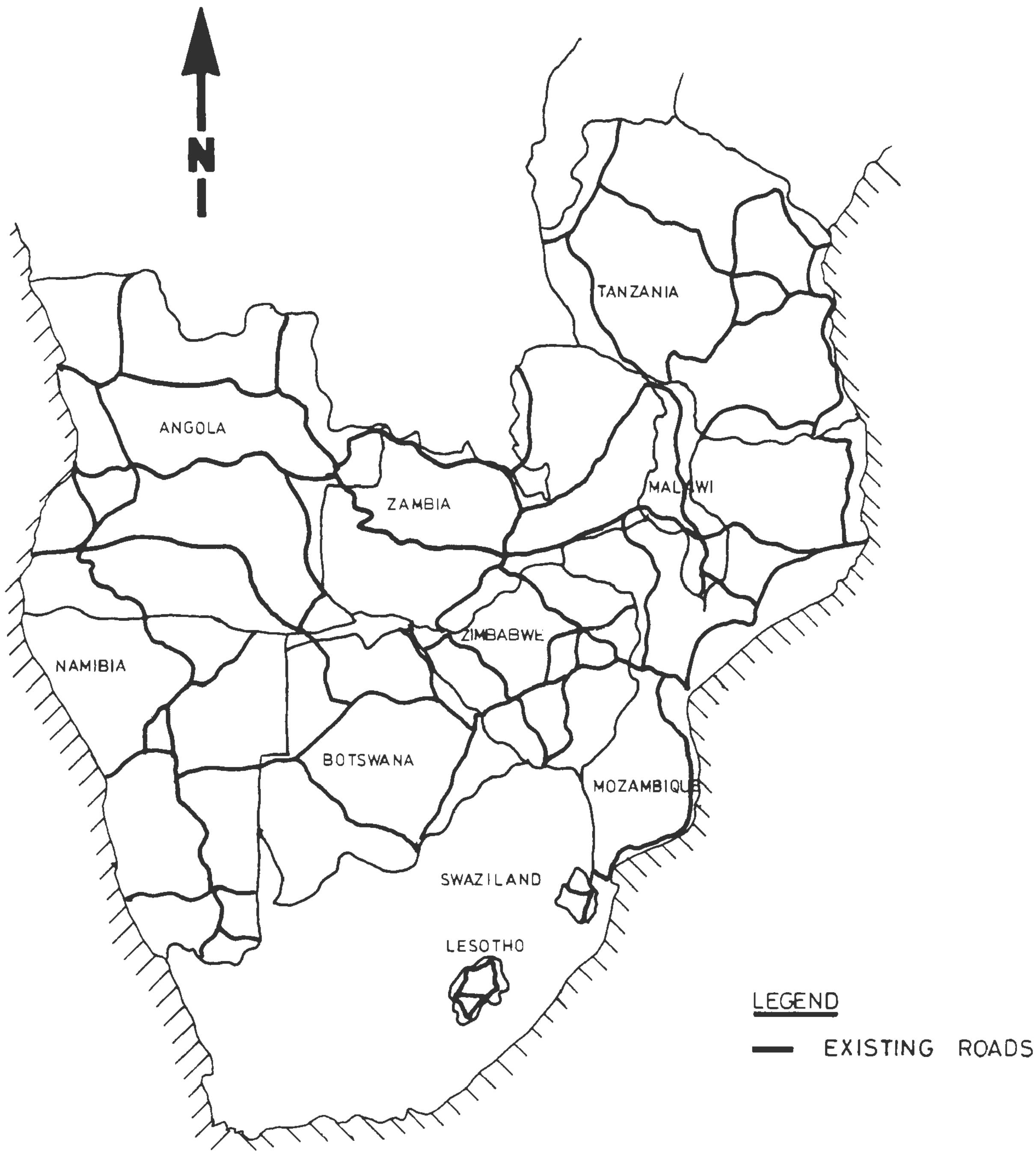

FIGURE 1 SADC regional trunk road network.

through 2000. However, rising costs, reduced resources, increased utilization of the road network, and budget constraints have all combined to make the task of managing road networks efficiently even more difficult than in the past.

Objectives

Under the conditions facing road agencies in SADC countries, a Road Management System (RMS) can play a vital role in optimizing the economic benefits and minimizing the total cost of road use and operation. The general development and current status of RMS in Southern Africa are briefly reviewed. Based on the experiences gained in developing and implementing an RMS in Botswana, an approach is then formulated to RMS development for the SADC countries of Southern Africa in a manner considered appropriate and affordable to the prevailing institutional, managerial, and technical environments. Consideration is then given to various implementation is-

TABLE 1 SADC Road Network by Country (1991–1992 Statistics)

SADC Country	Pop (Mill)	Area (1000 sq. m)	GNP per capita (US $)	Main Network				
				Length (km)		Density in kilometres per:		
				Total	% Paved	100 sq km	1,000 pop	$1 Mill of GNP
Angola	9,7	1 247	610	25 304	35,3	2,0	2,6	41,5
Botswana	1,3	582	2 040	8 761	41,8	1,5	6,7	4,3
Lesotho	1,8	30	530	2 597	32,0	8,6	1,4	4,9
Malawi	8,5	118	200	5 571	40,0	4,7	0,7	27,8
Mozambique	15,7	802	80	29 175	19,5	3,6	1,9	364,7
Namibia	1,4	824	1 500	39 672	11,6	3,1	28,3	26,5
Swaziland	0,8	17	810	2 723	24,2	16,0	3,4	3,4
Tanzania	24,5	946	110	55 500	15,8	2,5	2,2	210,9
Zambia	8,1	753	420	20 653	31,6	2,7	2,5	49,2
Zimbabwe	10,4	391	640	18 401	46,5	4,7	1,8	28,8
Total	72,2	5 710	-	206 289	-	-	-	-
Average	-	-	647	-	29,8	4,9	4,7	73,6

Sources: World Development Report, 1992; SADC Road Statistics 1992/93.

sues that are likely to affect the sustainability of an RMS in a typical SADC road agency. Finally, conclusions are drawn regarding an outline strategy for the development and implementation of RMSs in Southern Africa, where there is now a strong impetus for their introduction.

ROAD MANAGEMENT SYSTEMS

Outline Concepts

In principle, an RMS includes a set of established and documented procedures that can be used by road managers for evaluating alternative strategies in a systematic and coordinated manner with the objective of providing and maintaining a road system at minimum cost and maximum efficiency. The requirements of such a system entail data collection, storage, and analysis and involve procedures to predict, evaluate, optimize, and, ultimately, to facilitate decisions aimed at achieving the best course of action.

In the SADC region, an RMS would provide an all-embracing framework for making decisions on a number of diverse activities often carried out by different divisions of a road agency including, typically,

- Routine and periodic maintenance of gravel roads, paved roads, and bridges;
- Rehabilitation of pavements and bridges;
- Upgrading of gravel roads to paved standard;
- Improvement of geometric characteristics or capacity of roads;
- Provision of new roads and bridges; and
- Charging for the use of roads and bridges.

Each of the activities listed above presents a complex study on its own. However, they are all interdependent with respect to the overall need to optimize expenditure among competing components of the highway system and, in the final analysis, to levy appropriate user charges needed to finance them. Ultimately, therefore, a set of procedures is needed to ensure that the various competing components of the highway network are all managed in an optimal manner. Potentially, an RMS provides the essential tools to support and improve the decision-making process to achieve optimal solutions.

Historical Development

The need for improved management techniques as an aid for obtaining both economic efficiency in expenditures and technical effectiveness in preserving highway assets has led to the development of a variety of management systems, which have emanated mostly from the developed countries of North America, the United Kingdom, and Europe, dating back to the mid-1960s, and more recently from such countries as Australia, Indonesia, South Africa, and the Maghreb (Algeria, Libya, Mauritania, Morocco, and Tunisia). These systems have generally been highly customized and influenced by local practices, which have caused high local investment costs.

First-generation management systems have tended to deal with individual aspects of resource management in the roads sector and have often been identified under an ill-defined variety of labels such as pavement management systems, maintenance management systems, road maintenance management systems, and even road management systems. Such confusion arises from the variety of approaches and degrees of sophistication employed in their development and it is apparent that there is a major need for conceptual clarification of RMS functionality.

Notwithstanding the confusing terminology used to describe the first-generation management systems, what is clear is that they have generally concentrated on just a few components of the overall road system—traditionally the pavement component—which controls probably less than half of any road agency's budget. Clearly, in an economic climate where there is severe competition for scarce funds, there is a pressing need to consider in an integrated manner *all* components of the road system that consume these funds.

Impetus for Introduction to the SADC Region

In the SADC economic climate, where allocations to the roads sector have generally not kept pace with requirements, it is vitally important that scarce funds be allocated to competing components of the road system in an optimal manner. In addition, there is a need to recognize the linkage between expenditures on roads and the user charges needed to finance them. However, with the best of intentions, the determination of an appropriate balance of expenditure among competing components of the road system (e.g., between road rehabilitation or maintenance, new construction, or geometric improvement) cannot be competently assessed by traditional methods which have generally relied on fixed standards, subjective judgment and intuition; neither can the development of appropriate funding (cost-recovery) and pricing strategies for promoting more efficient use of resources in the roads sector—a topic that is currently receiving increasing attention by road agencies in the SADC region.

In view of the perceived inadequacies of current approaches to road management in the SADC region, member states are now giving consideration to the adoption of a "systems" approach to this all-embracing activity in order to provide a tool that can assist decision makers in making informed and cost-effective decisions based on sound principles of management and engineering. The development of such systems has been facilitated by the advent of modern information technology utilizing low-cost personal computer systems.

Unfortunately, management systems from developed countries cannot be transferred directly to developing countries because of the vast difference in the physical, economic, sociological, and technological environments that have shaped the latter's development. Consequently, careful consideration must be given to pursuing a strategy for the development of such systems which should be based on methodologies, techniques, and resources that are matched to local circumstances.

Status of Existing Management Systems

The first-generation systems that have been introduced to SADC countries, such as the Maintenance and Rehabilitation Management System (MARMS) in Malawi (*3*) and System BSM in Botswana (*4*) have been unitary or standalone systems with independent databases catering to specific aspects of road management. The drawback with such standalone systems is that often, even within the same road agency, they are operated in isolation of other systems which themselves utilize some common data elements which are collected separately and in a different format. In addition, a major limitation of some of the earlier-generation systems is their lack of economic prioritization procedures for determining the optimum distribution of funds across the *total* road network (e.g., between new construction, rehabilitation, and maintenance). Moreover, even the newer systems fail to provide a linkage between the road network condition, consequent macroeconomic effects, and the state's capacity to generate tax under various economic conditions.

In view of the above, first-generation approaches to road management system development are now recognized as being too narrow in outlook because they cater typically to the management of only part of the total road infrastructure. These systems generally offer limited scope for integrated expandability. Such shortcomings dictate a need to embark on a more comprehensive and integrated approach to road management that offers the ultimate capability for total road infrastructure management that can be pursued in a staged and balanced manner to suit the institutional and organizational environment in which the system has to operate.

Approach to RMS Development

Factors Affecting Design and Development

The guiding principle behind the design and development of any RMS is that it should be needs-driven rather than technology-driven and that it should take account of the prevailing conditions in the environment where it is to be introduced. In the SADC context there are a number of factors that are specific to the region and that place special demands on the development of an RMS. These various factors suggest that the RMS should be developed and designed in a manner that is

- Affordable and appropriate to the decision-making needs and scarce financial and human resources normally available within the administrative and institutional environment of a typical SADC road agency;
- Applicable to widely differing institutional circumstances ranging from large to small road agencies with strong to weak institutional capabilities and funding;

• Appropriate for dense to sparse networks with very high to very low traffic volumes;
• Flexible for staged development and implementation to suit the changing circumstances of the road agency;
• Conformable and integrable with the day-to-day activities of the road agency; and
• Sustainable with scarce human resources which are often transitory.

SADC System Requirements

The needs of the road agency shape the development of the RMS and should be established on a priority basis at the outset of the system development process. The emphasis in most SADC road agencies is now on preservation of existing network facilities and cost recovery compared to previous emphasis on construction of new roads at new locations. This has brought with it a strong demand for reliable, comprehensive, and accessible information to support the increasingly important role of total road asset management being undertaken by road agencies in the SADC region.

From the outcome of opinion canvassed from senior officials in SADC road agencies, the following key priority requirements have been identified as influential considerations in the RMS design process:

• Information to monitor the performance needs of the road network;
• Improvement in the planning, programming, and budgeting process;
• Determination of appropriate maintenance and design standards;
• Improvement in traffic data acquisition, storage, and analysis for planning purposes;
• Improvement in communications between road providers and road users;
• Establishment of linkages between marginal road usage costs and consequential appropriate user charging;
• Similarity between systems for minimizing RMS development costs and facilitating common methods of reporting on various aspects of the regional road network.

System Design

System sustainability and the flexibility for staged development are considered to be of paramount importance in the design of an RMS for the SADC region. A modular approach to the RMS design offers these advantages and, when based on the typical requirements of a SADC road agency, results in a framework that would typically include the following modules:

• Central database or core database: contains validated summary data generated by the subsystems and, as such, provides no real functionality within it;
• Planning: road upgrading and new road development feasibility studies;
• Pavement management: programming and budgeting of pavement and road maintenance works;
• General information and mapping: presentation of, and access to, all service and performance indicators;
• Traffic information: monitoring, analysis, and forecasting of road traffic, volumes, composition, and loading;
• Bridge management: programming and budgeting of bridgeworks (replacement, maintenance, materials);
• Maintenance management: development of performance standards, budgeting of resources, scheduling of activities, provision of management information; and
• Administration and cost control: cost accounting, budgets for expenditures and revenues.

The essential concept behind the RMS design is that of an integrated system in which the central or core database is linked to and interacts with a number of decision support systems (see Figure 2) that can be operated to achieve various objectives. Ultimately, the system framework is intended to encompass a variety of decision support systems reflecting the country-specific needs of SADC road agencies. A key point in this approach is that an overall system framework must be agreed on at the outset of the development process and followed through to its full implementation, even though this may be staged, to ensure overall compatibility of the end product.

The system architecture adopted for the SADC RMS is considered to be conceptually appropriate for a typical road agency in the SADC region, with subsystems de-

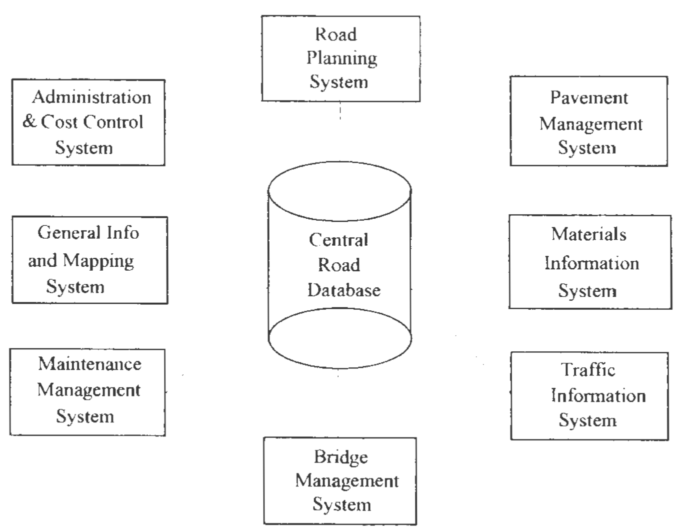

FIGURE 2 Conceptual outline of SADC road management system.

signed for individual divisions of the road agency. Ultimately, the system framework is intended to encompass a variety of decision support systems which should reflect the country-specific needs of SADC road agencies.

The integrated modular approach to the SADC RMS design differs significantly from the previous independent systems approaches and offers the following important advantages:

In the individual SADC country context:

- Undertakes total infrastructure management in a comprehensive and coherent manner;
- Allows application modules to be introduced separately as and when required without affecting the integrity of the system;
- Benefits from data integration and centralized maintenance and upkeep of a common database, including centralized updating; and
- Offers flexibility for operation of the subsystems either by individual divisions of the agency or by a dedicated unit.

In the regional SADC context:

- Allows economies to be derived from adopting a common design of the system framework;
- Provides common data standards for technical interchange between SADC countries;
- Allows common training to be undertaken and facilitates sharing of data collection and exchange of road performance and user characteristics; and
- Provides a similar basis for establishing road costs to help in the establishment of equitable user charges for transit traffic.

The RMS framework described above accords with recent World Bank guidelines on RMS design (*5*) that stress the attributes of modular system development for staged development to meet the changing needs of a road agency.

System Functionality

The architecture adopted allows the functionality of the RMS to be extended, as and when required, to cater for a wide variety of road agency functions. However, achievement of such functionality hinges critically on the choice of appropriate hardware and software since the latter, especially, influences all software operations and future expansion and upgrading of the system. Based on the need for flexibility of future upgrading to a workstation configuration within a UNIX environment, a fourth-generation language database management system is recommended for the software environment.

Analytical Tools

To achieve a capability for formal economic prioritization and optimization, and to minimize system development time, the World Bank's HDM-III model is recommended as the preferred basic analytical tool for the RMS. Verification studies to assess its applicability to local conditions led to a number of minor enhancements to the VOC and unpaved road deterioration relationships based on research work carried out in Southern Africa since the Brazilian study (*6,7*). Ultimately, however, the investigations carried out have shown that, with basic local/regional calibration, HDM-III remains probably the most reliable quantitative basis for highway project and program appraisals in Southern Africa (*8*).

In support of the need for providing a continuous calibration check on the predictive relationships in HDM-III, there is an important need to closely monitor a number of representative test sections on the SADC Regional Trunk Road Network. Such work should be carried out on a collaborative basis and in a closely controlled manner, possibly by the research arm of SADC.

Implementation Aspects

General

To ensure successful implementation of an RMS in any organization, it is essential that an implementation strategy be developed prior to its introduction. Such a strategy should address the various implementation factors that could affect the success of the system within the organization as well as the interactions of the human beings involved and their differing needs and desires.

The following implementation factors merit special consideration by SADC road agencies:

- Institutional,
- Organizational,
- Operational,
- Staffing, and
- Training.

Institutional Issues

Institutional issues include those issues that affect or are affected by the environment in which the road agency operates. These are discussed below.

Personnel Issues

A potential barrier to integration of the RMS within a road agency is misunderstanding of the system's capabilities or a perceived invasion of "personal turf" by some individuals. For these reasons, right from the outset the highest priority should be given to the involvement of personnel who will be operating and using the RMS. If line managers and supervisors are not familiar with or convinced of the benefits of the system, it will probably fail. Consequently, field personnel should be involved throughout the development process with the hope that they will adopt and subsequently promote the system as their own.

Although it is sometimes difficult to obtain and sustain, top management support is viewed as critical to the successful implementation of an RMS within an organization. It is therefore important to demonstrate to top management how an RMS can be used to support decision making. However, care must be taken not to oversell the technology.

Funding

Funding is a potential problem for both the development and operation of an RMS in the SADC region. Such systems cannot be introduced without incurring additional costs within the road agency. A realistic estimate of funding required for system development and subsequent operation should therefore be made as a basis for budgeting and to secure support from external sources.

The development of the Botswana RMS suggests that the cost of developing and implementing a basic RMS (central database plus three subsystems, including consultancy costs, hardware, and software) is on the order of approximately U.S.$300,000. In addition, operational costs, involving particularly periodic data collection, including inventory, condition, and visual assessment in HDM-III input format, can be expected to cost U.S.$100/km.

The additional costs of operating the system are likely to be small in comparison with total highway expenditures and should be compared with potential benefits under the following headings:

- Improved general management of the road system,
- Better design of maintenance and rehabilitation works,
- More cost-effective use of annual budgets, and
- More reliable basis for determining policies and budget levels

Communications

Since an RMS provides new information affecting many operating units within the organization, new communication channels, both formal and informal, must be established at all levels within the road agency. Provision of reliable and understandable information will also enhance support for the RMS initiative.

Organizational Issues

General

Introduction of an RMS to any organization constitutes a change of some magnitude. Ultimately, the extent to which an organization succeeds in adapting to such change has a direct bearing on the integration of the technology and the realization of its benefits. Hence, every effort should be made to integrate the new technology with as little disruption as possible within the organization.

A staged or incremental approach to the introduction of an RMS is considered necessary to enable the organization to gradually develop the institutional capability to cope with the introduction of new systems and to minimize impact on the agency's organization as well as to maximize the utilization of the system.

Organizational Factors

The integration of an RMS into any organization's decision-making process almost inevitably requires changes to its structure and work patterns. Staff invariably have to learn new skills and have to adapt to new tasks and a different working program. Moreover, there are cases in which acquired skills and knowledge are effectively lost. It is therefore essential that all levels of management be well informed of the details of the RMS as well as the benefits and limitations of the system. This minimizes the resistance to the successful implementation of the system.

The RMS architecture proposed for the SADC RMS offers flexibility for operation of the subsystems either by individual divisions within the agency or by a dedicated unit set up for that purpose. Such flexibility recognizes the varying needs and operational styles of SADC road agencies and ultimately facilitates the process of integrating the RMS into a particular organization with relative ease.

Two basic options, each with perceived advantages and disadvantages, are available to SADC road agencies:

1. Centralized operation by personnel operating as a single, dedicated unit within either an existing division or a new planning division; and
2. Decentralized operation with individual subsystems placed in functional and regional divisions each having independent access to the central database by a local area network (LAN).

Option 1 may be viewed as a top-down approach that offers the advantage of closer control on the use of the system including, importantly, easier upkeep and updating of the central database. This option is probably better suited to the lesser-resourced road agencies involved in the management of comparatively small networks.

Option 2 may be viewed as a bottom-up approach that offers the advantage of allowing a subsystem to be operated by a particular division thereby placing the data close to those most highly motivated to maintain, audit, and update the data. However, for such a system to be successful, there need to be clearly defined practices on the auditing, extent, and timing of updates to the data and on the usage of recent data that may be available on the other subsystems but not yet cleared to the central data base.

Option 2 requires strong management of the central database and close liaison with decentralized users and is probably more applicable to a large, well-resourced organization that is involved in the management of comparatively large networks.

The comparatively weak staffing environments of most of the SADC countries would suggest that, at least initially, a centralized operation by personnel within a dedicated road management unit (RMU) would be the preferred organizational arrangement. Once the system becomes well established and understood, there is scope for decentralization of its operations and devolution of decision making, if considered appropriate.

The role of the RMU is seen as a dual one in terms of providing

- A support function in terms of information and initial proposals, and
- A line function in terms of final programs, budget allocations, and action plans.

The unit would be held responsible for the collection and processing of data and distribution of information. It would therefore need to establish strong reciprocal information links within the overall organization. In view of its function and role, the RMU should preferably be located at a high level in the organization, close to the decision makers. This facilitates communication with those affected, including both top and lower management levels in the organization.

Operational Aspects

Probably the largest component of running costs for operating an RMS is that incurred in data collection. It is therefore important to select data acquisition technology that matches the requirements and resources of the road agency. In this regard, two basic options are available to SADC road agencies, as follows:

- Use of in-house staff using manual, semiautomated, or automated equipment; and
- By contract using external staff and equipment resources.

Ideally, there is a preference for using in-house staff for data collection as not only does this option offer the opportunity for staff to acquire "hands-on" experience, but also the necessary familiarity with the network to facilitate subsequent interpretation of the data. However, this option is viable only if adequate staff resources are available, failing which the use of contract services is the alternative option.

The choice of data collection equipment is also dependent on staff resources. Automated or semiautomated methods of data collection offer a number of advantages over manual methods such as:

- Increased number of parameters that can be accurately measured over the road network,
- Increased speed of data collection,
- Decreased costs and increased reliability in data transfers from survey to database,
- Decreased costs for training and retaining staff used only periodically,
- Decreased pressure on scarce staff resources, and
- Increased work safety.

However, when carried out in-house this type of equipment requires relatively highly skilled, trained staff for its operation and maintenance. In addition, for single-country networks of a few thousand kilometers, high-speed, automated equipment would be greatly underutilized but its viability would be enhanced if its use could be shared with other SADC countries on a continuous basis thereby living up to the eschewed principle of harmonized approaches to road management.

Adopting HDM-III as the preferred technoeconomic model within the RMS has the advantage of allowing shared equipment to be operated in a consistent and common manner for each country, thereby exploiting the economies of scale to be derived from such an approach.

In the SADC region, the comparatively weak staff resource environment would tend to inhibit the use of in-house staff for data collection. Thus, the option of sharing high-speed, automated equipment is an attractive proposition which should receive careful consideration by the SADC countries.

Staffing

In a small-database environment catering for a few thousand kilometers of roads, as is the case in most of the SADC countries, the RMU can be manned by two or three personnel from the road agency's staff, aided by external systems support personnel on an ad hoc basis.

The staff resources required to manage and operate an RMS in a SADC road agency would typically comprise the following:

- Road management engineer (senior grade)—responsible for overall management of the system and for providing all information, action plans, programs, and budgets, etc. to relevant end users within the road agency;

- Database/data collection engineer (middle grade)—responsible for overseeing all data collection including auditing and updating and providing assistance to the road management engineer in aspects of operation of the system;
- Computer technician (technical grade)—responsible for data verification and entry to the system databases and for providing assistance to the database/data collection engineer in aspects of maintenance of the databases;
- Systems analyst (specialist)—inevitably, problems will with the operation of the system hardware requiring specialized inputs by a systems or computer specialist. Such staff are most unlikely to be available from within the resources of the road agency. Recourse to external support on an ad hoc or routine contract basis is therefore be necessary and should be budgeted for by the road agency.

As indicated above, the RMU staff would also be responsible for all data collection associated with the operation of the RMS. With a vested interest in obtaining the right quality and quantity of data for the RMS, they are best placed to undertake or at least oversee the important data collection exercise.

Training

As noted above, staffing in the SADC region is a very scarce resource and provides probably the greatest constraint to RMS sustainability. It is vitally important that personnel throughout the agency receive general training on the capabilities of the system and its role in the decision process within the organisation. In-depth training is also required for those directly involved with the continual operation of the system.

In view of the constant turnover of staff in SADC road agencies, continuous training should also be undertaken with the aim of avoiding reliance on just one or two individuals for system sustainability.

Summary and Conclusions

The introduction of RMSs to many of the SADC countries in Southern Africa is currently being contemplated. Unfortunately, there is as yet no common strategy for the development of such systems, which is important for a region seeking closer economic integration and wishing to harmonize their approaches to road management on the 30 000-km SADC regional trunk road network.

From experiences gained in the development of an RMS for Botswana, a strategy has been formulated for the SADC region which is considered to be appropriate to the scarce financial and human resources that typically prevail in the 10-country grouping. The strategy seeks to establish a common conceptual design for a SADC RMS and to promote the development of independent but compatible computing environments as well as common primary reporting procedures and performance indicators among all the SADC countries.

The following summary guidelines are recommended as a strategy for the development of a SADC RMS.

Technical Issues

- First-generation RMSs are not appropriate for application to the SADC region because they cater to just a few components of the overall road system and are not able to undertake total infrastructure management;
- The development of a SADC RMS should be tailored to local needs and should be kept as simple and practical as possible, starting with a central data base, which is the heart of the system; and
- A modular approach to the development of the system should be adopted that will allow the addition of decision support subsystems as and when required to suit the needs and circumstances of the road agency.

Institutional Issues

- Obtain the approval and support of top management to provide policy input, determine priority objectives, and facilitate the provision of operational funds, effecting the necessary organizational changes and obtaining other necessary resources;
- Involve relevant staff throughout the development process; and
- Ensure realistic estimates are made and budgets and human resources requirements are provided for the continuing operation of the RMS.

Organizational Issues

- Initially, a dedicated RMU should be set up for the management and operation of the RMS and should be located at a high level in the organization. Thereafter, decentralized operations can be considered.

Operational Issues

- Data acquisition technology should be adopted which matches the requirements and resources of the road agency;
- Selection and procurement of equipment can be undertaken independently according to individual country

preference, but there are significant economies to be derived from the use of shared equipment and production of similar reporting formats between countries.

Staffing Issues

- As a minimum staffing requirement to manage and operate the RMS, provision should be made for a road management engineer (senior grade), a database/data collection engineer (middle grade), a computer technician (senior technical grade), and specialist input from a systems analyst on an ad hoc basis;
- In view of high staff turnover, efforts should be made to avoid reliance on just one or two key individuals for system sustainability; and

Training

- Continuous training should be provided not only for technical staff involved in the management and operation but also for decision makers involved in using the system outputs.

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Developing a Customized Pavement Management System for Port Orange, Florida

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The Port Orange Pavement Management System (POPMS) was developed cooperatively by the city of Port Orange, Florida, and the Center for Urban Transportation Research (CUTR). This subject is timely for local municipalities contemplating the development of a pavement management system (PMS). Recent FHWA policies now require that each state have an operable PMS by January 1993 in order to receive federal aid funding. It is anticipated that the states will establish similar requirements for local municipalities to continue receiving state matching funds. In particular, the system "customizing" process serves as a valuable guideline and case study for local governments seeking to investigate and implement a small-scale PMS. This project was set in motion to provide a rational basis for determining the financial deficiencies of roadway maintenance and rehabilitation to be met by a proposed transportation utility fee (TUF) as a means of generating much-needed revenue. The city of Port Orange, with a population of 35,000, initiated an investigation to develop a simple but comprehensive PMS for its 142-mile (228.62 km) street network. Very minimal street inventory data, limited field staff time availability, and only elementary knowledge of PMSs were all considerations. Before a pavement condition survey was carried out by the city, CUTR conducted a training session on city street network sampling strategy, visual condition survey techniques, development and completion of conditions survey forms, and pavement surface-distress–type classification guidelines. CUTR prepared a customized Pavement Conditions Survey Manual to facilitate city staff training. Upon the city's completion of the field condition survey, the pavement condition data were cataloged into a microcomputer assessment model. A total of 386 sample segments, or about 6 percent of the total city street surface area, were identified and evaluated. (The POPMS model is a modified version of a program being utilized by Carson City, Nevada. The modifications reflect specific maintenance and rehabilitation decisions by Port Orange.) A POPMS Evaluation Report and "report card" were prepared by CUTR to translate the results of the assessment model to city policy makers, to quantify and set priorities for specific pavement maintenance and rehabilitation project costs, and ultimately to predict and combat the effect of delayed expenditures more effectively.

This paper describes the four key elements in the development of the Port Orange Pavement Management System (POPMS). The first section outlines the street network sampling strategy. This strategy included a delineation of sample sections as distinct from sample segments. The Port Orange city street network was categorized in three groups of roadways: (*a*) subdivision locals, (*b*) nonsubdivision locals, and (*c*) collectors. The inventory characteristics for each group of roadways are summarized.

The second section describes the presurvey training conducted by the Center for Urban Transportation Research (CUTR) and the pavement conditions survey conducted by the city. Visual condition survey techniques, the development and completion of conditions survey forms, and pavement surface-distress–type classification guidelines are discussed.

The third section describes the customized pavement assessment model developed for the city, specifically, the treatment alternatives selected, associated unit costs and life spans, severity and priority coding, and decision making for maintenance and rehabilitation actions.

The results of the assessment model are summarized in the final section. The detailed, multiple report outputs of the model were included in a separate notebook transmitted to the city. For the sake of completeness, this paper also includes the 1991 POPMS "report card," outlining required maintenance, rehabilitation, and reconstruction projects by treatment type.

Street Network Sampling Strategy

The most important distinction in street network sampling is the difference between sample sections and sample segments (*1*). Sample sections are the generalized groupings required for pavement sampling. Sample sections were separated into three primary categories: (*a*) subdivision locals, (*b*) nonsubdivision locals, and (*c*) collectors. Within each of these categories, subdivisions and streets were further stratified and subgrouped by age of pavement and type of subbase (limerock or soil-cement).

Sample segments are the specific pavement surface areas from each sample section that are surveyed for pavement surface distress conditions. Sample segments are typically 2,500 square feet (232.5 m^2) in area (according to AASHTO guidelines), and the number of sample segments within each sample section is determined by the desired sampling rate as a percentage of the total pavement surface area (*1*). For example, if the total sample section area is 250,000 square feet (23,250 m^2) and the desired sampling rate is 15 percent, then a total of 15 sample segments would be surveyed. The selected sample segments are to be representative of the overall sample section pavement conditions (*2*).

Sampling rates for each sample section were determined by the city of Port Orange. Collectors were the most critical for pavement condition evaluation, according to the Port Orange Public Works Department, and thus they required the maximum sampling rate for visual surveys suggested by AASHTO (15 percent). Nonsubdivision locals in the city handle significantly less traffic than collectors, but the age and type of the subbase generally were not well documented for this type of street. Therefore, a 5 percent sampling rate was selected for them. Finally, subdivision locals also handle less traffic than collectors, but the pavement inventory records for them were considered to be much more accurate and reliable than those for nonsubdivision locals. Therefore, an average sampling rate of 3.5 percent was selected for subdivision locals.

The range of sampling rates for each sample section under subdivision local streets varied from 1 to 5 percent, depending on the age and type of subbase. For example, at one extreme, soil-cement base pavement built before 1975 was sampled at 5 percent, whereas limerock base pavement constructed after 1985 was sampled at 1 percent. Clearly, there was visibly greater surface deterioration of soil-cement base pavement than of limerock base pavement. This finding, coupled with pavement age, led to the stratification of the sampling rate (1 to 5 percent) among the subdivision local street sample sections. Table 1 illustrates the generalized street network sampling strategy and specific sample section groupings established by the city.

Pavement Condition Survey

CUTR conducted a presurvey training session at the City of Port Orange offices. The city decided to utilize one, two-person survey crew for the POPMS survey because of limited availability of field staff. Including the presurvey training, the total time required by the city to carry out the survey and to review and check the completed survey forms was approximately 300 person-hours. The two city field engineers who conducted the survey had a combined total of 30 years of experience in roadway construction management and inspection. They were very familiar with the specific characteristics of roadway pavement conditions in Port Orange. The selection of these two par-

TABLE 1 Breakdown of Overall Street Network Sampling

Street Category	Miles/km	Sample Sections	Sample Segments	Sampling Rate *
Subdivision Locals	97/156km (68%)	27 (48%)	168 (45%)	3.5%
Non-Subdivision Locals	23/37km (16%)	11 (20%)	53 (14%)	5%
Collectors	23/37km (16%)	18 (32%)	153 (41%)	15%
Totals	142/230km	56	374	5.4%

* Based on total meters squared (not kilometers) of street categories

ticular individuals significantly reduced the subjectivity usually associated with visual surveys.

The purpose of the presurvey training was to review the visual survey procedures and to discuss the survey form as presented in the POPMS Condition Survey Manual that had been prepared by CUTR. A presurvey field review was also conducted by CUTR to assure thorough understanding of the typical questions and problems that might arise in the field. For this exercise three sample segments were selected, and practice surveys were performed independently by each surveyor. These were later reviewed with the surveyors for completeness, accuracy, and any inconsistencies (*3*).

Four pavement distress types were identified by the city as having the most importance in monitoring deterioration. The distress types were as follows:

1. Alligator cracking,
2. Longitudinal and transverse cracking (block cracking),
3. Patch deterioration, and
4. Edge cracking.

The presence of these four distress types was recorded by levels of extent and severity, and this information was used directly in the assessment model. The presence of rutting, raveling, and polished aggregate was also recorded, but for informational purposes only. As requested by the city, additional space was provided on the survey form for miscellaneous comments on other roadway-related conditions that might be observed in the field (i.e., areas of poor drainage and settling, inadequate utility cuts, etc.).

The values used for severity/extent and the corresponding priority coding are listed in Table 2. Ranges for extent of distress are listed in the table. Differences in severity (slight, moderate, and severe) had been identified and visually depicted in the POPMS Condition Survey Manual.

These values were approved by the city on the basis of a review and relative comparison of similar values employed in other pavement management systems (*4*). The assessment model, discussed later in this paper, is structured to determine the most appropriate maintenance or rehabilitation treatment according to the severity/extent cod-

TABLE 2 POPMS Distress Types, Severity/Extent Coding, and Deduct Values

Extent	Severity/Extent Coding			Deduct Values (Priority Coding)		
	Slight	Moderate	Severe	Slight	Moderate	Severe
Alligator Cracking						
0 not observed						
1 1-10%	1S	1M	1V	5	15	20
2 11-25%	2S	2M	2V	10	20	30
3 26-50%	3S	3M	3V	20	40	50
4 greater than 50%	4S	4M	4V	30	50	60
Block Cracking — Extent(per 100 L.F.)						
0 not observed						
1 1-100 in	1S	1M	1V	3	5	12
2 101-300 in	2S	2M	2V	5	10	16
3 greater than 300 in	3S	3M	3V	10	20	30
Edge Cracking						
0 not observed						
1 1-100 in	1S	1M	1V	2	4	6
2 101-300 in	2S	2M	2V	4	8	16
3 greater than 300 in	3S	3M	3V	6	16	20
Patch Deterioration						
0 not observed						
1 1-10%	1S	1M	1V	5	10	15
2 11-25%	2S	2M	2V	10	15	20
3 26-50%	3S	3M	3V	15	25	35
4 greater than 50%	4S	4M	4V	20	30	40

ing and to use the deduct values to establish the project priority (*5*).

Treatment and Priority Assessment Model

Several microcomputer software packages for PMSs were evaluated by CUTR. The model selected was developed and is currently being used by Carson City, Nevada (*6*). A DBASE III PLUS program executes the Carson City (POPMS) procedure and assists in managing the Port Orange pavement condition survey and street inventory files.

This program was selected because it is relatively simple, completely menu-driven, very suitable for the visual survey data and street network size of Port Orange, and capable of producing the types of evaluation reports most appropriate for Port Orange (*6*). The types of maintenance and rehabilitation treatments and the unit costs and life spans relative to Port Orange were integrated into the program used by Carson City to customize the program's operation for Port Orange. Also, pavement deterioration can be predicted as data are collected over the years (i.e., trend analysis) to predict the impact of delayed treatment actions more effectively.

The treatment options, unit costs, and life spans established by Port Orange are listed in Table 3 (*7*). It is also important to note that the expected average life span indicated for each treatment assumes that preventative surface maintenance is performed every 5 to 6 years.

The POPMS decision tree illustrated in Figure 1 depicts the entire methodology for the POPMS assessment model. Depending on the severity and extent of observed pavement distress conditions, treatment options, as specified by the city, were selected. The treatment selected (and costed) is the one that takes care of the severity/extent of the most severe distress type first (*8*): in other words, alligator cracking before patch deterioration, patch deterioration before block cracking, and block cracking before edge cracking.

TABLE 3 POPMS Treatment Options

Maintenance Treatments	Avg. Cost (sq.ft.)	Avg. Life (yrs.)
1. Crack Sealing-MA	$ 0.11	3
2. Patching-MB	$ 0.14	4
3. Chip Seal-MC	$ 0.17	5
Rehabilitation Treatments	**Avg. Cost (sq.ft.)**	**Avg. Life (yrs.)**
1. 1-inch overlay-RA	$ 0.33	10
2. 2-inch overlay-RB	$ 0.44	15
3. Re-Cycling-RC	$ 0.35	12
4. Total Replacement-RD	$ 1.11	20

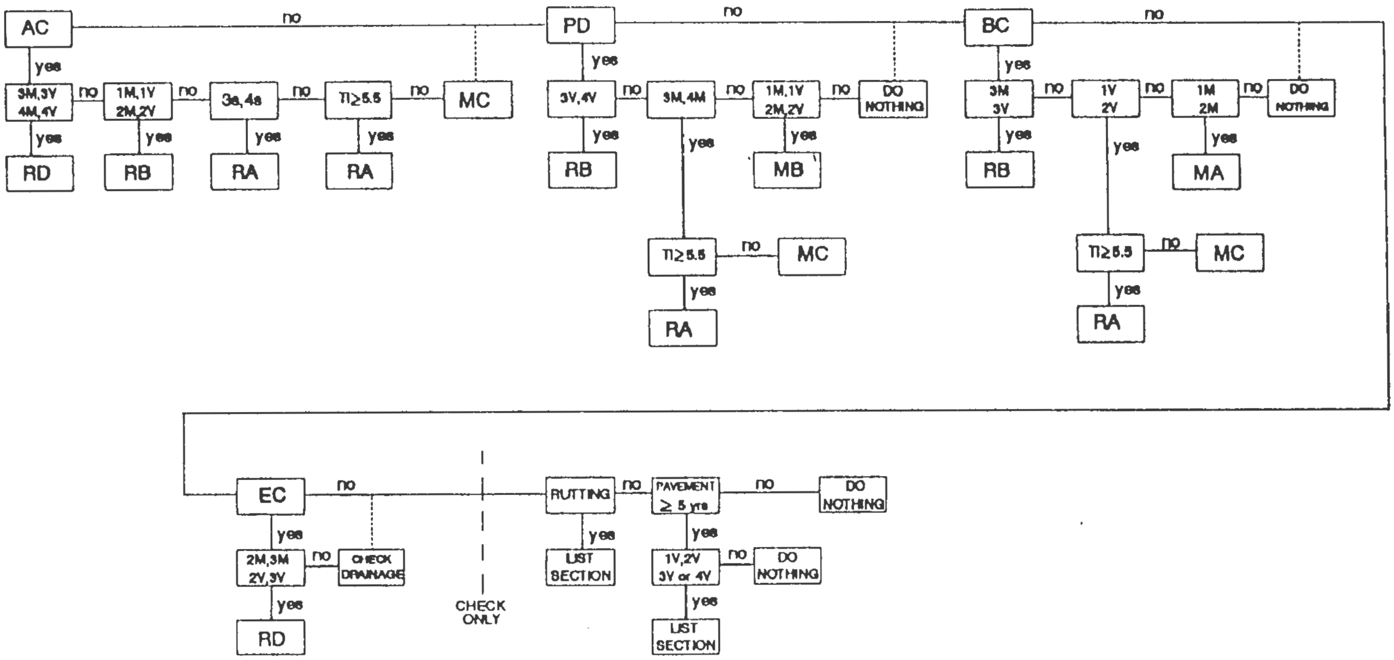
Deduct values (listed in Table 2) corresponding with the observed distress severity and extent determine the priority for each recommended treatment. The maximum condition score (151-sum of deduct scores) is divided by the traffic index to calculate a project priority score.

Generally speaking, the lower the condition score the higher the priority for a given roadway treatment project. For example, a collector roadway that receives severity coding of 3M for alligator cracking, 3S for block cracking, 1V for edge cracking, and 2V for patch deterioration would have a total condition score of 75 [151 − (40 + 10 + 6 + 20)]. The project priority score is determined by dividing the condition score by the traffic index, or 75/5.5 = 13.64. The project priority score is compared to all other project priority scores, and the *lowest* overall score receives the *highest* priority.

All other scores (projects) are then ranked in ascending order (i.e., the worst would be first). The treatments selected by the POPMS decision tree serve only to differentiate between basic levels of maintenance, rehabilitation, and, finally, the need to reconstruct or replace (*9*). For example, chip seal (MC) does not imply that other forms of seal coat such as fog coat or sand slurry seal may not be more appropriate, given the specific site conditions. A 2-in. overlay (RB) stipulates that something more than a thin overlay is required, and hot mix recycling may in some cases be a cost-effective substitute to thin overlays. In most cases, pavement design engineering and coring should be anticipated in order to determine the specific treatment. The POPMS decision tree can be refined over time to reflect more closely the historical trends, specific treatment triggers, and proven alternative options in the Port Orange area.

Based on the current POPMS decision tree and treatment and priority coding, several implications have been formulated by the city of Port Orange.

1. Problems associated with alligator cracking are most critical, followed in order by those from patch deterioration, block cracking, and edge cracking. Project costs are driven by the most critical distress type observed, not by the combination of all distress types (*10*).
2. The only distress conditions that warrant total replacement are 3M, 3V, 4M, or 4V for alligator cracking, and 2M, 2V, 3M, or 3V for edge cracking.
3. Chip sealing is not a preferred treatment on roadways classified as collectors, or above (*11*).
4. If edge cracking is observed but is not in the high severe/moderate condition range, a listing of the roadway will be printed in a special report to trigger an evaluation of site drainage conditions.
5. Any rutting observed will trigger a listing of that roadway's name in a special report.
6. Any roadway pavement constructed 5 or fewer years ago and indicating high severity/extent of any distress type will be listed in a special report.



DISTRESS TYPES

AC = Alligator Cracking
EC = Edge Cracking
PD = Patch Deterioration
BC = Block Cracking

TREATMENTS

MA = Crack Sealing
MB = Patching
MC = Chip Seal
RA = 1-inch Overlay
RB = 2-inch Overlay
RC = Re-Cycling (not currently utilized)
RD = Total Replacement

TI = TRAFFIC INDEX

4.0 = Residential Dead-end
4.5 = Residential-local
5.5 = Collector
6.0 = Industrial-local
6.5 = Arterials
7.0 = Truck and Bus Routes

FIGURE 1 POPMS decision tree.

Evaluation Results

The POPMS assessment model was developed to determine the costs associated with city pavement maintenance and rehabilitation needs. The needs are based on a visual survey of representative pavement surface distress conditions and prescribed treatments determined by the city. It must be understood that the results (costs) are derived from the policy of the city as described in this paper. Future iterations of the assessment model can reflect modifications to the current policy if that is desired.

The initial assessment model run was compiled without financial constraints (or budget limitations) in order to obtain the worst case scenario for funding. It was most important to determine the magnitude of funding that would have to be generated to bring the entire city street system up to acceptable conditions. Total maintenance costs were estimated to be approximately $990,000, and total rehabilitation costs were estimated to be approximately $3.5 million. This estimate of about $4.5 million for the entire city street system was assumed to be programmed over a significant period of time, which would be determined by the city. A 1991 POPMS "report card", shown in Figure 2, was developed to indicate the allocation of treatments across the entire city street system.

As can be observed from Figure 2, 7 percent (about 9.5 miles, or 15.3 km) of the city street system requires total replacement, and 18 percent (about 25 miles, or 40 km) requires no maintenance or rehabilitation. Further, 27 percent requires a 2-in. overlay, 24 percent calls for crack sealing, and 17 percent of the system has been identified for poor drainage areas (i.e., MD). A separate POPMS assessment model output and general instruction package was prepared by CUTR to assist the city in the interpretation of results. Generally, this output package included the following detailed information:

1. Basic instruction for POPMS program operation and menu listing.
2. Detailed reports on condition scoring, rehabilitation and maintenance by priority number and street, and a specially generated cost report by street in project pri-

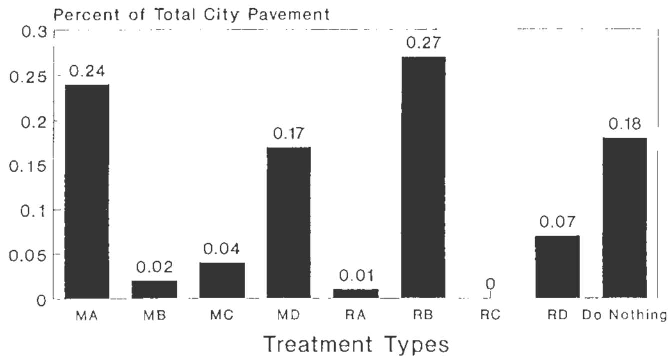


FIGURE 2 1991 POPMS report card. (Note: See abbreviation key in Figure 1.)

ority order. Three other specially requested reports on rutting, severe edge cracking, and new pavement with severe distress conditions were also included.

3. Table of contents and information on POPMS subprograms.

4. Alphabetical index of all street numbers, and database field listings.

Recommendations

It was recommended that POPMS be used by the city of Port Orange as a roadway maintenance and rehabilitation tool, but not without further site-specific engineering as needed to determine final design treatments (*12*). Further, as additional pavement condition surveys are conducted, the operation of POPMS should become a centralized responsibility within one city department. The cost estimates provided by this effort should be interpreted as the order-of-magnitude from which to base a proposed transportation utility fee; a reasonable staging time frame for the projects with established priorities should also be developed by the city.

It was strongly suggested that the city review the strategies, unit costs, and maintenance and rehabilitation treatment options structured into the POPMS model. It is important to understand that this effort represents the first iteration. Future refinement and adjustments are certainly to be expected.

Finally, as pointed out by the pavement condition survey crew, it appears that a reassessment of the specification for pavement design is needed to include all limerock base. Also, the enforcement of a more rigid specification for utility cuts certainly appears to be warranted.

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Norwegian Public Roads Administration: A Complete Pavement Management System in Operation

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The Norwegian Public Roads Administration developed a complete pavement management system (PMS) during the period 1986 through 1990. The system incorporates existing subsystems, such as condition surveys and tender preparation, and is supplemented with a programmed project and network-level maintenance and rehabilitation planning system. Today the complete system consists of pavement condition surveys, road inventory surveys, road data bank, project planning and network optimization including performance trend (past history and future predictions) and life cycle cost analysis, and tender preparation including as-built cost statistics, which all are interconnected by data processing links. Annual government grants for the maintenance and rehabilitation of national roads amount to $450,000,000. Each year 3 000 km of hard surfacings (out of total network of 53,000 km) are renewed at a cost of $150,000,000. Future developments of the pavement management system include the implementation of expert systems for selecting maintenance activities, a new interactive data base system, and an updating of the user interface.

Pavement Condition and Road Inventory Surveys

Automatic equipment based on ultrasonic sensors and digitizing boards is used for recording pavement condition (rutting, roughness, and distress). More than 20 measuring units are currently in operation. In addition, other recording equipments are used for road inventory. Road condition surveys are carried out every year. The recorded data are processed and stored in a road data bank.

Pavement Performance Prediction

Models for pavement performance prediction have been developed based on rutting and roughness. Together with traffic and pavement data, this information forms the basis for selecting appropriate maintenance and rehabilitation methods.

The performance trend models are partly empirical and partly mechanistic. In the future, the selection of maintenance and rehabilitation activities will be assisted by implementing an expert system.

Road User Costs

The consequences of the chosen maintenance and rehabilitation strategies are calculated as effects on road user costs. Models calculating vehicle, accident, and time costs as a function of pavement condition have been developed and are used in optimizing procedures for obtaining the greatest life cycle benefits for road users and road authorities, taking into account the budget restraints.

PAVEMENT MANAGEMENT SYSTEM

The center of the Norwegian pavement management system (PMS) is a personal computer (PC)-based system for project planning and network optimization, which includes performance predictions and life cycle cost analysis.

The system is used by the 19 local county public roads administrations in Norway for planning pavement maintenance and rehabilitation. The total national road network is made up of 53 000 km with annual daily traffic ranging from a few hundred to 100,000. Annual government grants for the maintenance and rehabilitation of national roads are $450,000,000. Annually 3 000 km of hard surfacings are renewed at $150,000,000.

The system includes four main modules in addition to several secondary modules for generating reports:

- Pavement section data;
- Data base containing data about road geometry, structural design, pavement condition, and traffic volume;
- Maintenance and Rehabilitation; and
- Data base containing different maintenance data base and rehabilitation activities (type, material, thickness, and cost).

Project Planning

This is an interactive module permitting the user to predict pavement performance, select maintenance and rehabilitation activities, and calculate agency costs and user costs related to the chosen strategy. A maximum of four different section plans can be established.

Network Optimization

This is a module selecting the optimum strategy according to the following criteria:

1. Lowest total cost (= agency cost + user cost), and
2. Agency cost < available budget.

Resource restraints for pavement maintenance and rehabilitation activities are given as fixed budget levels for each county.

Sociopolitical requirements are taken into account by use of maintenance standards for rutting and roughness. These standards, shown below, are not to be exceeded. Maintenance should be performed when these values are exceeded on 10 percent of the road section considered.

Rut depth 25 mm

	Roughness in IRI (mm/m)	
ADT	*Trunk Roads*	*Secondary Roads*
<300	4.5	6.0
300–1500	4.5	5.5
1500–5000	4.0	5.0
>5000	3.5	4.5

For maintenance strategies complying with these standards, road user costs are used as criteria for optimizing the maintenance and rehabilitation activities.

The PMS implies the pavement technology requirements given by the design and material specifications issued by the Norwegian Public Roads Administration (NPRA).

The NPRA PMS was developed from 1986 through 1990. The development aimed at incorporating all existing subsystems in an overall complete system before initiating work on further development of the different subsystems. Most of the subsystems of a complete PMS existed, but supplements had to be made within the programmed project and network-level maintenance and rehabilitation planning subsystem.

This strategy was chosen because it made it possible to incorporate existing standards and routines into the PMS, thus reducing the cost of implementing the system. The same arguments were also the basis for the decision by the NPRA to build a national PMS rather than implement an existing foreign PMS. This decision was made after screening 35 international PMSs.

The screening of the different international PMSs made it clear that all pavement management systems consist of the same basic modules. But it was also evident that the design of each module must be accommodated to the specifications and administrative routines of the local agencies if the PMS is to be successfully implemented.

The implementation of a systematic PMS may be executed in accordance with two different strategies. One is to make the existing pavement management routines more efficient by using new tools, and the other is to introduce new routines. Within NPRA, the implementation of a systematic pavement management system was based on the first of these strategies. This was the main reason for the decision to choose a tailor-made PMS.

In addition, certain factors make pavement management in Norway different from other countries. These factors are

- Extensive frost heave problems,
- Extensive use of thin asphalt surfacings (40 mm), and
- Use of studded tires [88 to 98 percent of cars and 50 to 60 percent of trucks use studded tires in winter (October through April)].

Assessment and prediction of pavement condition must take these factors into account, thus making ready-made international PMSs unsuitable for Norway.

It was also important to NPRA to be able to develop and change the system whenever they wanted. This called for an open system with source codes owned by the NPRA.

In summary, these considerations formed the basis of the NPRA's decision to develop a PMS according to its own specifications rather than implement a PMS available commercially.

Pavement Condition and Road Inventory Surveys

The main pavement condition parameters used in the NPRA PMS are transversal evenness (rut depth), longitudinal roughness, cracks, and crazing. From the measured cross-sectional profile the rut depth, rut area, and rut width are calculated. Standardized calculations of the international roughness index (IRI) are based on data describing the longitudinal profile. Intervention levels for rut depth and road roughness, so-called maintenance standards, have been established for pavement sections of the road network (see tabulation above).

Norwegian ultrasonic measuring units are operated by the local road authorities. Most of the road network, including all new pavement sections, is measured every year. Sections with high traffic volume are measured in both autumn and spring because of extensive wear caused by studded tires.

The latest equipment model, ALFRED, (Figure 1) is a combined unit measuring both cross section, including crossfall, and longitudinal profile. A divided beam 4 000 mm long with 17 ultrasonic sensors with a spacing of 250 mm is the main part of the equipment. Effective measuring speed is 0 to 80 km/hr. Cross sectional profiles are measured by the 17 sensors from the divided beam with a variable length of 2 000–3 375 mm. The resulting individual sensor spacing is 125 to 250 mm. For PMS purposes a beam length of 2 000 mm has been standardized. Rut depth is measured for each 1 m along the road. For special purposes the measuring distance can be reduced to 25 cm between transverse profiles (Figure 2).

For the longitudinal profile, the 4 000-mm beam measures the 17 distances to the road surface at 1-m intervals. Every 1 m length is described in this way by five distances measured four times, resulting in a very accurate description of the longitudinal profile. The distance between measurements can be reduced to 0.25 m.

PC programs have been developed to take care of quality assurance, graphical presentation, and reporting of the automatically collected raw data. In addition to standard rut depth, area, width, and crossfall calculations, rules have also been developed to interpret the cross-profile shape. Rut shape data combined with traffic volume, lane widths, and so forth are valuable parameters in the PMS decision process.

FIGURE 1 Equipment for measuring rut depth, crossfall, and road roughness.

On the basis of the longitudinal profile, PC programs present the IRI for 100-m intervals. The same profile data are also the basis for 3-m straightedge simulation used in asphalt contracts. Combined straightedge and IRI data give pavement engineers valuable tools to follow-up different PMS sections through spring thaw.

A central road data bank is the permanent storage place for all pavement condition measurements. Since 1987 rut depth and IRI data for about 40 000 km of public roads (80 percent of network) have been transferred annually to dedicated registers. By 1992 PMS plans for most sections were based on 4 to 6 years of measured condition development. These historical data combined with updated trend model prognoses give PMS users good tools for final maintenance and rehabilitation plans (Figure 3).

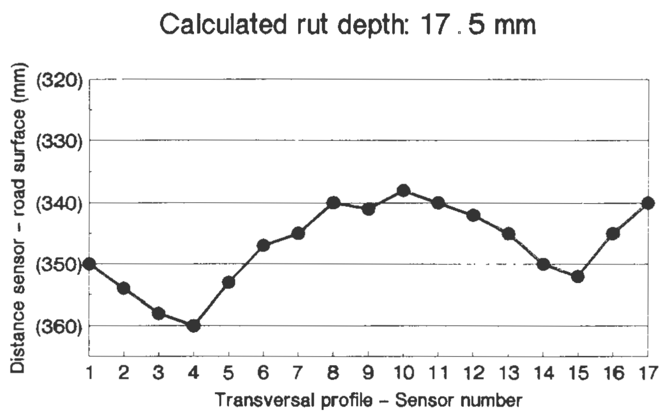


FIGURE 2 Rut depth—transverse profile as measured by 17 sensors.

In cooperation with the asphalt industry, Norwegian road authorities have developed contract bonus and deduction rules based on the measured rut depths (initial and after 3 years) and longitudinal roughness measured as straightedge values. Both contract partners agree that contracts based on delivered quality are preferable in most cases.

Pavement Performance Prediction

Roughness (IRI value) and rut depth are recorded by ultrasonic equipment at least once a year all over the national road network.

The 90th percentile for the initial and latest recorded roughness and rut depth is calculated for each PMS section and forms the basis for a prediction of the further development of roughness and rut depth.

The development of roughness is considered to follow the parabola

$$IRI_d = IRI_i + (IRI_l - IRI_i) * \left(\frac{A_d}{A_l}\right) \wedge 1.5$$

where

IRI_d = predicted roughness at a desired future date (IRI value, mm/m);
IRI_i = roughness just after the latest rehabilitation (IRI value, mm/m);
IRI_l = latest recorded roughness (IRI value, mm/m);
A_d = age of the pavement surface at the desired future date (years); and
A_l = age of the pavement surface when the latest roughness recording was made (years).

A graphical presentation of the development of roughness is shown in Figure 4.

The development of rut depth (mainly due to wear from studded tires) is considered to follow a straight line, except for the first year when the development of rut depth is accelerated. The equation for calculating rut depth is not presented here, but the principle is shown in Figure 5.

This simple way of predicting the pavement performance has the advantage that several site-specific conditions (wear resistance, cross section, axle load limit, traffic conditions, traveling speed, and climate), which are difficult to monitor, are reflected in the surface condition recordings. Thus they need not be monitored separately for this purpose.

When pavement performance predictions are to be made before recordings are available, the user of the PMS program must estimate both the initial and some future value for roughness and rut depth. If the latest rehabilitation measure was similar to the previous one, the pavement performance during this period might be a good estimate for future performance.

If the latest rehabilitation action differs significantly from the previous one (e.g., if it includes strengthening or broadening), there will be a problem in making good pavement performance predictions using the PMS program. However, after a year when the first recordings are available, the prediction model can be used.

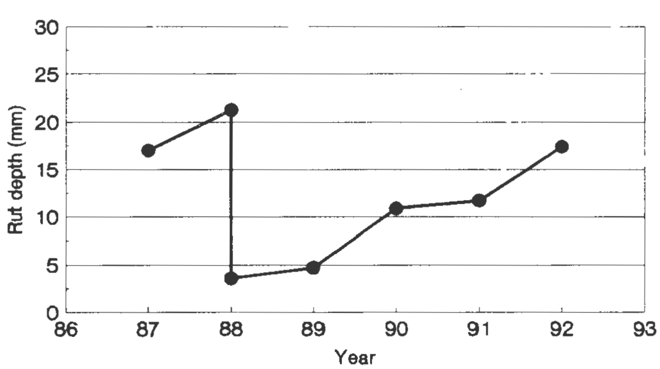


FIGURE 3 Rut depth development—pavement rehabilitation in 1988.

FIGURE 4 Development of roughness—measurements performed in years 0 and 4.

FIGURE 5 Development of rut depth—measurements performed in years 0 and 2.

The main problem associated with this way of predicting pavement performance appears when there are considerable changes in factors that have significant influence on the pavement performance, such as changes in axle load limit, traffic volume, or traveling speed.

To include these situations, a more comprehensive theoretical and empirical model has been created. This model calculates pavement distresses and performance based on input including pavement structure, cross section, traffic volume and loads, and climatic conditions. However, this model is not yet a part of the PMS planning tool.

Knowledge-Based System for Selecting Maintenance and Rehabilitation Activities

Recently, a prototype of an expert system for distress diagnosis and for selecting maintenance and rehabilitation activities on roads with flexible pavements has been developed. The system, called DEkspert, will act as a standalone system as well as a module in the next generation of the Norwegian PMS.

Pavement condition and structural strength, based on measurements and observations, are the main input to the system. The distresses handled by DEkspert are

- Alligator cracking,
- Longitudinal cracking,
- Transverse cracking,
- Rutting,
- Roughness, and
- Potholes.

Furthermore, DEkspert is able to use input about pavement design and environmental factors

- Pavement structure (thickness, type of material, age of each layer);
- Width of traffic lane and shoulder;
- Type of pavement cross section (fill/cut, soil/rock);
- Closed or open ditch;
- Slope, depth, and width of ditch;
- Traffic volume;
- Pavement deflection (falling weight deflectometer); and
- Climate.

Several sets of data covering a longer period of time can be stored. This makes it possible to study the development rate of some important distress categories. The system may take special actions or give special advice if the distresses increase at a rate higher than normally expected.

DEkspert classifies the distress situation and its cause (surface problem, drainage problem, structural strength problem) and suggests maintenance or rehabilitation activity.

DEkspert does not include cost calculations. The system presents several possible activities for which the costs have to be calculated to select the optimum solution. DEkspert is intended to supply alternative solutions to the PMS program where the cost calculations and optimizing will be performed.

Road User Costs in the Norwegian PMS

Roughness and rutting greatly affect road user costs. Several experimental or full-scale tests in different countries have proved this. Norwegian surveys and results from these international tests are a basis for the road user costs model in the PMS.

The model calculates vehicle costs, accident costs, time costs, and comfort costs as a function of the road surface condition (i.e., roughness and rutting). It also calculates the economic benefits of raising the allowable axle load up to 10 tons.

The model operates with two vehicle types—passenger cars and heavy vehicles. The characteristics of the heavy vehicle type are a weighted average of light and heavy trucks. Road user costs are calculated for each vehicle type. In this paper the functions that describe the effects of surface characteristics on road user costs related to passenger cars are highlighted.

Vehicle Costs

Vehicle costs are costs of fuel, lubricants, tires, repairs, and depreciation. Only the vehicle running costs are calculated as a function of road surface condition. Table 1 shows the average vehicle cost in cents per vehicle-kilometer (1993). The figures are economic cost (i.e., taxes are excluded).

TABLE 1 Average Vehicle Running Costs—Passenger Car and Heavy Goods Vehicle (Cents Per Vehicle Kilometer)

Cost factor	Passenger car	Heavy vehicle
Fuel	3,7	14,0
Lubricants	0,6	1,9
Tires	1,1	10,9
Repairs	6,0	29,3
Depreciation	3,4	5,0
Sum	14,8	61,1

Cost of Fuel and Lubricants

As a first step, the road user cost model calculates fuel consumption as a function of speed and the road geometry (mainly rise and fall). Second, the model calculates a multiplicative factor as a function of IRI. Figure 6 shows that the impact of an increasing IRI is just a small percentage increase in fuel consumption. The cost of lubricants varies in the same proportion.

The impact of rutting on fuel consumption is negligible with dry surfaces. In rain, when the ruts are full of water, the rolling resistance increases as a function of water depth. The average water depth is a result of crossfall, rut depth, precipitation levels and intensity, traffic volume, and the driver's behavior.

The increase in rolling resistance gives an increase in fuel consumption when driving on wet surfaces, as shown in Figure 7. The PMS also calculates the distribution of traffic on dry, wet, and snow-covered surfaces.

Cost of Tires

Cost of tires is related to roughness and rutting. The wear caused by studded tires gives, under certain conditions, a smoother surface, which in turn reduces normal tire wear. This reduction increases with increasing rut depth. Cost of tires in cents per vehicle-kilometer is extremely low with wet surfaces.

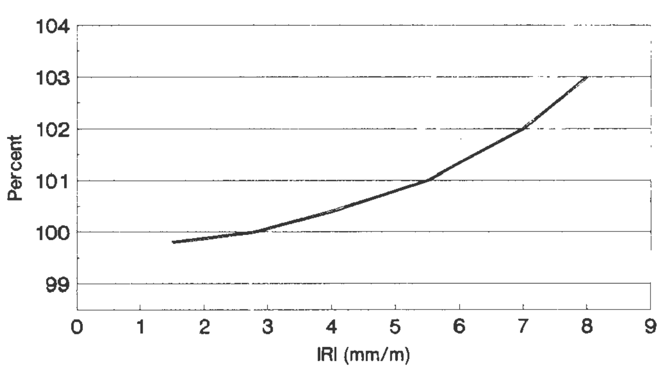


FIGURE 6 Relative increase in fuel consumption related to road roughness (IRI).

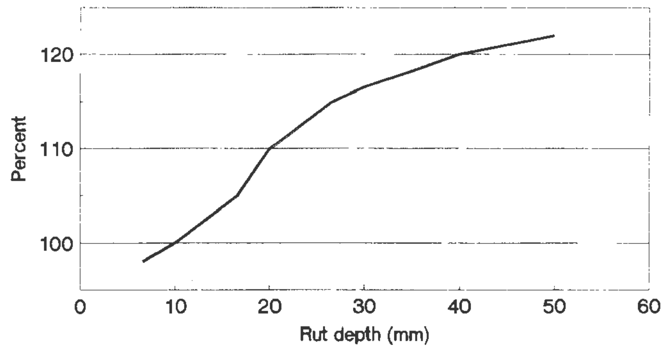


FIGURE 7 Relative increase in fuel consumption while driving on wet surface related to rut depth.

In spite of winter and rain, most of the vehicle-kilometers are driven on dry surfaces. With this condition, an increase in IRI gives an increase in tire cost, as shown in Figure 8.

Cost of Repairs

In PMS, cost of repairs is related to roughness. Rutting is not considered a relevant factor. In Norway it is assumed that roughness can affect 50 percent of repair costs for passenger cars and 25 percent for heavy goods vehicles.

Figure 9 shows how the cost of repairs increase with increasing IRI. The level of 100 percent represents the figures in Table 1.

Cost of Depreciation

Part of the depreciation depends on vehicle age (70 percent). The other part depends on kilometers driven (30 percent). Depreciation related to kilometers driven depends on roughness, as shown in Figure 10. The average depreciation in cents per vehicle-kilometer, as shown in Table 1, is 100 percent.

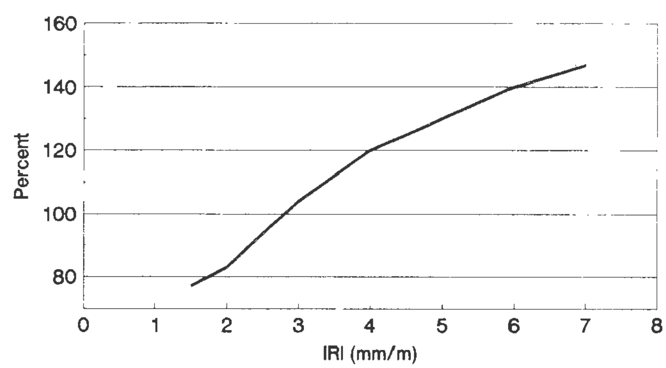


FIGURE 8 Relative increase in cost of tires related to road roughness (IRI).

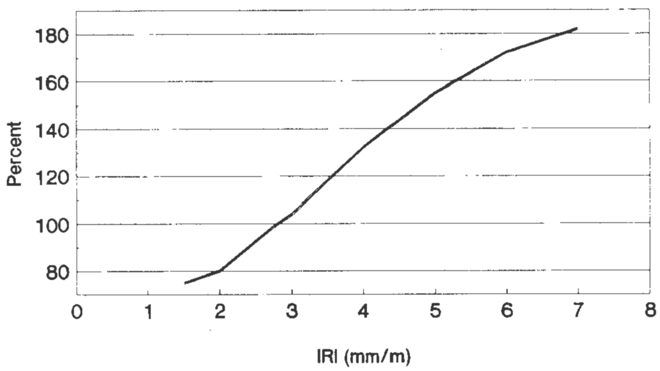


FIGURE 9 Relative increase in cost of repairs related to road roughness (IRI).

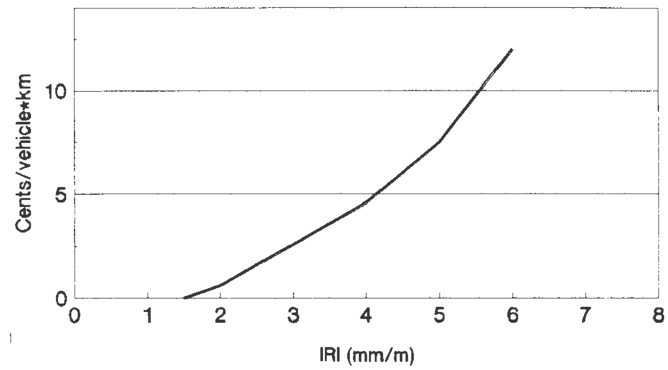


FIGURE 11 Comfort costs related to road roughness (IRI).

Comfort Costs

The comfort costs reflect the driver's readiness to travel a longer but smoother road to avoid a shorter but poorer road. The costs can be direct in that the drivers make a detour instead of drive on a poor road or indirect in that the drivers say they are ready to make a detour if one is available. Comfort costs as used in PMS are shown in Figure 11. Along a road section with IRI equal to 5, the costs are 7 cents/km.

Time Costs

The cost of travel time is a product of value of time and the time to travel a certain distance. In Norway, the value of travel time is US$9.80/hr for passenger cars and US$28.80/hr for heavy goods vehicles.

Traveling time is a result of traveling speed. The road user cost model calculates speed as a function of speed limit, road width, horizontal curvature, and roughness. The effect of roughness depends on speed level generated by speed limit, road width, and curvature.

Figure 12 gives an example of how roughness affects travel speed. Speed limit, road width, and curvature generate a speed of 70 km/hr at an average roughness of 2.7 (IRI).

Accident Costs

The number of accidents within a road section is a product of accident rate (accidents per million vehicle kilometers) and vehicle kilometers driven. The road user cost model calculates a base rate as a function of speed limit, road width, and number of intersections.

The base rate is affected by roughness and rutting. An increase in IRI from 2 to 7 yields approximately an 8 percent increase in the accident rate. Rutting gives little effect on the accident rate under dry surface condition. When the surface is wet, the rate increases, as shown in Figure 13.

Changes in accident costs are calculated as a product of changes in the number of accidents and the unit cost of accidents. In Norway the unit cost of accidents is US$47.60 per accident with personal injury.

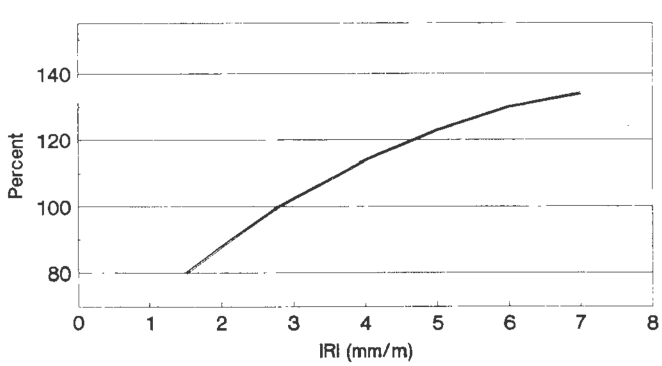


FIGURE 10 Relative increase in cost of depreciation related to road roughness (IRI).

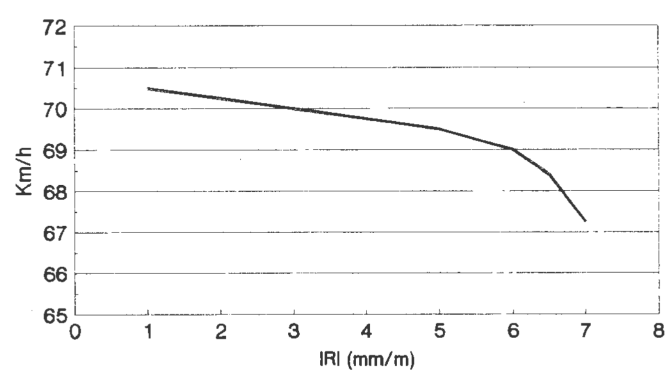


FIGURE 12 Speed in km/hr as a function of road roughness (IRI).

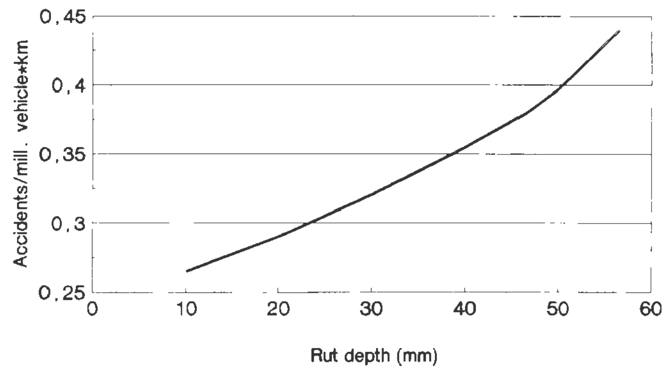


FIGURE 13 Accident rate on wet surfaces as a function of rut depth.

Output from the PMS Program

The NPRA PMS can be used to document the consequences of several optional maintenance strategies. The consequences for a period of 10 years are presented as the effect on

- Agency (maintenance) costs,
- Predicted pavement condition (rut depth and road roughness), and
- Road user costs.

Table 2 gives the summary report of a complete plan of action, showing the differences between the optimal plan of action (with minimum total costs) and the budget-adjusted plan of action (maintenance cost within budget level).

Future Developments

A new PMS for use by the local county public roads administrations in Norway will be developed and implemented during the coming years. The main new features of this system will be

- Use of the latest software and computer technology to make the system more user-friendly;

TABLE 2 Alternative Plans of Action with Cost Differences

Public Roads Adm. NORWAY	PLAN OF ACTION	Page 1
Akershus/1992	Report T01 (PMS ver. 2.20)	Date: 15.04.1991

Name of plan	: National road E6	Selected region	:
Date of plan	: 15.04.1993	Selected municipality	:
File name	: OPTI9202.*	Selected road	: **E 6**

Budget for 1992 (1000 NOK) : 10000
Permissible excess (%) : 5

Maintenance costs, optimal (1000 NOK)

1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
12958	7475	5868	15670	10096	577	9319	13780	1667	5879

Maintenance costs, budget-adjusted (1000 NOK)

1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
9908	12324	5868	15670	9536	1137	10898	13780	12197	10191

PLAN OF ACTION, alternatives 1 - 4:

Current value (1000 NOK)	Maintenance costs	Annual costs	User costs	Total costs	Difference
1 Optimal	51085	7274	19707186	19758270	
2 Budget-adjusted	52512	7478	19735366	19787878	29608
3 Minimum maint. costs	40265	5734	19785318	19825582	67312
4 Minimum road user costs	60790	8656	19704748	19765538	7268

• Direct access from the planning modules to data bases containing detailed results from condition surveys (rutting, roughness, distress);

• Easy access to all data bases for generating user-defined reports;

• Experience from 5 years of systematic condition surveys of the pavement performance prediction models; and

• Multiuser version allowing users of different organization levels (operation, planning, budgeting, management) to make use of the system and its information.

The new PMS will take into account all aspects of pavement management, as shown in Figure 14. The development of this new PMS was begun in 1992. The system will be implemented in 1994–1995.

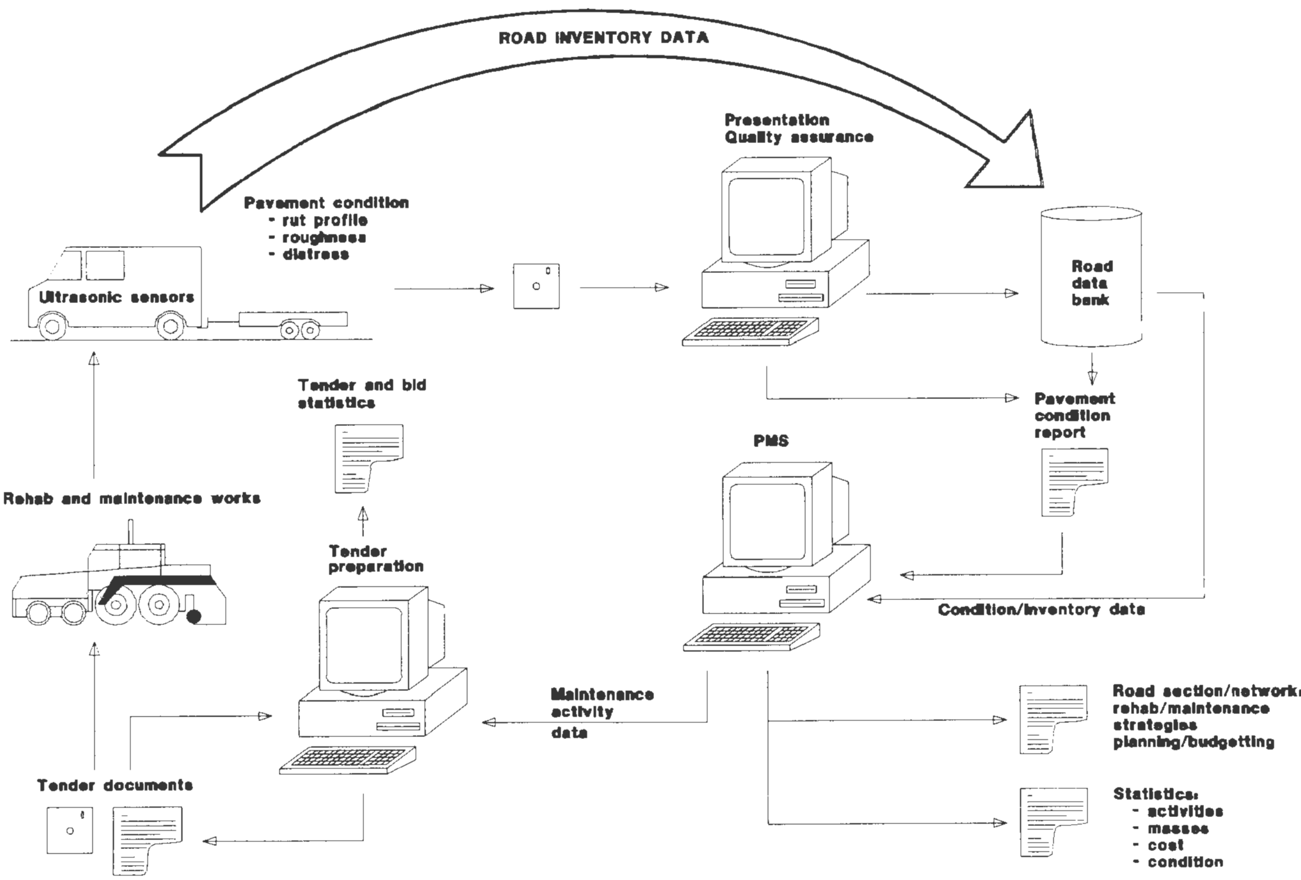


FIGURE 14 The NPRA pavement management system.

Florida Airport System Pavement Management Program

William H. Green and J. David Scherling, *Florida Department of Transportation*

The Florida airport system consists of more than 100 publicly owned paved civil airports. Because many civil airports were originally constructed for military use, Florida has an abundance of paved airports. In fact, many airports have more airside pavement than can be economically maintained. The state does not own its airport system. Each airport is owned by a municipality, and each municipality decides how and when its airport will develop. The state's role is one of forecasting air transportation needs and encouraging and assisting municipalities to maintain suitable airport facilities to meet Florida's demand for air transportation. The Florida Department of Transportation is implementing a comprehensive management program to identify and priority-rank needed improvements and to ensure that owning municipalities are fully integrated into the program. Development of the pavement management program requires several steps. **Inventory** consists of review of pavement history and determination of pavement condition. **Forecasts** of need are based on existing pavement conditions and historical deterioration patterns. **Coordination** with owning municipalities includes sharing information on conditions and forecast needs and negotiating improvement plans of mutual benefit. **Optimization** is the process of matching needs with available dollars and scheduling highest-priority improvements first. **Execution** is the end product of pavement management, ensuring that dollars invested produce highest-quality pavements through excellence in design and construction.

At first glance, the state of Florida airport system would appear to be typical of state airport systems around the country. It consists of 98 paved publicly owned airports, which is typical of about half of the state airport systems in the United States. However, Florida's airport system is not typical of other states' systems, and the event that makes it different occurred more than 50 years ago.

With the threat of world war in the late 1930s, the United States began preparations for a massive buildup of military forces. Because the aircraft was the potentially dominant weapon of the time, the military buildup in Florida included 50 air training centers each built around an airfield with two or more big paved runways.

Florida offered a nearly ideal environment for flight training. It was sparsely populated; land was flat; weather was flyable more than 90 percent of the time; the subtropical climate required minimum construction against the elements; soils were mostly sandy, providing excellent construction foundations; the nearby Atlantic Ocean and Gulf of Mexico were ideal for Naval flight training; and the available seaports aided logistics.

This twofold increase in the airports in Florida did much to make Florida's aviation system what it is today: second in the nation in total airport operations and passenger enplanements and third in cargo traffic. With this activity, influence, and economic development comes the challenge to maintain and protect these vital transportation resources.

Airport Ownership

At the end of the war, the United States divested itself of most of its military bases in Florida by deeding facilities to municipalities for civil aviation. These were windfall opportunities for local governments, offering gateways to air transportation at virtually no up-front cost.

Today, city and county governments, along with legislatively established airport authorities, own and operate the majority of public use airports in Florida—many of which were initially constructed in the 1940s. The legacy for these owners is that these facilities are growing old and are in increasing need of rehabilitation. Many owners are finding that they have more pavement than is required to meet forecast needs and that the pavement is demanding increasing funds for maintenance. On the other hand, the airports are all in competition for air service, and each fears that reducing facilities now may limit opportunities in the future.

Department of Transportation

The Florida Department of Transportation (FDOT) is responsible for the planning and development of a safe, serviceable airport system to serve the citizens of the state. Although the state does not own any airports, FDOT pursues its responsibilities by providing publicly owned and publicly operated airports with planning, technical, and funding assistance for airport expansion, modernization, and rehabilitation. FDOT also provides liaison with FAA for allocation of federal grants to public airports in the state.

The department administers its aviation program through a central aviation office in Tallahassee and seven district offices located throughout the state. An overall plan for the airport system, technical assistance, and centralized control of financing is maintained in the central aviation office. Grants assistance is provided by aviation specialists in the district offices. District aviation specialists report to their respective district public transportation managers and receive technical support and assistance from the central aviation office.

Challenge

The challenge to the FDOT central aviation office is apparent in at least three areas:

- The critical importance of the aviation system's pavement infrastructure;
- The FAA's new emphasis on planning and state grants program cooperation; and
- Coordination of the management of a system with ownership diversity.

The 98 paved publicly owned airports in Florida maintain about 22 million yd^2 of airside pavement, equivalent to approximately 3,600 lane-mi of highway. Pavement makes up a large part of the Florida airport system assets. In fact, more than $15 million of Florida grants and $86 million of total funds (state, local, and FAA) are spent annually for pavement construction and rehabilitation. Florida's $15 million in pavement grants makes up approximately 20 percent of the grants program budget and 45 percent of the aviation capital improvement grant funds invested annually. Management of these pavement assets has become imperative, not only for the individual airport owner, but also for the funding agencies.

The Southern Region of the FAA, in response to U.S. Department of Transportation (DOT) downsizing directives, has recently proposed a series of strategic initiatives that include, among others:

- Concentrate more on up-front planning. Be more proactive and less reactive. Invest time and resources in prevention rather than cure.
- Maximize state involvement in program areas, particularly general aviation.
- Maximize use of automation resources.

An example of how these strategic initiatives seek to streamline FAA production is the incorporation of the state's 5-year capital improvement program into the FAA grants program. Florida's initiative in pavement infrastructure management is an effort to meet the challenge of the FAA's concentration on planning cooperation.

Lacking ownership control, FDOT is faced with a further challenge in coordinating improvements to the state system of airports. Allocation of state funds under grant, subject to conditions of use, is an effective but imperfect means of achieving this end. Regular contact with owners, together with education and technical support, are also effective in encouraging owners to act positively to ensure a safe, serviceable system of airports.

Airport owners have the right to develop and maintain their airports in the manner they choose. However, they all know that grants-in-aid are available from the FAA and FDOT for development of airport facilities. They also know that they may apply for these grants. If they are not in the appropriate airport system plan, they learn that eligibility is very limited. If they are in the system plan, they find that they can develop much better airport facilities with the help of these grants. Finally, they learn that in exchange for grant funds they must agree to maintain certain standards at their airports.

SOLUTION

In 1992 FDOT began development of pavement management program for its airport system. The program has improved the state's knowledge of pavement conditions at airports in the state system, identified needs at individual airports, and established standards to deal with future needs. The program has been very effective in gaining support of airport owners for implementation of this portion of the state airport system plan.

The program may be described under the following five headings:

- Inventory,
- Forecasts,
- Coordination,
- Optimization, and
- Execution.

Inventory

Inventory consists of a detailed search of records of all system airports to establish pavement configuration and construction history of runways, taxiways, and parking aprons used by aircraft. The pavement configuration is recorded on an airport layout sketch, and construction history is recorded to supplement the sketch. Pavement is then physically inspected, documenting distresses with a standardized procedure so that all pavement can be rated on the basis of common parameters. Pavement condition is determined and assigned a numerical value according to the amount and types of distress.

Forecasts

Predictions of future deterioration are based on the known history of each pavement section, with adjustments to account for generic deterioration patterns of the same pavement type throughout the airport system. These predictions enable condition forecasting. When the forecast condition of a pavement section is compared with a minimum desired condition, that section may be programmed for rehabilitation at the optimum time in its life cycle.

Examination of distress in a pavement section also leads to selection of a best method of rehabilitation. When density and severity of individual distress types are forecast to the optimum point in the life of a pavement section, a rehabilitation strategy may be chosen that will best correct the distress. The Florida program permits analysis of alternative strategies, giving consideration to service life and cost.

Florida's pavement management program presents capital improvements for each airport in the state system. The year of optimum rehabilitation of each pavement section, the best rehabilitation strategy, and the estimated cost of that strategy are shown. A preliminary capital improvements plan is developed by computer and presented in spreadsheet format. Strategies and costs may then be evaluated for all pavement sections in the airport. Changes may be made to accommodate budget restrictions, project continuity, and owner preferences.

The Florida program also presents capital improvement requirements for the entire state system. After individual airport needs are approved, all airports in the system are priority ranked and consolidated into a statewide capital improvements plan. This program is also developed by computer and presented in spreadsheet format. Annual costs are presented by airport, and the total pavement needs of the entire state airport system are shown for each year of the planning period.

Coordination

The full value of the program is realized when district aviation specialists coordinate individual airport needs with owner representatives. Needs are documented by inventory, and recommended actions are justified by cost and service life. The owner and FDOT now begin negotiations with a full set of facts at hand.

Both have common objectives—to maintain safe and serviceable facilities—but the owner may desire other actions or priorities. FDOT may agree to support the owner—or it may not, in which case the owner must decide to proceed without state funding support or to accept FDOT recommendations. This decision always rests with the owner. Usually, compromises are possible that meet both the owner's needs and FDOT requirements. Negotiations proceed in an atmosphere of mutual respect and understanding. Of course, there will always be some owners who will not participate.

Optimization

Once individual airport needs have been coordinated, FDOT solidifies the first, or "accomplishment," year of the plan. This is the year for which funding must be secured. When available funds match required funds, the job is simple.

Usually, however, there are a number of details to be worked out. First, the degree of FAA support must be determined. Should the state enter a block grant program with the FAA, this will require but a single negotiation. For the time being, however, each airport must be considered on its own merits.

Next the amount of funding available from FDOT sources must be allocated. This requires consideration of support to airports targeted for FAA grants and state funding for projects that are not included in the FAA allocation. The choices are not always easy. However, an atmosphere of mutual cooperation between the FDOT and the FAA reduces the burden of this task.

Then assurances of local funding and support must be secured. This is often simply a matter of formally approving a program long since accepted by the community. Inevitably, however, for any number of valid reasons, an airport will slip back in the program, and adjustments must be made.

When all funding has been secured, and all parties are in agreement about the program for the accomplishment year, a similar planning process must take place for each succeeding year, bringing other airports on line at an acceptable level of readiness. Only when this procedure has been completed is the plan optimized.

Execution

Grant assurances must be met. Professionals must be selected and placed under contract for design and construction management services. Plans and specifications must be prepared and approved. Notifications must be issued and permits granted. The work must be accomplished. The construction phase of the program typically takes about 10 percent of the time in a project schedule, and 90 percent of the money in the budget.

Is execution important? By all means! Does the state's pavement management program help make execution easier? Perhaps not, but it surely helps to ensure that the most necessary projects receive attention first, and that individual airports—and the system—are as safe and serviceable as they can be.

Program Development

Synopsis

The Florida Airport System Pavement Management Program is being phased in over a 3-year period. The six largest commercial airports in the state are all exempted from this program since they already have pavement management programs in effect.

Data are being collected to establish an initial database for the system. Thirty-two airports were initially entered into the program and are being managed under the new system. The program is continuing with inspection of 30 additional airports under way in 1994, and the balance of the Florida airport system scheduled for inspection in late 1994 or early 1995.

A computer software system has been installed to assist with data management and evaluation. The system is on line at the central aviation office and the district offices and is available for use by owners of airports in the system. All district installations are connected by telephone modem to the central aviation office, and the goal is to have each airport installation connected by modem to its respective district office. Data may also be transferred by diskette.

Inventory data and analytical output is stored in ASCII code and is readily transferable to any MS-DOS–compatible program or spread sheet.

Data Collection

Research and Sketches

Research began in November 1992 for 32 airports. Early records, especially at former military bases, often were not available, so visits are being made to each site and visible construction changes are noted. Local officials are interviewed to obtain additional information about age and composition of pavement sections.

Pavement layout sketches are prepared for each airport showing outlines of pavement sections. Each section represents pavement with common construction history and composition. Sections are further subdivided into sample units for inspection.

Inspections

Before the start of each phase of inspections, a 1-day classroom orientation is presented to introduce the project. The pavement condition index (PCI) inspection procedure and techniques to be used during the survey are reviewed. Airport owners in the state are notified of the orientation and invited to attend.

The PCI inspection procedure outlined in FAA Advisory Circular 150/5380-6 is used. Two survey crews, consisting of two inspectors each, conduct the inspections.

Runways to 100 ft wide and taxiways are inspected at a sampling rate of approximately one sample unit in three. Parking aprons and the outer portions of runways wider than 100 ft are inspected at a sampling rate of approximately one in six.

In addition to inspecting pavement, surveyors verify sketch information visually and by measurement of section boundaries. They also examine pavement conditions, and subdivide sections or designate additional sample units when warranted to maintain procedural integrity. In many instances, they conduct interviews with on-site personnel to verify historical information.

Data Input

Following the field surveys, data are cross-verified with field master sketches and documented histories, and entered into the program database. All inventory data and analytical output are stored in ASCII code, and are readily transferable to any MS-DOS–compatible program or spreadsheet.

Computer Programs

A computer software library called AIRPAV was chosen for the Florida Airport System Pavement Management Program. AIRPAV is a new generation of software developed to expand on the PAVER concept. Pronounced "air pave," this system offers all the analytical power and flexibility sought by FDOT. Furthermore, AIRPAV is readily adaptable to specific requirements of the department. AIRPAV software is menu-driven and modular, which will allow the FDOT to add to or update programs in the future.

The FDOT system includes the modules described in the following.

AIRPCI is a program that calculates the PCI of a pavement from visual survey in conformance with FAA Advisory Circular 150/5380-6. It is used to create the pavement condition database.

AIRFIL is a multifunction utility that uses the files created by AIRPCI and reorganizes the data into section format, the basic analytical unit.

AIRPMS, the primary analytical module, is the heart of the system. AIRPMS provides for additional storage of data such as construction history and test results and creates master files for the system. Supplemental data storage can be added as needed. AIRPMS uses data files created by AIRPCI and AIRFIL and selects viable rehabilitation strategies for each pavement section. It produces a cost estimate for each and forecasts the life expectancy of the section for each strategy. A graphic on-screen analysis is provided for each section. Hard copy presentation is optional.

An example of the graphical display of alternative analysis is shown in Figure 1.

AIRPMS bases analysis on distress types, quantities, and severalties encountered during the field survey and produces strategies that meet predetermined parameters.

AUTOCIP performs the same function as AIRPMS, but in an automated format. This allows the FDOT to vary control parameters, such as minimum service levels and costs, and to reanalyze the entire airport system without interaction by the operator.

AIRCIP employs analytical results from the AIRPMS module to create capital improvement programs for individual airports. AIRCIP is completely interactive and allows the operator to control costs, add or delete projects, move projects between years, and upgrade or downgrade the scope of a project. The operator may also introduce projects not connected with the pavement system, such as

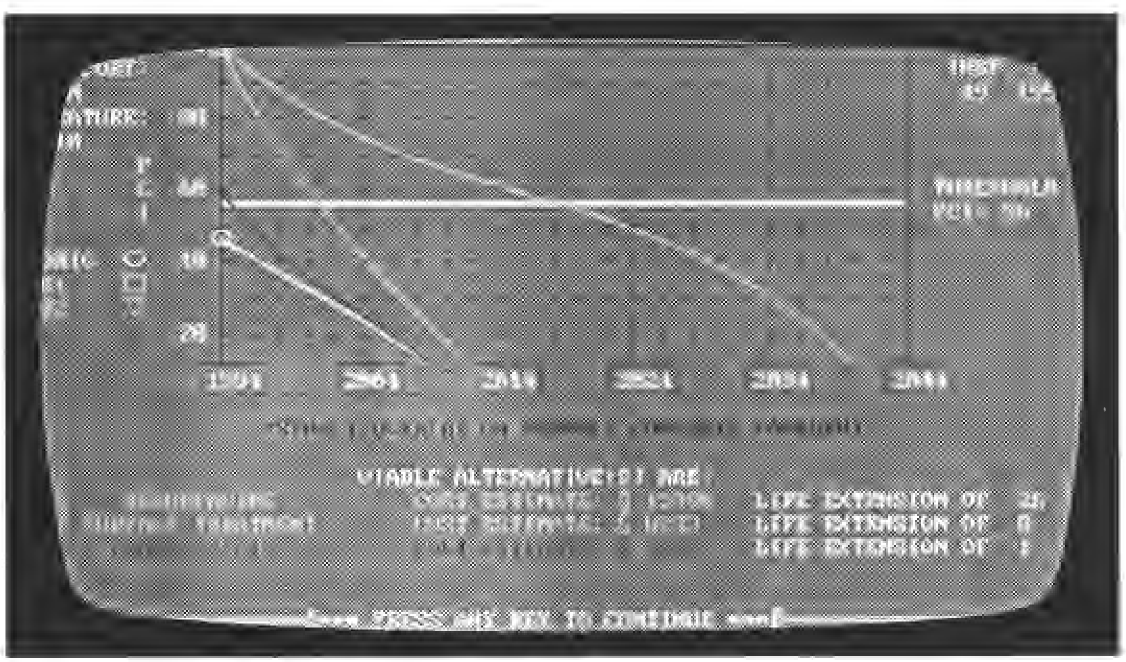


FIGURE 1 AIRPMS display of alternative analysis.

ARFF equipment, fencing, or hangars, to round out a capital improvement program.

The operator may direct AIRCIP to select among AIRPMS alternative strategies according to longest service life, least annual cost, or lowest first cost. AIRCIP displays capital improvement programs in an easy-to-use spreadsheet format with all functions available to the operator by simple keystroke.

An example of an AIRCIP capital improvements program display is shown in Figure 2.

AIRNET accumulates results of AIRCIP working sessions to assist in development of multiyear capital improvement programs for the Florida airport system. AIRNET employs the same type of easy-to-use spreadsheet format used in AIRCIP, as is shown in Figure 3.

AIRMIP reads distress information and formulates maintenance strategies for individual airports. AIRMIP calculates distress quantities, determines amount and cost of materials required, and estimates man-hours and equipment needed to perform the repairs. The operator has complete control over AIRMIP parameters, including unit cost, man-hours, and rates of application of materials. AIRMIP presents a maintenance opportunities, by category and type, in the form of a maintenance work plan, an example of which is shown in Figure 4.

AIRQUERY is a database interrogation program that permits the user to extract lists of pavement features that meet selected parameters. Parameters used in the FDOT system at present are shown in Figure 5. They may be revised and added to as experience dictates. The illustration in Figure 5 is an on-screen depiction of a menu that is typical of the AIRPAV system.

Information summaries for individual pavement sections may also be reviewed graphically, as illustrated in Figure 6. AIRQUERY presents information for a single airport or for the entire state airport system.

The MAPVIEW module allows the user to view airport pavement sketches on the screen with the touch of a key. A color-coded condition sketch, showing pavement condition, by section, is available for each airport (Figure 7). A more detailed sketch showing sample units and section information is also available (Figure 8). Sketches are bitmap representations of AUTOCAD drawings. AUTOCAD is not required to view or revise these sketches.

Operation and Control

The central aviation office maintains the master AIRPAV system which contains the database for all Florida system airports. Each district office has the AIRPAV system with a database for airports within the area of district office responsibility. The Orlando office of the FAA has AIRCIP and AIRQUERY modules of the system. Individual air-

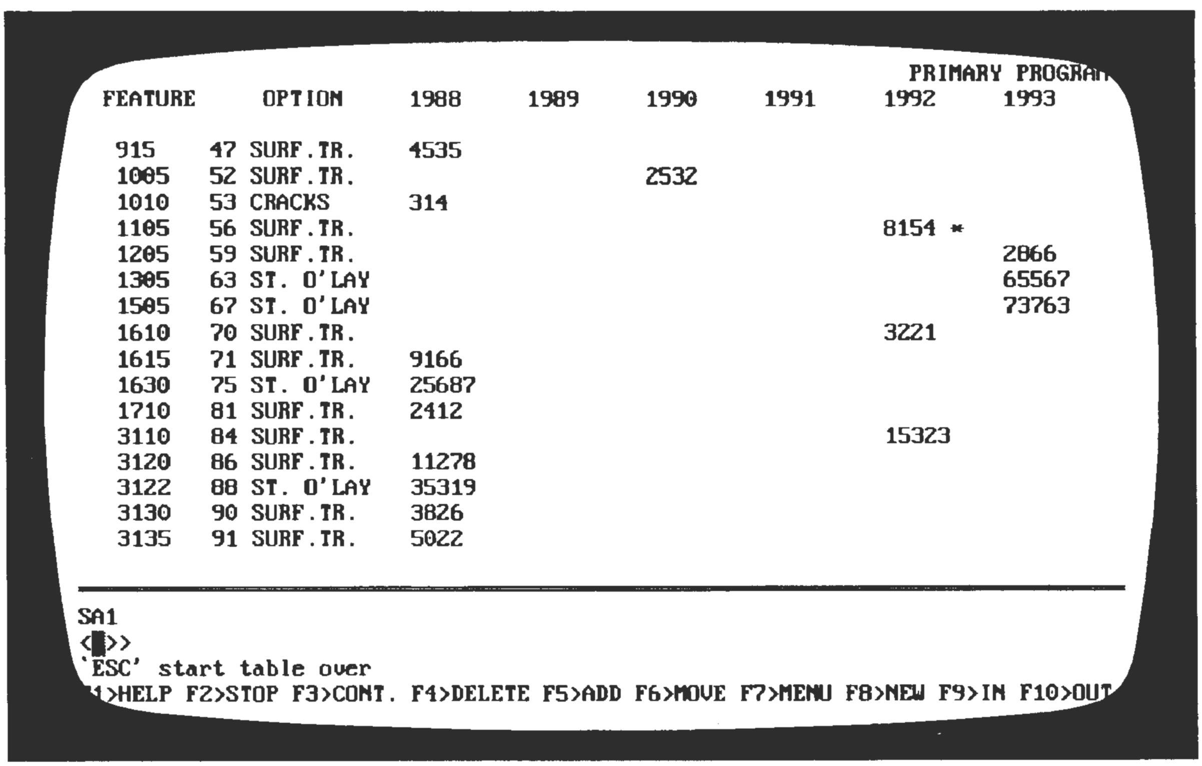


FIGURE 2 AIRCIF display.

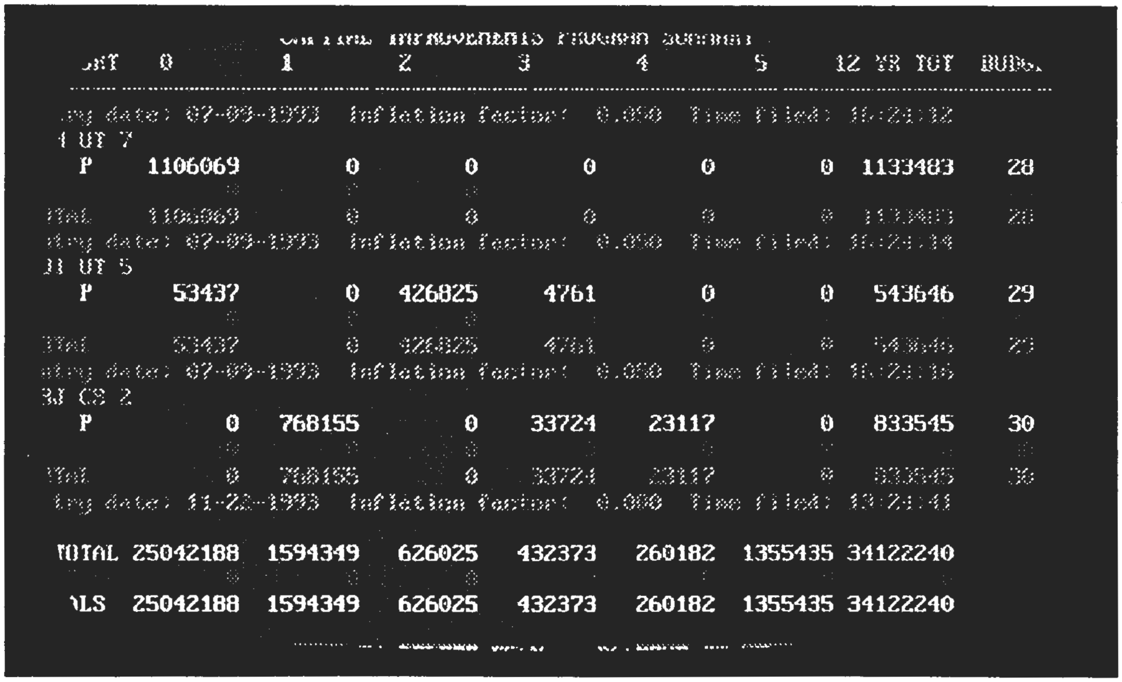


FIGURE 3 AIRNET display.

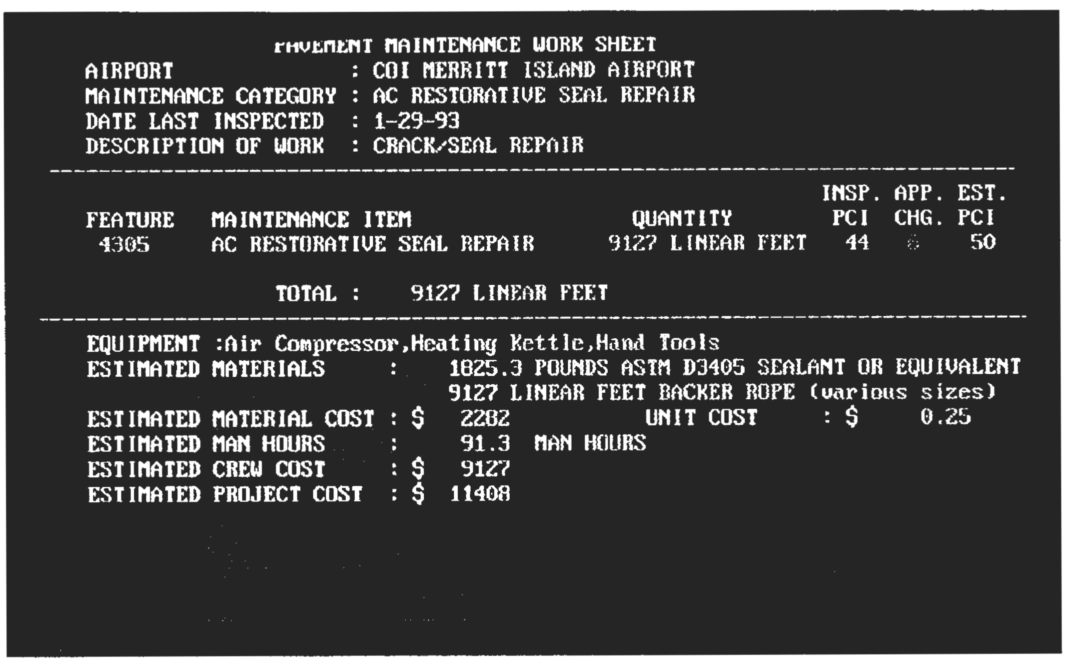


FIGURE 4 AIRMAP display.

port owners are offered AIRPAV, provided that they acquire computer equipment capable of operating the software. Owner software includes the airport database. The owner has the capability to input new data, add, delete, or change projects, modify cost estimates, and print and store alternative capital improvement programs. FDOT controls the ability, at the district office, to revise deterioration curves, change minimum service levels, and analyze new data. This control ensures that FDOT will be informed when revisions are made at the local level. It also encourages owners to interact with FDOT personnel when considering a new direction for the airport.

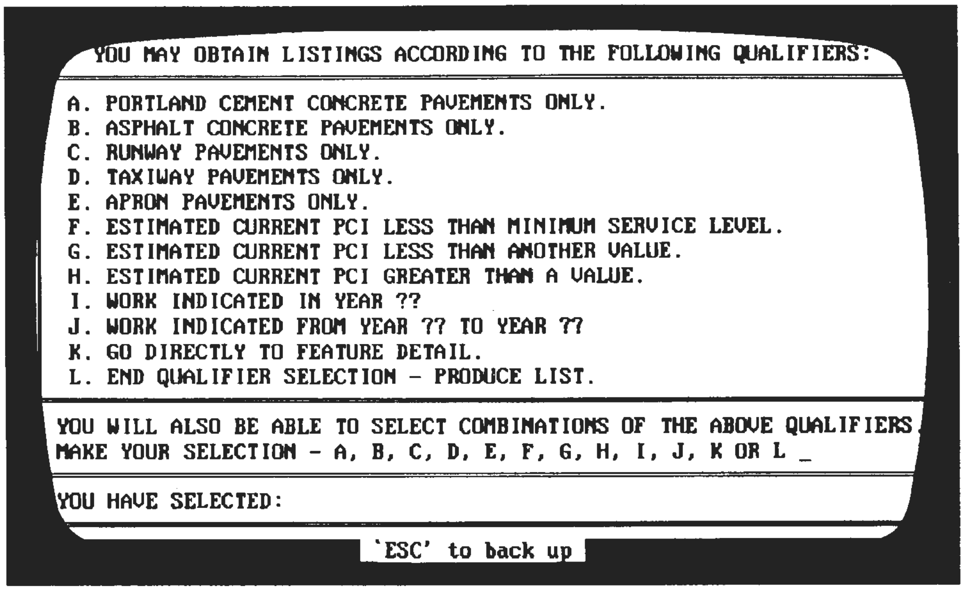


FIGURE 5 AIRQUERY display of parameters.

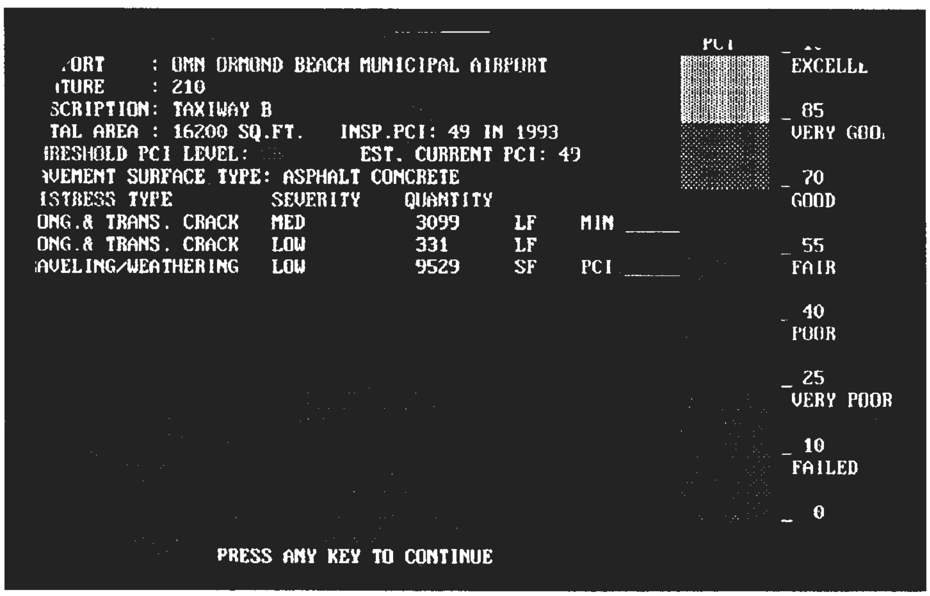


FIGURE 6 AIRQUERY display of information summaries.

When the first full cycle of evaluations for pavements at all participating airports is complete, the pavement management system (PMS) will be an integral segment of the overall Florida aviation information management system. This is a stand-alone computer system built on a personal computer platform that provides automated information for both airports and FDOT. Included are obstruction evaluation modules for both FAA Part 77 and TERPS surfaces [generating both data and three dimensional (3-D) graphic displays of surfaces and intruding objects], 3-D computer-aided drafting and design (CADD) applications (aircraft and Navaid libraries, line-of-sight and shadow diagram automation, automated surface contouring, and 3-D viewing techniques), and graphic integration with the current FAA noise modeling software.

The PMS provides an important automated tool that links many of the airport financial support needs directly to a verifiable information source when making the diffi-

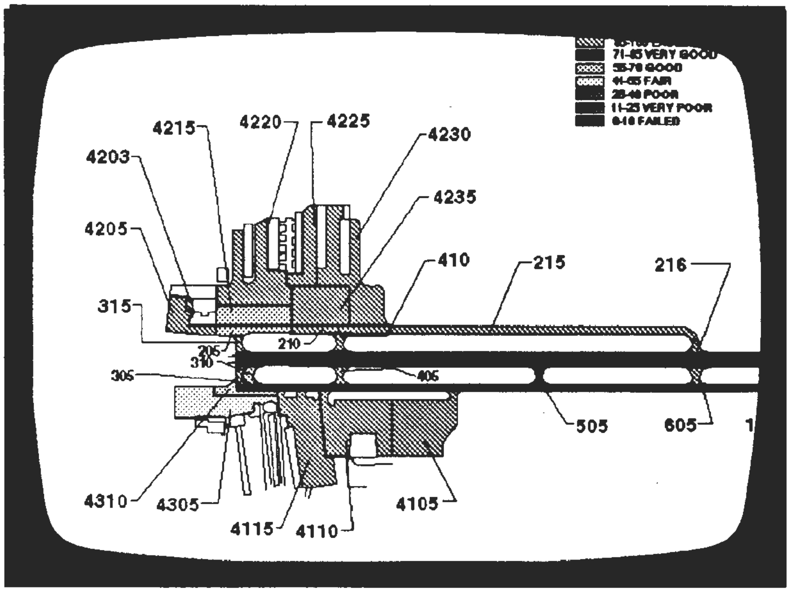


FIGURE 7 MAPVIEW condition sketch.

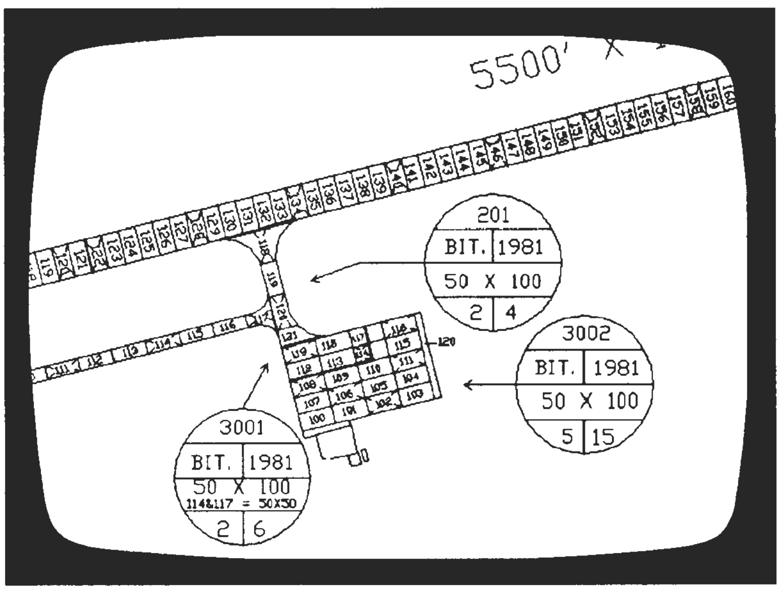


FIGURE 8 Detailed MAPVIEW condition sketch.

cult decisions involved in allocating very limited airport funding to seemingly unlimited needs.

Summary and Conclusions

The Florida Airport System Pavement Management Program provides FDOT with important information and powerful tools with which to guide the future of the state's airport system. The state is faced with many difficult decisions relative to services versus cost in the system. Proper and timely decisions can be made only when the extent and condition of the system are known. Decisions made by FDOT can bring continuity to system improvements only with the cooperation of airport owners. And such cooperation is possible only when owner representatives are fully informed of the direction of the state's program and of benefits to be realized locally as a result of system improvements. This Pavement Management Program is the means by which the state of Florida will meet the challenges of the future for its airport system.

Description and Implementation of RO.MA. for Urban Road and Highway Network Maintenance

Gianfranco Battiato, *RO.DE.CO.SRL, Italy*
Edmondo Amé, *RO.DE.CO.SRL, Italy*
Tom Wagner, *RO.DE.CO. North America, Inc.*

The RO.MA. pavement management system (PMS) developed for urban roads and highway networks in Italy is described and a short description of its elements is reported. Problems encountered in the implementation and start-up of the system, as well as the interaction with the users are detailed. Additionally, a review of the main information stored in the RO.MA. road data base and the criteria used for its design are discussed. Since 1988 the RO.MA. method has been successfully used for yearly maintenance planning of the entire Autovie Venete S.P.A. highway network, a north-east toll highway from Venice to Trieste, and a 1000-km provincial road network in Sardinia. Highlights of various PMS results during 1993 are reported. RO.MA. methodologies have been successfully applied in some municipalities in Northern Italy, and an example of urban road rehabilitation related to the municipality of Padua is discussed. For the Padua project, a multiannual rehabilitation program was applied and according to the available budget, a priority list of maintenance projects for the urban roads network was prepared.

For optimum results, public and private agencies will need to dedicate substantial investment toward the rehabilitation and maintenance of their road networks. Moreover, budgetary changes and constraints that cannot easily be foreseen, as well as political, economic, and administrative considerations, create the need for a comprehensive pavement management system (PMS) for roads.

The RO.MA. (Road Management System) methodology for urban and highway networks represents a powerful tool to assist agencies in improving the level of road service through the use of rehabilitation and preventive maintenance planning.

Moreover, the application of new technologies such as the nondestructive, high-performance systems used in RO.MA. for pavement evaluation can reduce the total cost and the time needed for determining the surface and structural characteristics of roads.

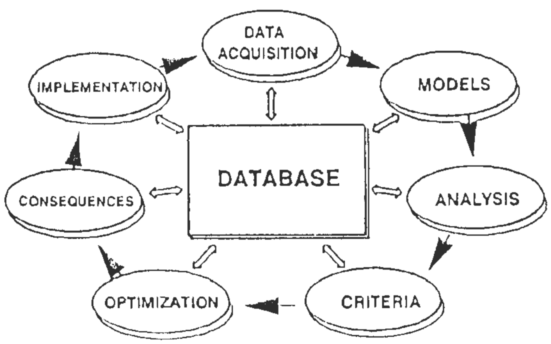
Substantial effort was spent using RO.MA. methods to produce a comprehensive and useful road data base as well as to set different maintenance alternatives according to budgetary changes and limitations.

Three examples of the application of the RO.MA. method will be discussed: (*a*) the maintenance planning of the entire toll Autovie Venete highway network in the north of Italy, (*b*) a 1000-km network of provincial roads in Cagliari (Sardinia), and (*c*) the rehabilitation of the main urban road network in the Padua municipality. In all cases, the interaction with users and the analysis of results generated by the application of the PMS were the most useful base for further adjustment of the RO.MA. method to improve its ability to handle users' requirements, political constraints, and economic decisions.

ELEMENTS OF RO.MA. PMS

The main components of the RO.MA. PMS are shown in Figure 1 (*top*) and can be summarized as follows:

1. Construction and rehabilitation history:
   a. Maintenance policy;
   b. Geometrical data on the pavements (thickness, layer composition, and number of lanes and their width);
   c. Survey of traffic data (volume and type);
   d. Physical constraints, especially for urban roads;
   e. Environmental conditions and types of maintenance allowed;
   f. Weather conditions (temperature, humidity, etc.); and
   g. Local cost of maintenance.
2. Pavement evaluation using new technologies such as nondestructive high-performance systems for measuring the condition of surfacing and structure of pavement:
   a. Surface distress;
   b. Evenness and the longitudinal and cross profiles of the road using a high-precision laser profilometer (Figure 1, *bottom*);
   c. Layer stratigraphy using radar technology;
   d. Bearing capacity using the falling-weight deflectometer (FWD); and
   e. Skid resistance.
3. The road data base, built according to user requirements: for successful application of the PMS, management of the data base by the users should be:
   a. User-friendly;
   b. Tailor made for users' needs;
   c. Presented in terms of homogeneous section subdivisions; and
   d. dynamic, allowing the user to easily update the information stored in the data base and to introduce modifications concerning economic models or analysis.
4. Different management systems are included for highways, provincial roads, and urban roads. Particular attention is paid to the different types of maintenance measures that have to be considered and to the functioning of user maintenance policy or physical or economic constraints.



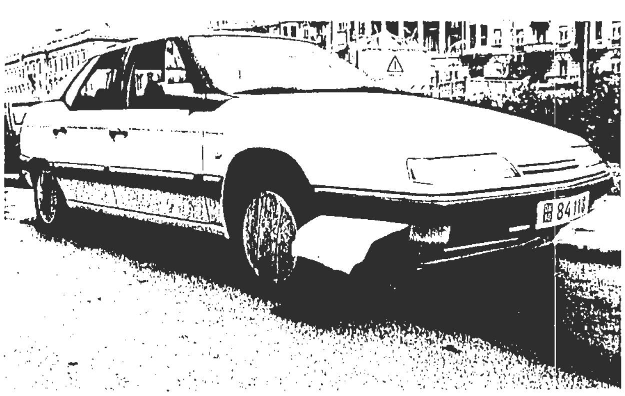


FIGURE 1 ***Top:*** **elements of a pavement management system;** ***bottom:*** **laser profilometer for measuring evenness and longitudinal and cross profiles of road.**

The PMS has to provide cost/benefit analysis in terms of single projects as well as network levels. The modern electronic data collection equipment available today produces a lot of data. For this reason it is essential that the PMS provide meaningful results and presentations to make the interpretation of data easier for the user to understand.

IMPLEMENTATION OF RO.MA. FOR URBAN ROADS

In April 1992 a PMS study was conducted for the rehabilitation of the main urban roads in the municipality of Padua. The test included over 40 km of roads, most of it around the center of Padua, and they were subjected to a heavy traffic volume.

The scope of work was to develop a PMS for maintenance rehabilitation over a 2-year period, and the related amount of available budget was fixed by the administration. Before starting, a great deal of time was spent with the users to set the correct design for each of the following elements of the project:

- Maintenance policy;
- Alternative measures for each road, depending on the location, the presence of sidewalks, the possibility of the use of scarification measures, and so on;
- Pavement evaluation, that is which types of data to collect and the interpretation of the data defining the level of the pavement performance expected in term of evenness, bearing capacity, skid resistance, and so on; and
- Drainage characteristics and their impact on the rehabilitation costs.

Pavement Evaluation

The following high-performance systems were employed for the pavement evaluation of the municipality of Padua:

- FWD for pavement bearing capacity evaluation;
- Laser profilometer for evenness pavement condition in term of International Roughness Index (IRI);
- SCRIM system to determine skid resistance;
- Distress analysis of seven types and three severity levels.

Models

A number of different models were used to prepare final data for the economic evaluation:

- Deflection-value interpretation by the Road Moduli Evaluation (RO.M.E.) program. The modulus evaluation is carried out using basically Boussinesq equations for strain and stress calculations and Odemark/Kirk modifications known as the method of equivalent thicknesses. Besides modulus evaluation, RO.M.E. is able to calculate the remaining fatigue life of the pavement and the overlay needed to sustain the expected traffic.
- Road homogeneous subsection division using the ISO program. Based on field data acquisition and external constraints, the program provides homogeneous sections for the whole network. This is a very important step to provide a good PMS for urban roads, because as the number of physical constraints or political and administrative considerations to take into account is very high.
- Economic models including analysis of uneven roads, vehicle operating cost, environmental conditions, and pavement forecasting conditions in terms of benefit/cost analysis of the different maintenance alternatives proposed.
- Models to prepare a priority list for maintenance.

Figure 2 shows typical output of some pavement evaluation results. Included are

- Distress analysis (seven types of distress were considered at three different severity levels),
- IRI value (mm/meter),
- Skid resistance value, and
- Summarized outputs of RO.M.E. (moduli of asphalt layers—granular base and subgrade layers—remaining pavement life in terms of equivalent standard axles, and needed reinforcement).

Pavement Priorities and Management

On the basis of the average condition of the homogeneous pavement sections and on physical and political considerations, a cost/benefit ratio analysis was carried out for individual projects as well as for the network level. The effect of an optimized rehabilitation strategy on the future condition of the road network was then analyzed according to the budget constraints, and a multiannual rehabilitation program (over 2 years) was proposed. The following rehabilitation alternatives were considered: 3 to 4 cm of reinforcement, 3 to 4 cm of scarification and reinforcement with binder and surface course, surface treatment, and rehabilitation with full reconstruction (18-cm depth).

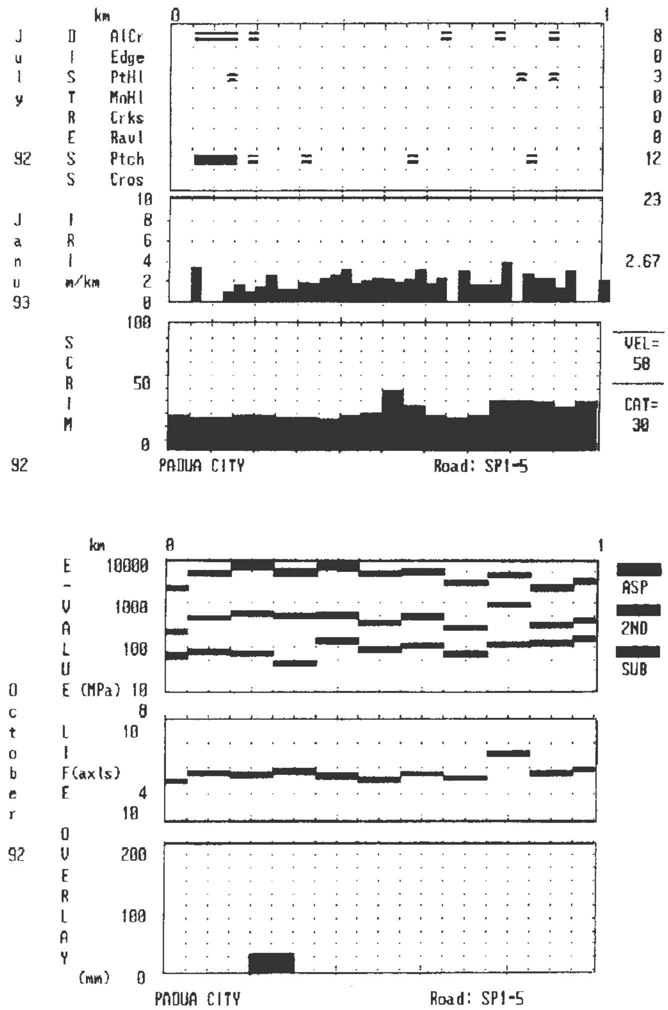


FIGURE 2 Typical output of RO.MA. pavement evaluation.

Table 1 shows an example of the rehabilitation program for 1993 as reported for each homogeneous section, including name of the road, initial and final homogeneous sections and chainage, area, IRI value (unevenness values greater than 3 mm/m are considered bad); distress per kilometer (low distress value, 0 to 20; medium distress, 20 to 40; high distress, over 40), reinforcement in millimeters, CAT (skid resistance) values lower than 40 are bad, rehabilitation proposed, and cost in millions of lire.

TABLE 1 Padua Urban Roads: Maintenance Measures for 1993

Num	Street	From	To	Area	IRI	Distr	Rein	Cat	Maint Measures	Price
1	ACQUAPI	0	0.325	2275	3.85	52	48	42	Reinforce 3+3cm.	22.7
2	ACQUAPI	.325	.85	3675	3.41	52	67	41	Reinforce 3+3cm.	36.7
3	BEZZECC1	0	.525	3675	5.42	63	3	42	Scar.3cm+Reinforce 4 cm	39.8
4	BEZZECC1	.525	1.35	5775	4.67	46	127	45	Reconstruction 18 cm (9+5+4)	242.0
5	PIOVESE1	0	.3	2100	4.11	23	9	54	Nothing	0
6	PIOVESE1	.3	.675	2625	5.71	37	83	52	Scar.4cm + Reinforce 3+3	40.1
7	PIOVESE1	.675	1.2	3675	4.54	55	5	36	Scar. 3cm +Reinforce 4 cm	39.8
8	PLEBIS1	0	.3	1050	3.43	40	32	50	Reinforce 3 cm.	5.78
9	PLEBIS1	.3	.6	1050	2.94	10	19	49	Nothing	0
10	PLEBIS1	.6	1.225	2188	2.8	50	18	51	Reinforce 3+3 cm.	21.8
11	PLEBIS1	1.225	1.75	1837	3.78	25	14	46	Nothing	0

All the information collected was loaded into the data base with the other collected data. Particular attention was paid to the software design of the data base according to the needs of the user. Highlights of the user needs included the possibility of full interaction between users and the data base, modifications and updating of the data base, forecasting models of future pavement condition, and searching program to produce a priority list of the roads according to user inputs such as listing of the worst homogeneous sections based on evenness or skid resistance conditions.

Furthermore, the user is allowed to modify the type and cost of the different rehabilitation measures. The maintenance planning for the Padua municipality is summarized as follows:

Year	*Area (mq)*	*Cost (lira millions)*
1993	158 000	3210
1994	146 000	2270
	304 000	5480

PMS 1993 for Autovie Venete Toll Highway Network

Since 1988 the RO.DE.CO. group has been involved in preparing the Autovie Venete toll highway network rehabilitation program. The application of the RO.MA. method during this period and interactions with the users have allowed quality improvements to be made. The results of the PMS were used to determine the best economic solution.

For example, the change in the evenness equipment survey from using PSR (or PSI) values to a new laser profilometer system allowed the possibility of a full analysis of the longitudinal and cross profiles and rutting, with a substantial improvement in PMS quality results. Using a laser profilometer, one can identify, for example, aquaplaning sections or incorrect cross profiles.

Filtering IRI values in terms of APL values (short and medium wave lengths), it is possible to recognize the type and the cause of uneven pavement conditions. The data base can be used to suggest which type of improvement should be made in order to provide better management.

For the pavement evaluation of the PMS for 1993, the following pavement characteristics were evaluated (on slow and fast lanes) on more than 126 km of highway:

- Longitudinal and cross profile (IRI-APL values),
- Rutting,
- Skid resistance, and
- Distress analysis.

Figure 3 shows the typical output of the laser profilometer measurements. For safety reasons, particular attention was paid to skid resistance values. The 1993 pavement evaluation data were compared with the data stored in the data base for 1992 in order to note and explain the change in pavement conditions.

This work, conducted over a 5- to 6-year period, allowed the RO.MA. method to improve its capability to foresee future pavement conditions with a more tailored decay law for skid resistance values, IRI values, and so on.

The cost/benefit analysis for Autovie Venete was carried out considering the client's four types of maintenance rehabilitation methodologies:

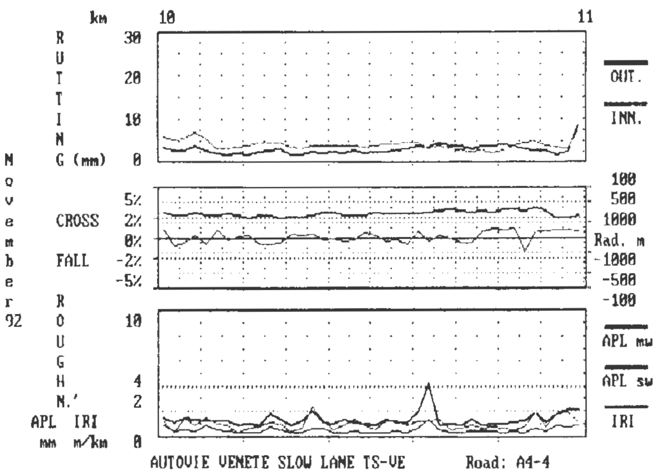


FIGURE 3 Typical output of laser profilometer.

- Surface treatment (slurry seal),
- Scarification and reconstruction of 4 cm of asphalt layer (this measure has the advantage of being performed on one lane only),
- Reinforcement with special draining mixes with modified asphalts (3 cm), and
- Reconstruction (45 cm) with subbase stabilization by hydraulic binders.

The optimization program analyzes the different maintenance alternatives taking into account that for a cost/benefit analysis, some of them have to be extended on both the slow and fast lanes.

Table 2 shows a partial output of the PMS for the slow lane of Autovie Venete in terms of homogeneous sections. The following data are given:

- Indication of the highway lane,
- Year of the last maintenance on the homogeneous section,
- Chainage (initial to final) of homogeneous sections,
- IRI value (a good IRI value for newly paved road is lower than 2 mm/m),
- Surface life in years,
- Distress per kilometer,
- Skid resistance (CAT) values,
- Maintenance type, and
- Cost.

The total budget available from the agency for highway network maintenance (650 lane-km) was approximately 10 billion lire (U.S. $6 million). According to the RO.MA. PMS results, this budget is sufficient to increase the general functional and structural conditions of the road network.

Figure 4 shows the improvement in pavement performance in terms of IRI values from 1989 to 1992, using the RO.MA. PMS for maintenance planning. It should be noted that the number of road sections with insufficient IRI values has been reduced by more than 50 percent in 4 years.

PMS 1993 for Cagliari Provincial Road Network

During 1993, a full PMS study was completed of 1000 km of provincial roads in Cagliari, Sardinia. The functional and structural pavement condition was evaluated using the following systems:

- Longitudinal pavement profile by laser profilometer and skid resistance by SCRIM system,
- Pavement bearing capacity by FWD,
- Distress analysis, and
- Ground penetrating radar system (GPRS) to determine the thicknesses and composition of the different pavement layers.

The use of GPRS was essential to provide accurate and reliable data for use in the road Modulus evaluation step.

The pavement management study included over 150 provincial roads, and a multiannual maintenance program was prepared considering both free budget and fixed budget cases as suggested by the user. For both cases examined, a maintenance priority list was prepared based on cost/benefit analyses of the alternative measures.

Table 3 is an example of the maintenance priority list for a fixed budget. The total cost proposed for the whole network provincial road was more than 19 billion lire.

A complete road data base was prepared and implemented on the user's personal computer. After a few days of training, the user was able to manage the data base alone. The data base is a powerful tool for administrations to use annually in managing and preparing the proper maintenance rehabilitation program for their roads. According to the PMS results, a priority list provides the administration with appropriate information as to which roads need attention and which type of maintenance is necessary based on the available annual budget.

In the case of the Cagliari provincial road network, special software was prepared to associate the graphic and alphanumeric information of the road data base. The graphic representation made the interpretation of the data easier for the user to understand because a great deal of data was collected for the analysis.

The new software (Road Information System) consists of

- A geographic data base for displaying the cartography of the territory and geographically localizing relevant information and elements,

TABLE 2 Maintenance and Rehabilitation Measures on A4-1 (Slow Lane)

High Way ID	Year Last Maint.	From	To	Area	IRI	VSS	Distress	SCRIM	Maintenance Measures	Price
A4-1	92	0	0.5	2100	3.13	4	0	52	Nothing	0
A4-1	90	0.5	1.825	5565	1.83	6	0	51	Nothing	0
A4-1	80	1.825	2.9	4515	2.18	4	17	45	Nothing	0
A4-1	92	2.9	3.9	4200	1.38	7	0	65	Nothing	0
A4-1	86	3.9	6.125	9345	1.04	5	2	46	Nothing	0
A4-1	86	6.125	6.75	2625	1.36	3	35	48	Nothing	0
A4-1	86	6.75	8	5250	0.87	5	2	46	Nothing	0
A4-1	92	8	11.65	15330	1.19	8	1	67	Nothing	0
A4-1	88	11.65	13.8	9030	1.98	6	0	53	Nothing	0
A4-1	89 to 91	13.8	26.8	54600	1.79	6	1	51	Nothing	0
A4-1	80	26.8	34.5	32340	1.28	3	28	43	Nothing	0
A4-1	80	34.5	36.95	13965	1.56	4	11	40	Drain. Asph.	361.7
A4-1	89	36.965	39.8	11970	1.57	5	4	48	Nothing	0
A4-1	80	39.8	41.55	7350	1.29	5	1	43	Nothing	0
A4-1	91	41.55	42.05	2100	2.29	6	0	55	Nothing	0
A4-1	86	42.05	43.15	6270	1.61	4	5	37	Drain.Asph.	162.4
A4-1	91	43.15	53.05	41580	1.46	6	3	50	Nothing	0
A4-1	86	53.05	57	16590	1.83	4	27	46	Nothing	0
A4-1	80	57	59.3	9660	1.49	3	28	45	Nothing	0
A4-1	86	59.3	59.8	2100	1.4	5	8	45	Nothing	0
A4-1	86	59.8	60.5	2940	1.39	4	24	47	Nothing	0
A4-1	86	60.5	61.175	2835	1.37	4	9	44	Nothing	0
A4-1	86	61.175	61.825	2730	1.26	3	31	45	Nothing	0
A4-1	86	61.825	67.125	22260	1.59	4	9	44	Nothing	0
A4-1	78	67.125	68.7	6615	1.97	4	13	44	Nothing	0
A4-1	91	68.7	69.675	4095	2.05	5	3	46	Nothing	0
A4-1	84	69.675	71.4	7245	1.52	4	31	49	Slurryseal	78.7
A4-1	78	71.4	74.25	11970	1.49	4	25	55	Slurryseal	130
A4-1	88	74.25	79.6	22470	1.37	6	3	55	Nothing	0
A4-1	92	79.6	81.6	8400	1.71	7	0	55	Nothing	0
A4-1	82	81.6	82.9	5460	1.52	6	0	51	Nothing	0
A4-1	84	82.9	83.55	2730	3.01	3	26	50	Nothing	0
A4-1	88	83.55	88.1	19110	2.02	6	5	53	Nothing	0
A4-1	89	88.1	93.5	22680	1.6	6	0	52	Nothing	0
A4-1	91	93.5	95.95	10290	0.92	6	1	47	Nothing	0
A4-1	88	95.95	99	12810	0.92	5	1	40	Scar.4+Rein 4cm	182.54
A4-1	79	99	109.7	44940	1.14	5	1	41	Scar.4+Rein 4cm	640.39
A4-1	91	109.7	119	39060	1.14	5	0	47	Nothing	0
A4-1	74	119	121.35	9870	1.7	5	6	45	Nothing	0
A4-1	92	121.35	123.9	10710	1.45	8	0	69	Nothing	0
A4-1	91	123.9	126	8820	1.77	7	4	60	Nothing	0

Total Cost (Lira): 1.5557E+09

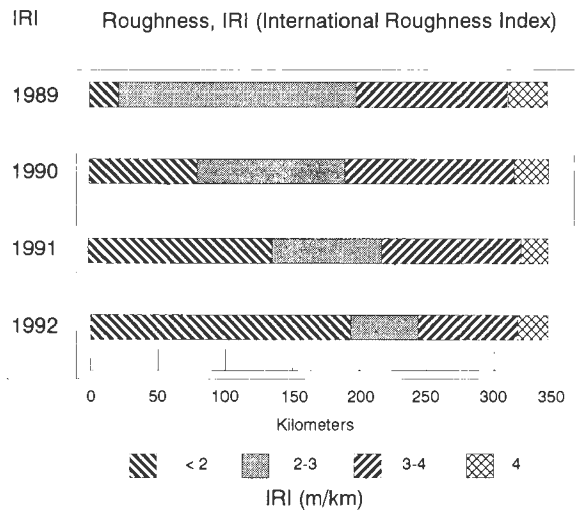


FIGURE 4 Pavement performance improvement using RO.MA. PMS: Autovie Venete (slow lanes only).

- Alphanumeric data base containing detailed information on the road network (structural and function pavement conditions), and
- Image data base containing photographic images and drawings.

The Road Information System represents a powerful tool for managing information and was built in such a way as to allow the user to add new elements to the road network, such as bridges, structures, ancillary work, and other equipment.

Conclusions

Three examples of the use of the RO.MA. PMS were presented for urban, provincial, and highway networks. In all the cases examined, a brief description of the pavement evaluation and PMS phases of the RO.MA. method were given. The appropriateness of the proposed method has been discussed in terms of technical and economic aspects.

The implementation of a road data base on the user's PC containing PE and PMS data allows and forces the user to prepare more realistic annual maintenance budgets based on a scientific approach to maintenance rehabilitation problems.

Moreover, the use of new software for graphic representations on a PC of the cartography of the territory increases the information available for the agency to manage its road network in terms of efficiency and economy, and the graphic presentation of the data allows the user to easily understand the results of the RO.MA. analysis.

TABLE 3 Maintenance Priority List for Cagliari Provincial Road Network

Num	Street	From	To	IRI(m/km)	Distr	Maint Measure	Price
1	SP1-10	0	0.5	6.58	0	Reinf. 5 cm binder	19.5
2	SP1-10	0.5	1.35	2.28	79	Reinf 6 cm. binder	38.25
3	SP1-10	1.35	1.9	2.7	25	Slurryseal	13.2
4	SP1-10	1.9	2.8	7.63	26	Reinf. 6 cm binder	40.5
5	SP1-10	2.8	3.325	4.56	63	Reinf 5 cm binder	20.48
6	SP1-10	3.325	4	6.07	41	Reinf 5 cm binder	26.33
1	SP1-18	0	0.55	2.59	42	Reinf 3 cm	15.73
2	SP1-18	0.55	4.95	2.74	80	Reinf 6 cm binder	181.5
3	SP1-18	4.95	5.475	2.91	32	Reinf 3 cm	15.02
4	SP1-18	5.475	7.1	2.76	100	Reinf 6 cm binder	67.03
5	SP1-18	7.1	8.1	2.97	29	Reinf 3 cm	28.6
6	SP1-18	8.1	8.65	3.16	71	Reinf 5 cm binder	19.66
1	SP1-23	0	7.9	3.7	89	Reinf 6 cm binder	325.88
2	SP1-23	7.9	8.85	2.63	41	Reinf 3 cm	27.17
1	SP1-29	0	0.5	2.53	52	Reinf 4 cm	21.13
2	SP1-29	0.5	5.025	2.99	83	Reinf 6 cm binder	220.6
3	SP1-29	5.025	5.8	4.45	44	Reinf 4 cm	32.75
1	SP2-2	0	4.825	5.62	115	Reinf 6 cm binder	212.17
2	SP2-2	4.825	5.4	4.05	19	Reinf 3 cm	17.94
3	SP2-2	5.4	6.05	5.79	98	Reinf 6 cm binder	29.25
4	SP2-2	6.05	6.8	2.81	1	Nothing	0

The use of the RO.MA. system in all three cases presented in this paper resulted in optimization of the maintenance budgets for all three agencies. This was accomplished through the use of RO.MA. techniques to identify specific areas of the roadway that are in need of maintenance. Similarly, RO.MA. identified areas of the roadway that did not need maintenance. The users benefitted from this analysis by knowing exactly where to implement maintenance techniques as well as what those techniques should be. By identifying the problem areas of the roadway, the users' maintenance budget was optimized.

INSTITUTIONAL ISSUES IN PAVEMENT MANAGEMENT

Overview of Institutional Issues in Pavement Management Implementation and Use

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James P. Hall, *Illinois Department of Transportation*

Pavement management concepts were developed in the 1970s and matured in the 1980s. However, many agencies still are not using structured pavement management processes in their daily management activities. Federal and state mandates are compelling state and local agencies to implement pavement management systems; however, some of these agencies appear to be adopting pavement management to meet a requirement rather than using them to assist in making management decisions. With more agencies recently attempting implementation, it has become apparent that the institutional issues must also be addressed before effective, full use of pavement management practices becomes common among the agencies responsible for managing pavements. These institutional issues are related to both the operational characteristics of the agencies and the people in the organizations. Previous papers have addressed specific institutional problems and methods to overcome them in particular cases. The overall institutional issues that have been found to influence the adoption and use of pavement management practices at both the state and local levels are addressed. Approaches are identified that have been found to prevent, overcome, bypass, or reduce the problems caused by institutional issues.

Pavement management systems (PMSs) have been available for several years (*1*). Pavement management began as a systems approach to pavement design, or a project-level analysis. This led to the use of systems concepts in planning, programming, and network-level analysis. Although several agencies have adopted a PMS, many more agencies could and should be using a structured PMS. Recently, agencies that use federal funds for pavements have been required to implement PMSs (*2*). This has primarily forced implementation of pavement management on state highway agencies; they must ensure that all federal-aid pavements within their jurisdiction are managed with a PMS. However, some states also require local agencies to adopt a PMS to be eligible for certain funds.

Although some members of the highway community believe that forcing agencies to adopt pavement management will solve the problem, several agencies that have adopted a PMS use only part of the capabilities available to them. Some agencies appear to have adopted a PMS to meet the federal requirement, but the actual pavement decision-making processes remain unchanged. Several local agencies that adopted a PMS discontinued use after initial adoption wasting large investments of funds and human resources previously spent on development and implementation of the PMS.

This leads to a need for a new definition of implementation. Implementation should be considered complete only when pavement management becomes the critical component for making pavement decisions. The PMS is a set of decision support tools that are used in the pavement management process to help make systematic decisions about pavements in a structured manner. The personnel in the organization who make decisions about pavements are as much a part of the PMS as the software. A PMS should be considered implemented only when the recommendations of the software are routinely used to assist in selecting pavements to repair, allocating funds among competing pavement requirements, determining overall network needs, and justifying funding needs to governing authorities and the public.

There are many barriers to adoption, implementation, and effective use of pavement management systems. In the early years of PMS implementation and development, some of the most important barriers were technical; the PMS concept was not well-developed and the analysis techniques required considerable research to find those that were most helpful. Most automation of analysis techniques was completed on mainframe computers that were both cumbersome to use and often difficult to access. However, over the last several years, the microcomputer revolution has provided greater access to computers and created a more friendly computational environment. The state-of-the-art in PMS analysis techniques has advanced to such a level that many of the technical problems have been addressed, or the approaches to solving them have been identified. Most of the content of earlier conferences addressed the technical problems (*3,4*). All problems have not been completely solved, and there is still a need for improving existing and developing new pavement management data collection techniques, analysis procedures, and decision support software. However, even in the early days of pavement management, there was a recognition that institutional problems could have an influence on implementation and use of pavement management systems (*5,6*). Since then there has been an increase in interest in this area (*7–9*). Also, there has been a recognition that PMS should be viewed in terms of information management systems in general (*10*). This paper identifies the broad institutional issues and provides some guidance on how to prevent, overcome, or bypass those problems.

INSTITUTIONAL ISSUES

Institutional issues include people, organization, and communication situations that inhibit the adoption of a PMS. These are sometimes called barriers, although the term "barrier" is considered too severe by some people. A barrier can generally be described as a barricade, obstruction, or anything that prevents advance. Barriers can limit, obstruct, or prevent PMS adoption, implementation, or effective use. Not all institutional issues are true barriers. Many of them just require a different approach than if the PMS was adopted by an individual. There are several different types of issues and barriers that can affect PMS implementation. Many of the most troublesome are organizational or people related. Some of these people-related barriers are built into the organizations into which the PMS must be integrated. Others are attitudes of individuals within the organization that must be addressed.

The institutional issues and barriers can be loosely grouped into three classes: barriers related to (*a*) people, (*b*) the organization, or (*c*) development and implementation. The following describes several issues and barriers encountered in pavement management implementation efforts that have been placed in these three groups. It is helpful to think of them in these groups to try to develop methods to address them; however, it is apparent that some fall in more than one class. Any one of these may prevent implementation or limit use of PMS, but more than one are often encountered simultaneously.

People Issues and Barriers

This type of issue or barrier is related to the personalities and interpersonal relationships of individuals in an organization. Barriers result from personnel conflicts, inappropriate competition, and communication problems.

These problems may not always be immediately apparent, especially if the PMS has been mandated. In that situation, these people problems can lead to the appearance of PMS adoption and implementation from the perspective of an outsider, but they can prevent the effective use of the PMS in the actual decision making. The people problems can be some of the most difficult to address because they can show up as issues in so many places and can reappear as barriers after the issues appear to have been addressed. Sometimes it only takes one person in a critical position to prevent adoption or effective use of pavement management. People problems also constantly change as personnel at all levels enter and leave an organization.

Turf Protection

A PMS provides information and analysis procedures that often cross several formal and informal lines of authority and communication within an organization. It provides information on planning for funding needs, programming and selecting sections of pavement for both maintenance and rehabilitation, and determining the impact of funding decisions on the future condition of the network and future funding needs.

Information is power in an organization, and access to information may influence who has the formal authority or informal power to make decisions. This often affects not only the decisions currently being made by planning, maintenance, design, operations, and administrative groups within a single organization, but it may also affect who makes those decisions in the future. When a PMS is implemented in an existing or newly formed group of the organization, the remaining groups within the organization often feel threatened by the new power of the PMS operating group, especially if the PMS group appears to be preparing to make decisions for which the other groups were previously responsible. They may resist implementation of a PMS to prevent a perceived loss of power.

Fear of Exposure

Pavement management systems provide structured information that often is not widely available prior to the adoption and implementation of a PMS. Those who have been making decisions with less than complete information may resist implementation of a PMS because they fear that the PMS will show that their decisions were incorrect or less accurate than they had stated. They are afraid of possible censure or ridicule by their superiors or others in the organization who now have ready access to pavement information.

Place of Development

A few personnel may refuse to use anything that was not thought of or developed within the agency: "if it wasn't developed here, it can't be any good," they say. Because of this approach, an excessive amount of money may be spent in developing a pavement management component when an existing process could be adopted with a few relatively inexpensive modifications. There is a balance needed between standard pavement management components and agency-specific needs. It is true that almost every highway and public works agency is somewhat differently organized than the others; however, they all have similar management needs and requirements. Some customization is necessary in almost any implementation. However, some of the basic elements of pavement management are similar for similar-sized agencies. The components from one agency can often be modified to allow use in another agency at far less cost than developing a new one.

Resistance to Change

Some people just do not want to change. These people are present in many public agencies. Some of the other issues just described may be a part of the reasons they do not want to change, but some people just do not want to spend the effort needed to reshape their thinking, decision-making process, and work habits. They will set up barriers because they prefer to keep everything the way it is until they retire. They find all kinds of excuses for not changing and will generally only change when they are forced. Most of these individual are insecure with their own positions and knowledge and are afraid to try something different.

Organizational Issues and Barriers

A number of conditions and situations in any organization can make change difficult or at times nearly impossible. Many are issues that must be addressed during implementation to keep them from developing into barriers to effective use. The following gives some of the most common situations.

Size

Some agencies consist of a single public works director with a few employees all working out of a single office. Other agencies have thousands of employees involved with pavement planning, programming, design, construction, maintenance, rehabilitation, and reconstruction spread throughout several functional departments and regional districts. The staff in an agency must be educated in the purpose of pavement and trained in the effective use of the pavement management procedures. Larger agencies require more effort to get the information and training to all of those that will be affected simply because there are more people who can have an impact on adoption, implementation, and especially effective use of pavement management. A large agency presents more opportunities for pavement management use to be undermined by those informal leaders in the agency who do not support the pavement management approach.

Structure

Effective pavement management decisions cross the boundaries of many traditional divisions within most highway and public works agencies. The structure of the organization can have a significant impact on the effective use of pavement management. Some organizations encourage intercommunication among the various central office functional departments and the regional or field groups. Others require that communications go up the chain before they cross areas of responsibility. The lack of effective direct communication among pavement management users can have a detrimental effect on implementation and effective use of pavement management.

Agencies can have several different types of structure. Some agencies have organizational structures that were developed when constructing new facilities was their primary activity. In many of those agencies, maintenance received the lowest priority for staffing and funding. As the need to maintain, rehabilitate, and retrofit the existing pavement network became more important, there was no realignment in the structure of the agency to better address these functions. If the structure of the agency does not match the functions that they must fulfill, there will not be an adequate allocation of resources to address the problems that the agency must face. When this occurs, implementation and effective use of pavement management will be more difficult.

Some agencies have centralized decision-making processes. In those agencies, the subdivisions, such as districts or maintenance areas, are responsible for effective implementation of the program developed by the central office. In other agencies, the central office allocates funds to each subdivision, and the subdivision then determines how to spend that money. Decentralized organizations require a different type of decision support outputs for pavement management than for centralized organizations. In decentralized programs, all of the decision makers in the subdivisions must be convinced that effective pavement management is beneficial to them before it will be effectively used.

Organizational Level

Since a PMS provides new information affecting many major operating units within the organization, new communication channels, both formal and informal, must often be established. When the PMS operating unit is buried deep within the organizational structure, it is difficult for the person responsible for the PMS to communicate and have access to all of those affected by the implementation of the system. Many times, the PMS engineer or manager is relegated to communicating with those on the same organizational level because of protocol and tradition within the organization. Those at the same level as the PMS engineer or manager in other operating units are far enough down the organizational hierarchy that they may have little impact on the actual decision-making process. This may result in the development of new informal communication channels; however, it may also hinder the full implementation and use of the PMS because the real decision makers are neither getting nor using the information prepared by the lower operator in another unit.

Past Management and Decision-Making Practices

The effective implementation and use of PMS is affected by past management and decision-making practices in an agency. Some agencies have developed good management practices even though they do not have pavement management decision support software and formalized inspections. For them, the conversion to a structured PMS is a natural evolution of management practices. Other agencies only react to the latest emergency. They think that planning for pavement maintenance and rehabilitation in their agency is an exercise in futility. It is difficult to implement a structured management approach adopted in those organizations because planning and programming are foreign concepts to them.

Several types of decision-making processes are used to reach a decision in different agencies and sometimes within different groups of the same agency. These may include

- Optional decisions: choices to adopt or reject are made by an individual independent of the other members of the agency;
- Collective decisions: choices are made by consensus of the members of the agency;
- Authoritative decisions: choices are made by relatively few in the system who have the power, status, or technical expertise; and
- Combination decisions: various elements of the choices may be made by some combination of the processes described earlier.

The type of decision making in the agency has an impact on the way in which the implementation process must be formulated.

Stability

Some agencies have a more stable structure than others. Some practically never change, and changes that do happen occur in small, incremental steps. Other agencies experience frequent and radical changes in staffing, structure, and management on regular basis. A more stable structure allows use of a more complex decision support system.

Planning Horizons

Some agencies basically plan for a single year at a time. They determine what pavement sections need work in the fall, put together a program in the winter, get it approved in the spring, and complete the work in the summer. Others must plan work for 4 or 5 years in advance. This is especially true for complex projects in major metropolitan areas and high-volume highways in remote areas where the work must be coordinated with other activities such as bridges and utilities. The 1-year horizon may allow implementation and use of a simple PMS that addresses and priority ranks current needs. Those with longer planning horizons need a method to predict condition in the future.

Constraints on Selection of Projects

In local agencies, the selection of a project for treatment may be constrained by some other activity on the street such as planned sewer repair in the near future. In complex highway projects, funds may be allocated to a single project for several years in order to complete the work that must be phased. In some cases, funding categories, political commitments, and management decisions constrain the work to specific geographic areas, certain types of work, or even specific projects. This requires that the

PMS be flexible enough to allow this information to be entered into the analysis and decision-making process and that committed projects be identified without being classified as being in need of additional work.

Fixed Facilities and Process

Some agencies have invested resources in a particular computer system, a location referencing system, a specific data collection process, an existing database manager, or a spatial database that constrains the decisions that can be made in the development, selection, implementation, and use of pavement management components. The PMS must make use of these existing facilities such as an information systems infrastructure because of prior management decisions and resource allocations.

Resources

Pavement management cannot be developed, implemented, or used effectively if resources are not available. This includes both the resources for those responsible for the PMS and funds for implementing the programs developed through the effective use of a PMS.

Those responsible for the development, implementation, and use of PMS must have funds and resources to complete those activities. Larger-size organizations may find this easier than smaller agencies, because in larger agencies it is often easier to find some resources to allocate to pavement management development and implementation than in a small local agency; however, it is more difficult to coordinate the activities on an agencywide basis. In most small to moderate-size local agencies, funds are often difficult to allocate to pavement management and pavement management is only one of several activities for which the manager is responsible. Some agencies have much more personnel resources than funds. Others can contract for work easier than they can hire staff. This constrains the resources available to support pavement management development, implementation, and continued use.

Effective pavement management requires the application of treatments at the most appropriate time in the life of a pavement to provide the most cost-effective pavement network. If an agency has a backlog of funding needs and pavements in extremely poor condition, much of the funds available may have to be spent on stopgap type maintenance to reduce the liability exposure of the agency. This can prevent the effective use of PMS-supported decisions to improve the condition of the network unless the PMS is structured to support backlog analysis and show the impact of this type of fund allocation on funding needs. If adequate funds are not allocated to apply preventive maintenance to good pavements and gradually reduce the backlog, PMS cannot improve the situation.

One-Person Show

Several agencies have invested their pavement management knowledge experience in one or two people in the organization. The PMS positions often are at a relatively low pay level, but they are often filled with young, bright individuals with skills such as computer expertise that are in high demand. These talented individuals often only stay for a limited time. When a promotion, transfer, or job change removes that person from responsibility for pavement management, it often takes several weeks to several months to replace the person. By the time the position is filled, the pavement management knowledge from the preceding PMS manager is often lost. The new person must start over on much of the system. Some smaller agencies have abandoned their PMS efforts when this key individual left. This problem is one of the most troublesome because it is so difficult to address. It is more prevalent in smaller agencies, but it occurs even in larger local and state agencies.

Cross training is often suggested as the solution. However, all staff members in practically every highway and public works agency have more work duties than they can effectively complete. They must allocate time on the basis of issues of immediate importance. Cross training is never the most important activity until the responsible person leaves—and then it is too late.

Competing Fund Needs

Almost every agency has more funding needs than resources, and there are always many competing funding needs. In some agencies, pavement funding needs must compete for funds with human services, population protection, and all other needs in the governing agency. In other agencies, certain funds are dedicated to transportation needs, and the pavements compete with other highway or transportation needs. Often funds are allocated to the element that has the highest visibility. Those who have spent considerable energies to adopt, develop, and implement a PMS only to see the results ignored because other needs are the current hot item often become discouraged and discontinue using the PMS. This problem is related to the availability of resources, and it has an impact on the type of reports and information the PMS must produce to support fund requests.

System Design, Development, or Selection

Although many of the hardware and management support issues should have been resolved in development, there are many options. The following describe some of the problems that can occur from selection of an inappropriate system.

Matched to Agency Needs

The most important step in selecting and implementing a PMS is selecting one that matches the agency's needs. PMS decision support products can provide recommended programs for pavement maintenance, rehabilitation, and reconstruction. It can also assist in providing support for funding requests. Some agencies have selected and implemented a PMS to justify budget requests only to find that the software only provided assistance in selecting sections needing maintenance and rehabilitation. They then discontinued the use of the software or used pavement management at a lower level than could have been provided by comprehensive decision support software. In other cases, when the agency tried to evaluate the PMS software-generated recommendations to prepare a final program, they found that the pavement sections, cost units, and treatments used in the decision support software did not match their management process. The manual effort to make the PMS software-generated recommendations match their normal management process was so massive that the system was abandoned.

A PMS can use a simple method to get relatively broad information on the condition of the pavement, or it can use an extensive survey to obtain detailed information about each section of pavement in the network. Each of these has advantages and limitations. Several agencies have discontinued use of a PMS because it cost too much money to keep the data current.

It is imperative that the selected PMS provide the decision support required by the agency. It is also imperative that the resources required to use the PMS effectively are not greater than those that the agency can realistically allocate to that effort.

Complexity

In some cases, the PMS decision support products have been so complex, or poorly documented, that the user could not understand the concepts used in the system and could not explain them to others. When those responsible for using the PMS took the recommendations to management, they could not explain the basis for programming specific streets for rehabilitation or the justification for selecting sections for preventive maintenance. They could neither explain the concepts on which fund request were made nor show the impact of different alternatives suggested by management.

The concepts included in the PMS must be simple enough for those who must use the PMS every day to explain them to their supervisors and funding authorities. The actual computer programs can be extremely complex as long as the concepts can be easily explained and simple problems illustrating these concepts can be analyzed with the software.

Black Box PMS

The black-box approach to PMS tries to get the user to place his or her trust in some magic system or program. The PMS software is considered a black box when it provides recommendations, but the rationale behind the recommendations is not known. In some cases, proprietary systems were developed in which the developer purposely refused to describe the programmed analysis procedures. In PMS, many early systems described the computer software as a PMS when in fact PMS is a concept that must be adopted by the entire organization and the software is a decision support tool. Some highway and public works engineers selected pavement management software with the understanding that it would provide all of the decisions needed for maintaining their pavement network. They could proudly point to the output of the program and state, "the computer told me to do it" when questioned about their decisions. However, they often did not know the reasoning behind the computer-generated programs. When the programs could not be carried out as the computer instructed, the systems were often discontinued.

Methods to Overcome Institutional Problems

Diffusion of innovations and technology transfer are fields of study that help define approaches that can be used to get new management approaches implemented (*11,12*). Engineers tend to think that if they develop a better device or approach to a problem, it will immediately be used. History shows that the existence of improved systems does not ensure adoption. There is a wide gap between what is known and what is actually used in many fields (*11*).

As an example, the present typewriter keyboard, known as the QWERTY board, was developed in 1873. At that time, the keys on a typewriter returned to the key rest by gravity pull. If the typist struck keys too quickly, one key would not return to the rest before the second came forward. This resulted in many instances of the keys hanging up and jamming. The present keyboard arrangement was actually designed to slow the typing speed and reduce the incidence of jamming keys. In 1932 Professor Dvorak conducted time and motion studies at the University of Washington to create a more efficient typewriter keyboard. The Dvorak typewriter keyboard results in approximately 70 percent of the strokes on the middle row of keys, 22 percent on the upper row, and 8 percent on the lower row with the amount of work assigned to each finger proportional to its strength and skill. In addition, the keys are arranged with the consonants under one hand and the vowels under the other to allow more keystrokes to be alternated from one hand to another. The net result is a keyboard that is easier to use and that significantly increases typing speed. Many speed typing records were set with the Dvorak keyboard in the 1930s and 1940s; however, it has not been adopted by most typists or agencies. (*11*).

There are no magic solutions to people and institutional problems. Major changes in most organizations take considerable time and effort. Changes that affect how decisions are made and the flow of information through an organization are some of the most difficult to implement effectively (*11*). The following information can be used to address and overcome as many obstacles as possible, minimize the impact of others, and identify those that must be bypassed. The discussion is presented in general groups to help define how to approach them, although concepts often cross the boundaries of these groups.

Communication

Several of the people problems described can best be addressed by effective and repeated communication. The proponents for pavement management must take every opportunity to explain pavement management concepts and processes to all that will listen. This includes formal presentations to meetings of the agency, to management, and to the funding authorities. It includes training sessions for all of those that will be directly involved so that they have a thorough understanding of the PMS and they can help pass the information to others. It includes informal discussions with all of those who will be influenced by the adoption and use of PMS.

In a recent survey completed in the San Francisco Bay Area, it was found that communication was one of the main differences between those making most effective use of pavement management products and those making marginal use of them. Those public works agencies that had developed good communications with the city and county managers and city councils and county boards concerning the purpose of pavement management and pavement management procedures were able to use the pavement management procedures effectively in the budget process. Those agencies that had not done an effective job of communicating with higher-level management about the pavement management process generally were not able to make effective use of pavement management products in the budget process. Some of the information that should be included in this communication is described in the following.

Pavement Management Products Described as Decision Support

One of the most difficult barriers to overcome is the organizational inertia that resists change and is allied with the fear of exposure. Communication should include a thorough discussion of what the pavement management decision support system will do and how the users should interact with it. There are those who have a misconception that they can buy some software, collect some data, put both in a computer, and have all the answers they need about pavements. It is extremely important to communicate that pavement management software is decision support software. Pavement management is a decision-making process that encompasses all of the decision makers. A PMS incorporates all of these into a functional operation.

In several instances, pavement management concepts have been misunderstood or misrepresented. Several agencies have come to believe that a PMS will manage their pavements. In fact, the pavement management decision support software is nothing more than a decision support tool. The personnel in the organization are the real management system. They make decisions; the software only provides organized information that is used in the decision-making process. This must be stressed again and again, especially to top management and decision makers. Some agencies are separating the terminology of a PMS from that of a pavement management information system. This helps distinguish the decision making and decision makers who manage pavements from computer programs that provide information in decision support.

Proper communication concerning what should be expected from pavement management decision support systems is used to help resolve turf protection problems. It is extremely important to show that the software packages are prepared to provide assistance and support to an experienced pavement engineer and that they may not provide the final answer.

Show Benefits

People are more willing to take a risk in trying a new approach if the potential benefits far outweigh the potential difficulties. This means the benefits must not only be to the agency but also to those persons who will be directly involved or who may prevent acceptance or full usage of pavement management. Some of the agency benefits include better utilization of funds and more effective justification of fund requests. Some of the personal benefits to those most directly involved include the ability to be more responsive to management, better coordination with utilities or other highway facilities, and more involvement in the decision-making process.

Development and Implementation

Development and implementation are discussed together because they are so intertwined in most implementation processes that it is difficult to separate them. Development generally includes selection of data collection processes, programming database and decision support software, and so forth. A consulting or software firm may develop these and then try to implement them; but in most public agencies, development and implementation run concurrently. In some agencies, there is a selection process but little actual development. One approach to implementation that is developed around the principles described in the following is presented by Smith in another paper in this publication.

Several characteristics of innovations have been identified that influence the potential for adoption and continued use (*11*). During the development and customization of a PMS to fit a specific agency, careful attention to these characteristics can reduce the resistance to the PMS (*9*).

Compatibility

Compatibility is the degree to which the PMS is perceived to be consistent with the current management process, existing procedures, political realities of the agency, and agency needs. The more compatible it is, the more likely that the PMS will be adopted and effectively used. This is probably the most important aspect to consider when selecting or developing a PMS. The organizational analysis in the implementation is essential to determine how to make the PMS fit within the organization.

The PMS must support the structure and programming process in the agency. If the agency uses a decentralized decision-making process to decide which sections of pavement are preventive maintenance but rehabilitation decisions are made in a centralized manner, then the PMS must support the districts and central office in each activity. The PMS must reflect the decision-making process rather than forcing the decision process to fit the pavement management decision support products. An attempt to change the agency structure invariably creates additional resistance.

The implementation process must carefully identify the formal and informal structures along with their respective lines of communication. The PMS implementation must carefully consider and develop communication links and decision flows to minimize turf formation and reduce barriers. If maintenance has traditionally had a say in which sections of pavement were selected for repair, the PMS must support this process, even if it is a manual review of recommendations from the pavement management decision support software.

The PMS must support the funding and design cycles of the agency. Some agencies require a lead time of 2 or more years. Some types of projects may take even longer. The PMS must support identification of sections needing work and selection of the most beneficial in the time frame that fits the agency's cycle. The shelf life of designed treatments is relatively short, and the PMS must be able to adjust treatments if they are not applied when first planned.

The PMS must support political and managerial commitments that override the recommendations of the decision support software. Committed projects come into existence for many reasons including advanced planning, and they may consume a large portion of the budget for a given year. In many agencies, projects that are perceived to support economic development are funded before maintenance and rehabilitation. The PMS must allow this, although it should still show the impact of applying the repairs.

The PMS must support the agency in decision making when the financial situation is dismal. Some agencies have such a backlog of needs that it is difficult for them to allocate funds to any pavements except those in the worst condition, and those funds are only stopgap treatments that are seldom cost-effective. This type of situation requires special consideration by the decision support software.

The PMS operational requirements must match the agency's resources. If the PMS requires more staff resources than the agency can support, the agency will discontinue use of the PMS or use it at a minimal level. Collecting and maintaining data can be expensive and overwhelming if not properly planned. Only data that are absolutely needed should be collected, and that data should only be collected when needed.

The decision support software must provide the information needed in the form that is most usable to managers. The content of each report must be developed for the management level for which it is targeted. The level of detail normally decreases at higher management levels. The style of the reports is often as important as the content to get acceptance. Some groups require tables of detailed information, whereas others want to see only summary charts and figures. Failure to produce these for each level can lead to a loss of support and eventual discontinuance.

All organizations are required to answer emergency requests for information for which no standard report has been established. Pavement management data structure and decision support software must provide for interactive custom reports. This allows the user to demonstrate the benefit of the PMS in ways that will gain it instant support from those that must provide those answers.

Complexity

Complexity is the degree to which the system is perceived to be difficult to understand and use. Ideas that are easier to understand are more likely to be adopted. The system that uses concepts and techniques that are familiar to the managers will be perceived as being less complex.

Minimizing the amount of data that the system uses and the number of steps required to complete a task by the user causes the system to be perceived as less complex. The format of the software interface with the user can have a dramatic impact on perceived complexity of the PMS.

The PMS must fit organizational reality. Software that tries to force the agency to match its decision-making process rather than support the decision-making processes of the agency will almost always be perceived as more complex. Many agencies have already invested heavily in computer hardware, data collection processes, databases, and location referencing systems. The PMS should use the existing systems as much as possible rather than develop new ones. This causes the PMS to appear to be less complex.

One of the most difficult problems to address is the one-person show or champion dependency. This occurs because of the lack of time for training others, but it is also due to the complexity of the PMS. A PMS that is less complex is easier to understand and use. This means that it takes less training to learn how to use it and makes it less champion-dependent.

Relative Advantage

Relative advantage is the degree to which the structured PMS is perceived to be better than the existing process. The greater the perceived advantage, the more likely adoption and continued use is to occur.

The PMS must show the benefits that it is providing to the agency and those working in the agency. Each group in the agency and each person that must invest time and effort in PMS implementation and use should be able to see some benefit. The implementation should make a special effort to ensure that all tangible and intangible benefits are identified and documented. This can be in terms of monetary benefit, such as the ability to repair more pavements with available funds, or it can be in terms of nonmonetary benefits such as the ability to answer management questions more objectively. By structuring the PMS to provide quick and accurate answers to the "what if" questions that are common at budget time, it provides an advantage to the managers by portraying them as more responsive and knowledgeable.

The PMS should be structured to help secure additional funds for the maintenance, rehabilitation, and reconstruction of pavements. Few agencies have the funds to complete all of the work needed. Most agencies have large backlogs of funding needs, and many agencies must compete for funding with other public needs. This leads to competition for funds within the funding authority with nontransportation needs and within the agency among transportation needs. The pavement management decision support software must provide reports and information in a form to support fund requests in this competitive environment. It must show the economic impact of different alternatives so that funding authorities can see the effects of their decisions. Graphical reports will be especially needed in this effort.

The PMS should provide a comprehensive and balanced analysis of all pavement needs including maintenance, rehabilitation, and reconstruction. This will provide the greatest benefit to the agency and provide support for the widest possible number of users increasing the advantage for each. This will support multiyear plans needed for long-term planning and trade-off analysis.

The PMS should provide multidisciplined decision support to all of the various groups in the organization that must deal with pavements. These include management, subdivisions such as districts or maintenance areas, planning, programming, construction, design, and maintenance. This will provide the greatest relative advantage by addressing the needs of more groups and individuals within the agency.

Adaptability

Adaptability is the degree to which the PMS can be modified to meet individual differences in needs. Decision support needs can change over time, and the ability to modify the PMS decision support system to meet these changes is desirable, but the PMS must allow changes without making the system unduly complex.

Although it seems that organizations may never change, internally there are often significant changes when individual managers change. Retirements and turnover are currently creating considerable changes in managers. The PMS must be capable of adapting to the changes in reports and formats but withstand changes to the substance of the process unless the structure is making a permanent change that requires modification of the decision support process. Modular programming, simplicity in design, and standard data base structures can all assist in providing adaptability without becoming too complex.

The PMS should be able to meet special needs. Planning and programming for maintenance, rehabilitation, reconstruction, and even abandonment may require special consideration and analysis in major urban areas and environmentally sensitive areas.

The PMS should coordinate with other road and street improvements. In state agencies, congestion, safety, bridge, public transportation, and intermodal management systems have also been mandated. In local agencies, many pavements have several utilities beneath the surface. The responsible agencies must make the best use of limited funds for all activities. These systems can interact at several levels including conflict analysis, needs analysis, and fund allocation. Establishing these links will lead to better transportation systems.

The PMS adopted must accommodate technological changes. New data collection techniques are under development that could reduce the cost of data collection and at least reduce the exposure of workers to accidents. Computer hardware keeps getting faster and more powerful. New, more realistic optimization techniques are being developed and tried. New pavement maintenance and rehabilitation treatments are being used. The PMS must be capable of incorporating these and other changes that will occur. Developing the decision support software in modular form and using standard procedures as much as possible will allow more efficient updating.

Support

Many people barriers such as turf protection and fear of exposure can be overcome only with support from upper-level management and a long-term commitment to using the PMS. Upper management may be able to force the formal communication channels to function, but sometimes new informal channels that bypass impediments may have to be developed. This is the same process that must be used to address those who intentionally block communication channels.

Management must establish long-term financial support for the maintenance and operation of the PMS if it is to be used effectively. This may include developing a special pavement management group within larger organizations with their own operating budget. Sachs and Smith discuss an approach to supporting PMS in local agencies by regional planning agencies (*13*).

Training

Training is vital to implementation and effective use of a PMS. The training must address all of those who will be affected by the PMS. It must be cyclic and continue indefinitely.

In the hands of someone unfamiliar with pavements who follows the PMS recommendations blindly, erroneous results can be produced. This can be alleviated by providing training for several levels of PMS efforts in an agency, which includes training and seminars on proper use of maintenance treatments, quality assurance, and specifications for maintenance and rehabilitation treatments. This approach creates an atmosphere in which PMS can be discussed in the context of how it helps make decisions about treatment selection and timing, so that it appears much less threatening to those who have made these decisions in the past.

Complexity is relative to the sophistication of the users and can be decreased by communication, on-call assistance, and training. Comprehensive documentation of the software and the operating concepts also help reduce the appearance of complexity.

Training should be conducted at several times and at several levels. When the PMS is being implemented, training should be conducted on the principles of the PMS, how to interact with the decision support software, how to prepare reports for different management levels, how to use the results to support budget requests, and how to compete for funds. The training should be directed initially at those most directly involved. These can then assist in training others.

Some types of training are more formal than others. Classroom instruction can be used to discuss pavement management principles, but hands-on training is more effective for teaching interaction with the software and hardware. Training in how to generate reports and develop budget requests can best be completed in a hands-on fashion or by producing examples.

Upper management, funding authorities, and the public will need training. This will often be bite-size training presented less formally for upper management and funding authorities. Public training will often be in the form of public information brochures and releases to the press.

Training should be directed at the areas of greatest resistance. When a particular manager or group within the organization appears to be blocking acceptance or full use, training should be directed at that point. Some of it can be formal, but much of it will need to be informal demonstrations.

Just when it appears that everyone is trained, there will be staff changes. Inspectors that work in data collection for only a few weeks each must be retrained before the beginning of the next data collection cycle. Training will need to repeated periodically for those activities. As enhancements are made to the data collection procedures and decision support software, new training will be needed. Experience shows that PMS personnel need training before they can be effective users; however, after they have been using the PMS, the same training repeated is even more effective.

Outside Support

Some outside agencies can assist in pavement agencies in adopting and effective implementation of PMS. The Local Transportation Assistance Program (LTAP) Technology Transfer (T^2) Centers often have staff members with PMS expertise that can provide assistance. These centers also call on members of the local academic community with PMS expertise. Several consulting engineer firms have developed PMS expertise. The FHWA work cited here (*14*) contains a list of consulting organizations with PMS experience. Regional FHWA offices, LTAP T^2 Centers, and local universities may also be able to help identify firms with PMS experience in the local area.

The "one-person show" problem has been countered in a few agencies in the United States and several international agencies by contracting with consulting firms to act as the pavement manager. The consultant helped implement the PMS in the agency, and then the firm contracted to provide PMS expertise to the agency by keeping the PMS data current, identifying pavements needing work, selecting the primary candidates for work, and even identifying the treatments to be used. Other agencies have contracted for specific expertise to be provided by the consulting firm. Some agencies lack adequate personnel to collect the data needed for initial and continuing surveys, and several firms have assisted them in PMS data collection. This approach effectively transfer some of the expertise problem to the consulting firm; however, the agency must still maintain some level of expertise to be able to use, present, and defend the recommendations provided by the consultant.

SUMMARY

Although there are always technical problems that need to be addressed in pavement management, many of the most troublesome types of problems currently affecting the implementation and use of PMS are people problems. Some of these are due to the personalities of the individuals that must adopt, implement, and use pavement management. Others are related to bureaucracies in which the PMS must be placed. Several types of issues were identified that often cause problems in the implementation and continued use of PMS. Understanding the problems that other agencies have encountered will help those in the process of adopting, developing, and implementing PMS overcome or minimize them.

There are no magic solutions. Some people problems are solved only when the persons responsible for the problems retire, are transferred, or are otherwise removed from positions in which they can block PMS. However, there are several things that can be done to remove, reduce, or overcome many of the barriers. Effective communication, suitable development, appropriate implementation, adequate support, and repetitive training are all important factors that can reduce problems encountered in PMS implementation and effective use.

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Pavement Management as Part of Strategic Road Management

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The investment in roads and road transportation forms a major part of a government's stock of public capital. Furthermore, the importance of roads and related economic assets make it vital that these should be well managed to ensure optimum use of the road network. The severe cutbacks in road funding during recent years have, however, made it difficult even to maintain the existing road network properly. The response of the South African Department of Transport has been to match expectations of the long-term funding arrangements with the needs of the road network through strategic management. Strategic management necessitated an integrated road management system especially because the Department of Transport is responsible for managing the entire road network administered by various regional authorities. South Africa opted for a modular system that embraces a number of subsystems, of which the pavement management system has been developed to a greater extent than the others. A further need was for compatibility among the various regional systems to obviate a possible mismatch of fund allocations by the Department of Transport. To this end, the Committee for the Compatibility of Pavement Management Systems was formed in 1989; this committee represented each government road authority. The committee has made substantial progress toward achieving compatibility through the publication of manuals and guideline documents and the standardization of data processing formulas. The process is, however, not complete, and a number of newly crystallized goals are being addressed.

The investment in roads and road transport forms a major part of a government's stock of public capital. In addition, the importance of roads and related economic assets make it vital that these should be well managed to ensure optimum use of the road network. In South Africa an excellent primary road network has been built up. However, the current social reform process, coupled with poor economic performance over past years, has drawn funds from transport in general and roads in particular.

In a developing country, road planning should look forward and seek to provide increasing numbers of people with access to markets. This requires adequate maintenance of the existing road network as well as its continued expansion and upgrading to accommodate the shifting, rapidly urbanizing population. The severe cutbacks in road funding during recent years have made it difficult even to maintain the existing road network properly, however.

The response by the Department of Transport has been to match expectations of the long-term funding arrangements with the needs of the road network through strategic management. At the heart of this approach lies the concept of road management systems, with most of the recent emphasis on pavement management.

Needs for Strengthening Management of Road Networks

Roads play a major role in the achievement of a government's overall social, economic, security, and developmental goals. They are also essential for the country's interaction with neighboring states, and they form an integral part of the nation's infrastructure. However, the identification and quantification of all the benefits to society from the improvement of the road network has been elusive. Several of the direct benefits to users of improved roads can readily be quantified, but other benefits directly attributable to such improvement defy measurement and can only be described. In addition, there are indirect or secondary benefits that may stem from or be introduced by improvement of roads but that also are difficult to quantify and value.

Infrastructure development offers an intriguing policy platform to many politicians. No economist will deny that infrastructure investments are important, but there is fierce debate among economists regarding the specific way in which this investment's return for the economy at large should, or can be, measured.

The major protagonist for the argument that core infrastructure investment is in tandem with a nation's productivity is perhaps David Aschauer, who has estimated that "every dollar invested in public infrastructure yields four dollars in return" (*1*, p. 124).

Despite this unresolved debate, there is no doubt that it is essential that the current infrastructure be managed optimally, if only to obtain the best possible returns on investment. In general, road transport is the dominant means of transport in most countries. Furthermore, the replacement costs of main roads in developing countries exceed $3 trillion, which is greater than the investment in power generation and distribution in these countries (*2*). (The figure for South Africa is approximately $30 billion.)

Governments worldwide are exploring ways of improving the management of roads. Although overall strategic decisions will continue to be influenced by the political process, improved management can clarify implications of these decisions and raise the quality of political dialogue surrounding such decisions.

The strategy for improving the management of roads includes setting clear management objectives and monitoring performance against these objectives. To evaluate the efficiency of management of a road agency (i.e., how well it plans its expenditures, undertakes maintenance, addresses road safety issues, and controls overloading), a set of performance measures is necessary. Evaluation of performance has generally focused on individual projects and has seldom addressed the performance of the road network as a whole. In South Africa, attention has been given to the development of an integrated strategic management system. This has evolved into a comprehensive set of integrated management processes that are directed toward maximizing the use of the existing network. Although fully formalized procedures do not yet exist, the elements of the system are used, to varying degrees, by the various road agencies in South Africa.

Redirecting Road Financial Planning Process—Strategic Planning Approach

In South Africa, the Department of Transport has been assigned the function of providing leadership in the strategic financial planning for the country's total road network. Before 1990 the financial planning for road provision was different. The various geographic regions were financed through separately administered budgets involving various levels of government. There was little or no overall coordination to counteract local parochial demands and to take into account the "network" effect of a country's road system.

The 16 road authorities in South Africa adopted different approaches and philosophies in their separate pavement management systems (PMSs) with levels of sophistication that varied from fairly basic visual assessment procedures to approaches that incorporated a host of machine-measured surveillance information. In addition, different models, evaluation procedures, and decision criteria were used. These differences were so great that rational comparison of the relative pavement rehabilitation needs was impossible.

In an environment of rapid socioeconomic development and increasing difficulty in financing roads, it became necessary to redirect the strategic financial planning process to properly integrated and coordinated supply-led planning. This was done to make optimum use of the limited resources through an integrated and coordinated project prioritization process, the essence of which is uniformity in criteria for assessing economic worth.

The response to the financial difficulties facing road authorities has been a deliberate attempt to dovetail financial planning with strategic planning, which, whether it is physical or financial, is essentially the matching of current actions to long-term goals. These goals are based on a view of future preferences and of procuring and allocating the necessary resources to carry out these actions. Stated otherwise, the aim of the road network strategic planning process is to satisfy optimally the economic and social goals and objectives of the community with respect to mobility, subject to flexibility and resource and impact constraints, within an integrated total road management system. This has led to an approach that attempts to treat road provision as an ongoing process and to avoid ad hoc or political decision making on a project-by-project basis.

Integrated Road Network Management

Significant research and implementation progress has been made by road authorities in the field of pavement management during the last decade or two, but the integration of the other activities in a strategic management approach has not been so successful. The broader concept aims to assist in the administration of road networks by addressing all facets of strategic and tactical planning, design, construction, and maintenance for roads in an integrated manner. These systems should also (and have locally been successfully applied to) facilitate interaction between the executive and the legislative authorities.

The management system is designed to provide real solutions to real problems by authoritative decision makers. It is for this reason that the formulation of the system is largely determined by the political (very often the dominant factor), organizational, procedural, and technical context in which it is embedded. In other words, it had to be strongly correlated with the administrative functions of the authority within which it operates. Thus, it is self-evident that the development of a road management system required a thorough analysis and deep knowledge of its environment so as not to be a purely intellectual exercise that would usurp reality.

The development of a road management system started with the integration and rationalization of the existing situation. For this reason, the implementation will proceed in stages or, more exactly, in modules within the framework of an overall rationale. There was no one road management system that could be used as a model or reference, and specific approaches were developed for each context.

Some characteristics of road management systems are essential. Because they are, in fact, a formal expression of modern administration or management principles, the administrative functions such as policy making, strategic planning, financing, monitoring, and control had to be taken into account in deriving the system. They had to, among other things, consider

- Short-, medium-, and long-term objectives;
- Definition of projects in both physical and economic terms;
- Development and implementation of plans, programs, and budgets; and
- Monitoring of implementation by means of appropriate indicators that permit
  - –The effectiveness of implementation to be assessed,
  - –The difference between what was planned and what was achieved to be measured, and
  - –The policy to be modified if necessary.

Thus, they are conceptually an integral part of the strategic planning process that has been pursued by many large institutions for several years and has replaced a more static or determinant method of management. Such strategic planning is designed to cope with an uncertain future and is based, in particular, on the selective handling of a very large body of data. As such, the road management system had to be open, interactive, and dynamic.

The openness of the system is necessary to allow it to cater for additions and modifications as a result of increasing experience and growing knowledge. For this reason, a significant degree of modularity in the system was necessary. Management systems had to be interactive as well, first to accommodate the feedback effect and, second, to be modeling and analytical tools sensitive to variation in input parameters. Because many of the variables to which the system must cater change over time (and sometimes even must be assumed in the first place), systems had to be dynamic.

In recent years South African development work in this field has been devoted to a system that embraces the following subsystems:

- PMSs,
- Road traffic management systems (including geometric improvements and traffic counting procedures),
- Gravel road management systems,
- Maintenance management systems,
- Structures management systems,
- Accident reporting procedures and systems, and
- New-road management systems.

Figure 1 diagrammatically shows the typical South African modular network management system, where certain data base items are shared between various management modules and where final outputs from the different modules are combined for final priority determination. As stated earlier, the pavement management subsystem has been developed to a greater extent than the other subsystems.

Need for Compatibility

In the past, up to 16 separate regional road authorities were independently managing parts of the South African road system economically that were probably worth less than that of Texas. Over time and with the realization

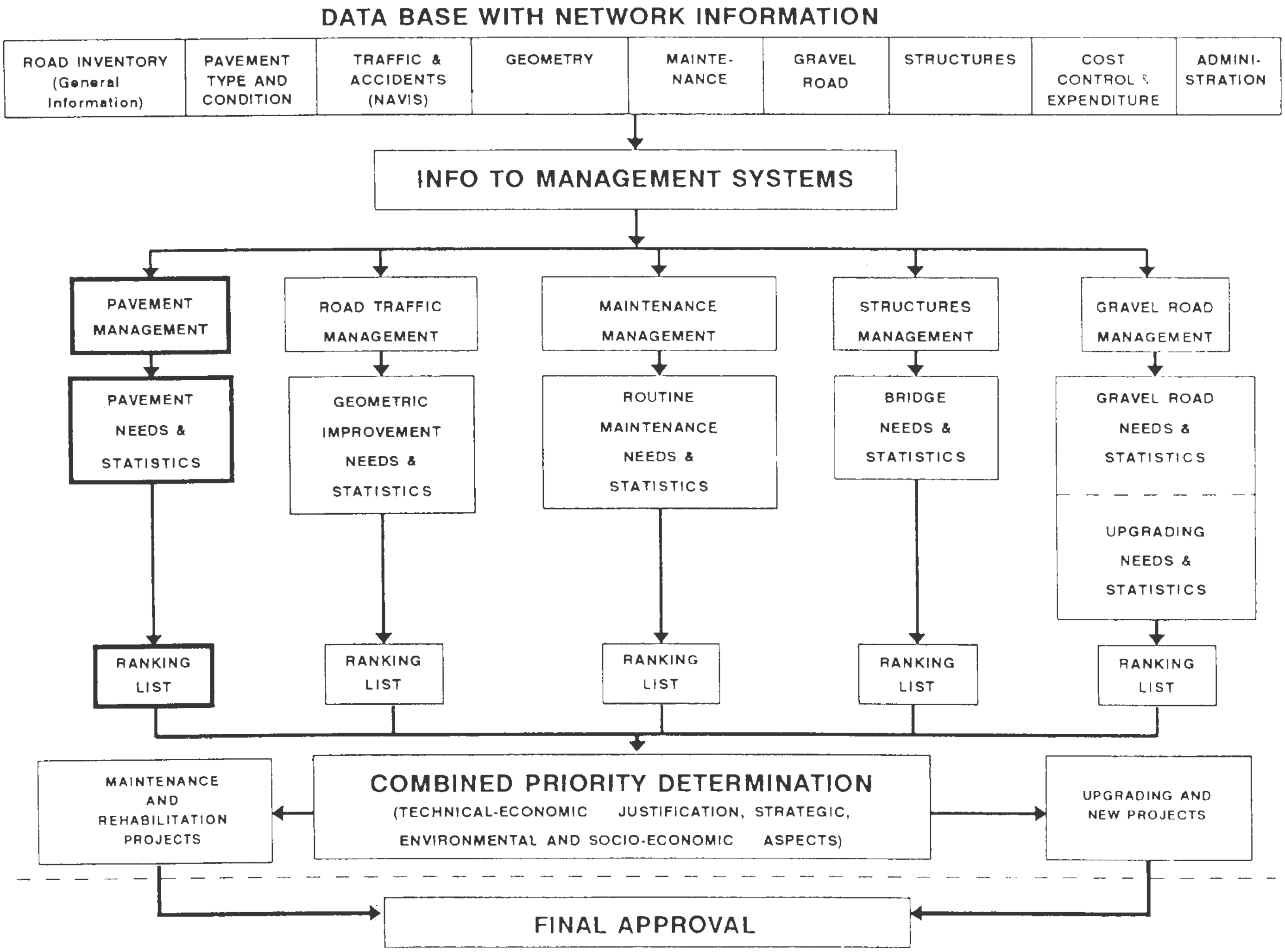

FIGURE 1 Combination of systems within a road management system.

that the primary road system for any country operated as a network rather than as individual links, an overall coordinating role for all roads matters was assigned to central government. This role was in addition to an executive responsibility for the primary road network.

Because the financing for intercity roads in South Africa is through a single treasury grant, which is thereafter allocated to the various central government and regional road authorities through the use of a system that leans heavily on economic cost/benefit parameters for specific projects, it is necessary that the road management system—and in terms of this paper and the pavement management subsystems used—should be amenable to coordination so that a level playing field pertains in respect to the fund allocation procedure. By taking into account that road pavement rehabilitation currently represents the largest budgetary vote for all road authorities, the need for compatibility between the various PMSs becomes apparent. In particular, there was a need for

- Compatible network statistics for total network as well as for subnetworks,
- Compatible funding needs for maintenance, and
- Compatible funding needs for upgrading.

Figure 2 shows how such compatible outputs are to be combined into 5-year programs and annual budgets.

Ensuring Compatibility Between PMSs

The different road authorities each developed their own PMS to meet local requirements. To resolve the problem of incompatibility and consequent likelihood of a mismatch of fund allocations between the various authorities, the Committee for the Compatibility of Pavement Management Systems was formed in 1989; it included representatives from each government road authority. In 1990 these were supported by a consulting engineer appointed

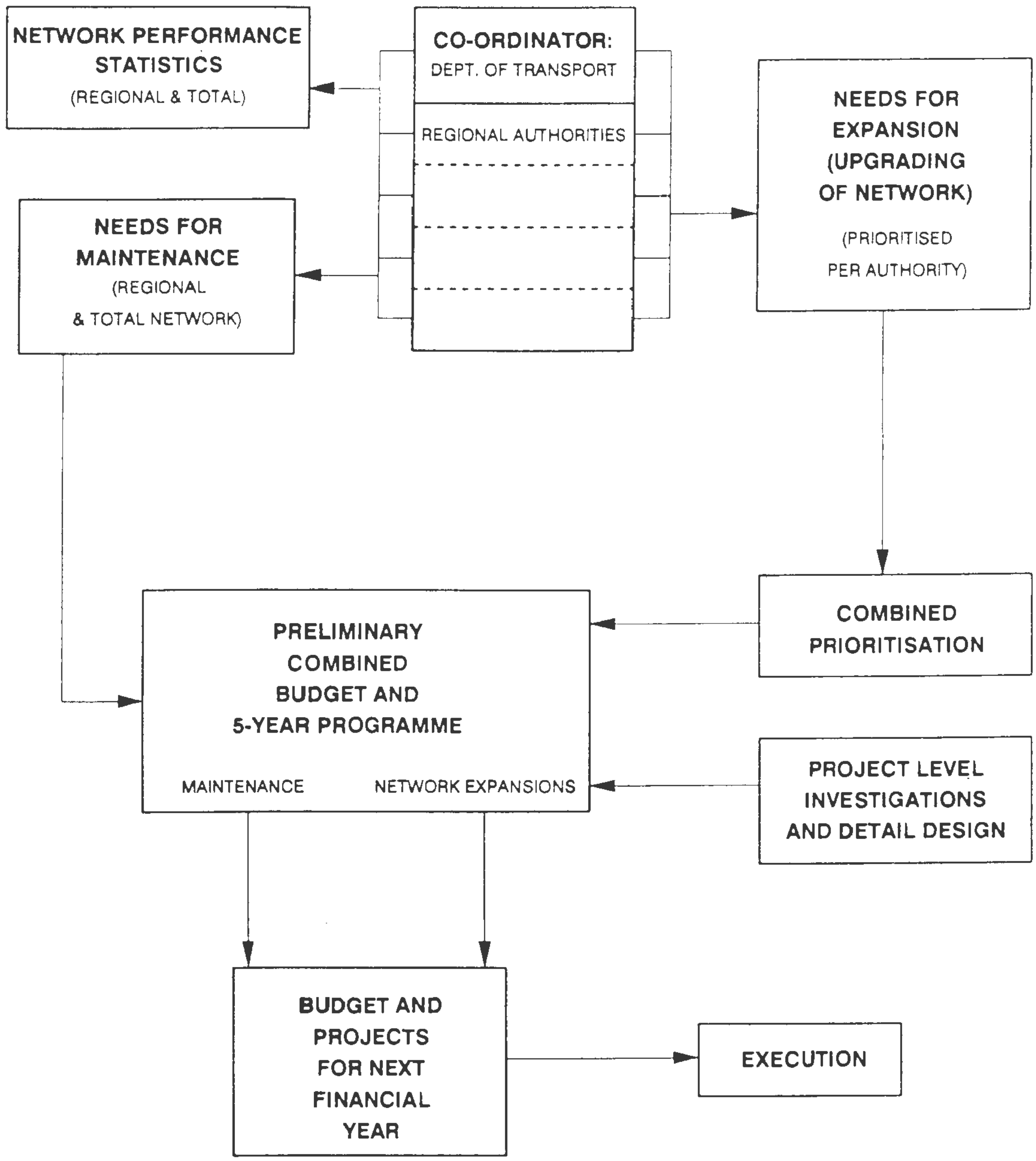

FIGURE 2 **Use of compatible outputs from road network management systems.**

by the Department of Transport. The task of the committee was to investigate the situation and to recommend procedures for achieving the necessary levels of compatibility. Financial controls introduced by the treasury gave further impetus to the process.

Initial investigations showed that the various systems were not directly compatible as a result of differences in methods, definitions, and data. It was found that compatibility was possible if conversion factors were developed and applied to the output data. Conversion would, however, become very complicated for higher-order calculations. Through discussions and the very close cooperation of all parties, it was agreed, as far as possible, to develop uniform rather than compatible systems. (Various government road authorities were reevaluating their own systems, and it was a golden opportunity to consider a new, more uniform system.)

Progress and Current Status

The original objective (i.e., achieving a high degree of compatibility between the different PMSs) has been realized. A high level of uniformity has been reached on all the basic items of PMSs. A summary of activities and outputs includes

- Uniform annual visual and riding quality surveys (3);
- Standard pavement management data categories, which will be used for all PMS data analysis formulas;
- Detailed investigations into the accuracy of PMS data analysis formulas;
- Standardized PMS formulas for network condition and network maintenance measures needs; and
- The first draft of Technical Recommendation for Highways (TRH) 22, entitled *Pavement Management Systems for State Road Authorities* (4).

However, a number of newly crystallized goals require further work:

- Refinement and finalization of data processing formulas with regard to network level needs for maintenance (i.e., network-level maintenance measures), to be used as first input to total funds required.
- Compatible PMS prioritization and optimization, including interaction with "outside" systems, for example, benefit-cost type analyses. Prioritization covers the full range—from initial ranking according to current condition to priorities determined from the analysis of life-cycle cost–related maintenance strategies, followed by determination of highest benefit-cost ratios or most cost-effective strategies. Cost-effectiveness prioritization is similar to benefit-cost analysis except that a proxy in terms of performance is used to represent the benefit associated to a particular strategy. The optimization models enable the simultaneous evaluation of an entire pavement network. The objective is to identify, as available budget and desired performance standards, the network maintenance strategies that maximize the total network benefits (or performance) or minimize total network costs subject to such network-level constraints. [Some of this work has been done in other studies (5) funded by the department, and such procedures will be included in PMSs.]
- Long-term pavement performance modeling that uses compatible PMS data.

TMH 9: *Pavement Management Systems: Standard Visual Assessment Manual*

Technical Methods for Highways (TMH 9) (3) provides national guidelines for the visual evaluation of the condition of flexible paved roads at network level for use in PMSs (Table 1). Rigid pavements should be assessed according to the Department of Transport's *Manual for the Visual Assessment of Pavement Distress: Part 2* (6).

Visual evaluations are used for determining

- Condition indexes,
- Priority indexes, and
- Maintenance and rehabilitation needs and priorities at network level.

In the future, this document will be used as a companion document to the proposed TRH 22 document on PMSs, that is being compiled by the Subcommittee on Compati-

TABLE 1 Aspects Covered by TMH 9 (3)

ASPECTS COVERED	DESCRIPTION
Segment lengths	Minimum and maximum lengths
Road segment information data	Road numbering Link start and end work description District/Region Climatic region classification Terrain type classification Road width definitions Pavement structure & surfacing classification Pavement age categories including age of surfacing Shoulder descriptions
Assessment procedures and quality assurance	Procedures, training of assessors, checking of assessments
Types of distress	Surfacing defects Structural defects eg cracking, pumping, deformation Functional aspects

bility of Pavement Management Systems of the Highway Materials Committee. This visual assessment manual is intended for visual assessors of pavement condition for PMSs, but it could also be used for training assessors.

The condition of the pavement is considered from two points of view: that of the road user and of the road engineer. Because the road user regards the road as a service, the condition of the pavement is appraised in terms of those characteristics that affect quality of travel—notably comfort, safety, and operating costs. The engineer, on the other hand, recognizes these functional requirements but also views the pavement as a load-bearing structure to be maintained in good time if it is to remain serviceable at optimum cost. Therefore, the assessment of the condition of the pavement is based on functional descriptions a well as descriptions related to the condition of the pavement surfacing and pavement structure.

Visible distress is an important input in the assessment of the condition of a pavement structure especially for typical South African pavement structures with thin surfacings (6). Distress is described by recording its main characteristics—the so-called attributes of distress, namely, the type, degree, and extent of occurrence. The document contains color photographs of all distress types, normally illustrating Degrees 1, 3, and 5. To reduce the subjectivity involved in the assessment, the assessor should follow the assessment procedures as set out in TMH 9 as closely as possible. Table 1 gives a summary of aspects covered by TMH 9.

The document was first published in 1990 as a draft. After being in use for 2 years, a final version was published early in 1993. Special seminars were held throughout the country to introduce this document. All the major road authorities use the manual. The rating teams typically consist of experienced engineers and technicians. Special training and calibration sessions are held annually to ensure uniformity of approach. Most authorities apply statistical checking procedures in order to achieve consistency of data. The visual inspections are also followed by panel inspections, when a group of experienced raters double-check ratings and outputs of the system on a sample of selected needs.

TMH 9, prepared by the Compatibility of Pavement Management Systems Subcommittee of the Highway Materials Committee, which is, in turn, a subcommittee of the Committee for State Road Authorities (CSRA), is published with the approval of the CSRA.

TRH 22: *Pavement Management Systems for State Road Authorities*

TRH 22 (4) is being compiled by the Compatibility of Pavement Management Systems Committee. The first draft for trial use is to be ready in the latter half of 1993. There are three major sections in TRH 22:

1. Introduction and Organizational Aspects,
2. The Basic System and Basic Outputs, and
3. Implementation and Interpretation of PMS Outputs.

Figure 3 shows the master flow diagram for the document and illustrates the subsections within the major sections. Aspects that have received special attention are

- Standardized formulas for determining pavement and network condition,
- Formulas for calculating network-level excess user costs related to pavement condition,
- formulas for calculating network-level maintenance needs, and
- uniform approaches to determining network-level budget needs for maintenance.

Calibration of Standardized Formulas

Various methods for the calculation of condition indices and network level maintenance needs were investigated. The proposed formula for calculating the visual condition index (VCI) is given in Equation 1:

$$\mathrm{VCI}_p = 100\left\{1 - C * \left(\sum_{n=1}^{N} F_n\right)\right\} \qquad (1)$$

where

VCI_p = preliminary VCI;
$C = 1 \div \sum F_{n\max}$;
$F_n = D_n * E_n * W_n$;
n = visual assessment item number;
$F_{n\max}$ = F_n for maximum ratings of degree and extent; use the average weight for assessment items with more than one weight, for example, patching;
D_n = degree rating of distress n (range 0 to 5);
E_n = extent rating of distress n (range 0 to 5);
W_n = weight of distress n; and
N = total number of distress items.

Equation 2 is applied to transform VCI_p to a standard interpretation of a percentage scale.

$$\mathrm{VCI} = (a * \mathrm{VCI}_p + b * \mathrm{VCI}_p^2)^2 \qquad (2)$$

where

$a = 0.02509$,
$b = 0.0007568$,
$\mathrm{VCI}_{\max} = 100$, and
$\mathrm{VCI}_{\min} = 0$.

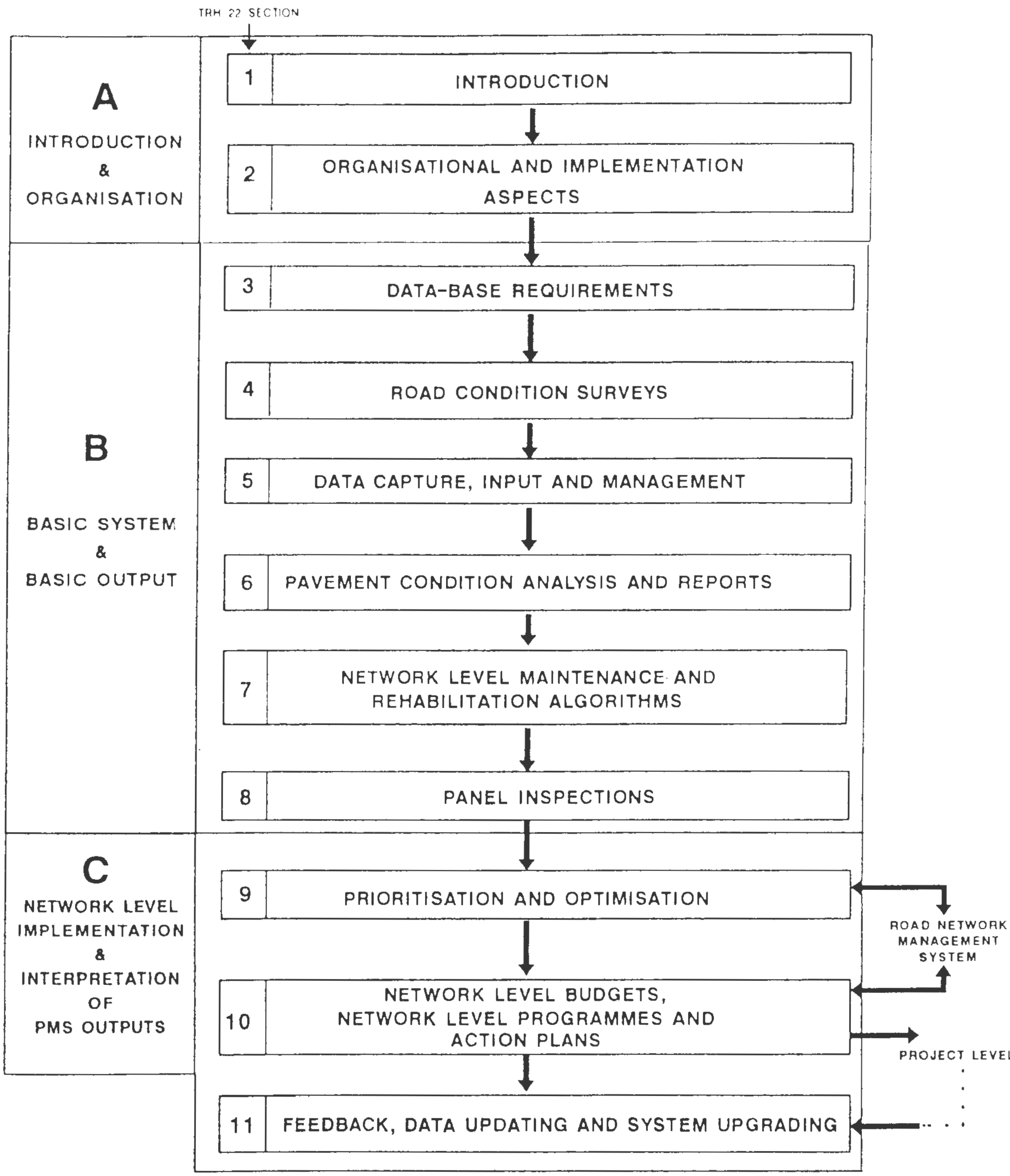

FIGURE 3 TRH 22 master flow diagram.

Description	*VCI Range*	*Color*
Very good	$\geq 90 \leq 100$	Green
Good	$\geq 70 < 90$	Blue
Fair	$\geq 50 < 70$	Yellow
Poor	$\geq 30 < 50$	Orange
Very poor	$\geq 0 < 30$	Red

Other indexes were developed for structural (deflection, rut depth) and functional (riding quality, skid resistance) conditions. These are used with the VCI to finally calculate an overall pavement index. Details of these formulas are given in conditions. These are used with the VCI to finally calculate an overall pavement index. Details of these formulas are given in Draft TRH-22 (*4*).

However, the committee could not reach full agreement on distress weight sets and condition category limits. To resolve the situation, it was decided to compile a data base of assessment data through field assessments in a number of the regions, by a panel consisting of all committee members or their representatives. The data base (acceptable to all authorities) could then be used to finalize methods of calculating a condition index as well as other PMS output requirements. The panel compiled a data base consisting of the following data for 93 road sections:

- Distress ratings,
- Assessment of condition categories,
- Assessment of maintenance needs, and
- Assessment of urgency of attention.

The objective of the data processing was to determine the best formula or algorithms to simulate the panel assessments mentioned earlier, given the distress ratings. Very satisfactory regression results were obtained ($R^2 > .85$) when calculated conditions were compared with panel judgments (*7*).

Theoretical limits for each condition category were determined from the data analyses. These limits were used to classify each road segment into a condition category. These results were then compared with the panel judgments. In general, there is 80 percent agreement between the calculated and the panel judgment. In the remaining 20 percent, the index rarely differed from the panel judgment by more than one condition class. This was considered satisfactory.

Future of Road Management Systems in South Africa

The significance of roads to a country's economy has been stressed in this paper. This is more so in South Africa, where the trend of growing road demands allied to declining funds is likely to persist for some time. Much attention has been devoted during recent years to the development of a strategic management approach for the road system. This approach, which uses comprehensive up-to-date information on the road system, attempts to assist in the overall management of the road system in an integrated manner by addressing all facets, or subsystems, and strategic planning in the roads field. To enable road agencies in South Africa to have some chance of meeting the roads needs, it will be imperative to refine and develop road management systems as a valuable tool in strategic management.

Future steps are the

- Further development of integration of systems, and
- Development of compatible subsystems other than pavement management systems.

Harmonized data resulting from compatible systems will also be used to develop real-life performance models. Data are being collected on all the major factors influencing performance (*8*), such as

- Pavement structure,
- Traffic loading,
- Age of structure and age of surfacing,
- Climatic factors and
- Distress.

Two approaches for the development of performance models are possible:

- Use network data alone and ignore other analysis and prediction techniques, and
- Use network data in parallel with mechanistic/empirical prediction models as well as knowledge gained through accelerated pavement testing.

The latter approach is favored, especially because the first approach could easily lead to confusion and loss of understanding. The combining of historical data with prediction models, and improvement of these models to fit historical performance, makes possible substantial improvements.

Conclusions

Through strategic planning, the need for integrated road network management has been identified. South Africa has opted for a modular system, which embraces a number of subsystems, of which the PMS has been developed to a greater extent than the others. The need for compatibility between regional PMSs has led to the establishment of a special committee on compatibility of PMSs. The committee has made substantial progress toward achieving compatibility through the publication of manuals and guideline documents and the standardization of data processing formulas (TMH 9 and TRH 22). The process is not complete, and a number of newly crystallized goals are being addressed.

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How Decision Makers at Various Levels Use Output from the Danish Pavement Management System, BELMAN

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A description is provided of how decision makers at various levels in Denmark use the output of BELMAN, the pavement management system used on the 4 600-km Danish National Road Network and a large portion of the regional road network. BELMAN helps support political and budget decisions by documenting the need for pavement maintenance and projecting the consequences of budget reductions in terms of the effect on road conditions. BELMAN provides (*a*) the ability to develop a series of options for maintenance programs and budgets that will be socioeconomically attractive and also ensure a uniform maintenance standard and (*b*) the ability to project the development of pavement condition several years into the future, on the basis of various budget levels or changes in a variety of other parameters, such as traffic load. The Danish Road Directorate publishes an annual report describing the condition of the national road network, changes over the past 10 years, and projections for the next 10 years. The information about current status and the forecasts for the future are taken from BELMAN's statistical and optimization output. In 1992, this report supported a 15 percent increase in appropriations for pavement maintenance in the state budget. The same information is also used to support decisions in budget negotiations between the Danish Road Directorate and the 14 county road authorities in Denmark. The state road network in Denmark represents a depreciated value of approximately 7 billion DKK (1.1 billion US$), and the average costs for maintenance have been 300 million DKK (46 million US$) over the past 10 years, with a downward trend in the 1990s. During the same period traffic has increased considerably, especially heavy traffic. With 5 percent annually, an increasing traffic load is the result of an increased use of super-single truck tires.

Denmark is a small country in northern Europe. The Danish road network has a total length of about 70 000 paved kilometers. The administrative and economic responsibility for the road network is shared by three levels of road authority

- National roads, including motorways, have a length of 4 600 km and are administrated by the Road Directorate;
- Regional roads covering 7 000 km, for which the 14 counties in Denmark are responsible; and
- Local roads (i.e., minor roads and streets), which cover 60 000 km and are administrated by the 275 municipalities.

The political decisions for the national road network are taken by the parliament, the 14 county councils are responsible for the regional roads, and the 275 local councils for the local roads. The Road Directorate administers the national roads, but daily maintenance and operation are performed by the 14 counties and 28 of the 275 municipalities.

The annual expenditures for road construction and maintenance of the total road network are approximately 7 billion DKK (1 billion US$) of which the Road Directorate's budget is approximately 2 billion DKK (300 million US$).

The total annual cost for operation and maintenance on the national road network is about 650 million DKK (100 million US$). For pavement maintenance the present appropriation is 300 million DKK (45 million US$).

The history of pavement management systems (PMSs) in Denmark dates back to 1976, when the first real road data bank was established. In 1978 the first simplified system was brought into operation for the national road network. This system was used until 1988 when a newly developed system was implemented in all 14 counties.

Presently there are two pavement management systems in Denmark, one system that is used by the Road Directorate and the counties and another that is used by the municipalities.

This paper describes the background for and the purpose of the Danish Pavement Management System—BELMAN—used on the national and regional roads, BELMAN's structure, and how data from the system are used. Finally, the experience of using a pavement management system at different levels is described.

Background for and Purpose of the Danish Pavement Management System

The importance to a country's economy of preserving an adequate condition of its road network is widely recognized. Highway transportation is by far the most important mode of transportation in most countries, and it is therefore vital to the economy. It is equally important that public funds spent to preserve the highway pavements be used efficiently. The basic purpose of a PMS is thus to assist the highway agency in answering the question, Given a certain budget level, which maintenance and rehabilitation (M&R) measures should be carried out, and when and where should these measures be carried out?

The PMS should produce a site-specific listing of the M&R measures (project level) that will result in the highest benefits for the total road network (network level). These recommendations should be based on the best available data on the present condition of each segment of road in the network.

The PMS should assist policy makers in answering the following questions:

- What will the future surface condition of the road network be, depending on the available budget, and
- Which M&R strategy will result in the highest rate of return to society on the investments made in preserving the pavements?

The PMS should, therefore, be capable of assisting the decision makers at several levels. It is a tool for the highway engineer responsible for maintaining the road network on a project-by-project basis as well as for the authorities responsible for allocating funds for the maintenance activities at the network level. Furthermore, the PMS can be used to tell the political funding authorities exactly what the need for appropriations are in the coming years.

The Danish PMS in use on the main road network is called BELMAN. The system has been fully operational since 1988. It is based on objectively measured functional and structural pavement characteristics, stored in a central road data base. It makes use of elastic layer theory to predict future pavement performance, but it also ensures that the knowledge and experience of local engineers are incorporated.

The objectives achieved by this approach are

1. The optimal combination of M&R measures is determined, so that the largest user benefits will be achieved, constrained by the available budget. The PMS output is a site-specific listing of projects to be carried out, year by year, within the period of program duration, usually 4 or 5 years;
2. The future functional condition (ride quality) and present structural condition (residual life) are predicted for each pavement section (project level) and summarized for the total network. This reveals whether the present condition of the network will be maintained or improved or whether it will deteriorate for a given (fixed) budget level;
3. By repeating the calculations with different budget levels, the optimal budget level may be determined (i.e., the M&R level that will result in the highest rate of return to society); and
4. The component parts of the total road network are included as "long-term monitoring sections," thus providing the best possible feedback for continued improvements to the submodels of the system.

Structure of BELMAN

BELMAN is divided into three functions—one for registration, one for optimization, and one for presentation.

Registration (Data Collection and Storage)

The purpose of the registration function is to provide condition information on the entire road network. The user divides the road network into sections (BELMAN sections). The sections are defined as stretches of road that are uniform in terms of condition, for maintenance purposes.

In Denmark, the 4 600-km national road network is divided into about 2900 sections. For each section, information about the road condition is entered. In Denmark, this information is obtained through routine measurements and an annual road condition inspection.

Routine Measurements

Pavement management in Denmark is based on detailed information about the condition of the entire pavement structure (surface and subsurface) obtained through routine measurements using advanced equipment. The Danish Road Institute has specially developed vehicles. The measurements data are stored in the Danish Road Data Bank. Data from the Road Data Bank are entered into BELMAN's internal register.

Condition Inspections

In addition to the routine measurements described, an annual condition inspection is conducted on each BELMAN section to obtain precise and uniform estimates of the residual life of the wearing course and repair expenditures.

For the purposes of the condition inspection each BELMAN section is further divided into "condition sections." The number and size of condition sections are determined by the user, but individual sections are never larger than the corresponding BELMAN section.

During the condition inspection the scope of damages and repair needs are set down by category. These data make it possible to estimate the residual life for the wearing course and the future repair expenditures.

Optimization (Data Processing and Analysis)

BELMAN combines information on road condition with a catalogue of the costs of various maintenance options and standard parameters (budget, time requirements, etc.), so that maintenance options and their consequences may be analyzed. BELMAN's optimization module presents alternatives for repairs, new wearing courses, or reinforcement of the road sections.

The output is a data file showing maintenance options and their consequences. Files are produced for each section, for each year specified.

Presentation

BELMAN's presentation function generates lists of interventions, general statistical information, and list of consequences for future years.

The list of interventions (Figure 1) contains information about the maintenance interventions to be carried out at the highest effect and cost ratio within the budget constraints.

The annual maintenance statistics (Figure 2) provide information on the total expenditure for maintenance, the residual budget, and the average condition of the pavements in the entire road network when the proposed interventions are implemented.

The future consequences (i.e., the pavement conditions for each road section and future maintenance needs

Optim year 1994

Mnt	D	Aut	No-P-S	Frm km/m	To km/m	Solution	WLS	SLS	REF	Effect	Cost	Price	Budget
70	0	0	367-0-0	36/0615	36/0875	150GAC+80AC	8	8	23	480	924	721	49992
						190GAC+80AC	11	15	6	677	957	764	130031
						170GAC+80AC	11	11	14	662	937	742	117899
						140GAC+80AC	7	7	28	409	916	711	9781
						REPAIR	0	0	126	0	4	1	2895
70	0	0	367-0-0	36/0875	38/0140	REPAIR	0	5	47	0	36	11	2895
						90ACCS	16	16	6	687	772	720	126373
						70AC	10	11	16	332	693	561	126214
						60DBM	7	7	31	189	670	486	126139
						45DBMI	6	6	37	151	636	458	125755
						SLURRY	4	5	44	42	554	336	105750
70	0	0	367-0-0	38/0140	40/0460	REPAIR	1	18	2	0	33	10	2895
						90ACCS	20	20	0	1542	1394	1373	167219
						70AC	10	20	0	579	1329	1042	166887
						SLURRY	4	20	0	72	1047	574	166419
70	0	0	367-0-0	40/0460	41/0700	NONE	8	8	31	0	0	0	2895
70	0	0	367-0-0	41/0700	42/0560	REPAIR	0	13	23	0	21	6	2895
						90ACCS	20	20	0	811	612	604	124110
						70ACI	12	20	0	415	609	528	124034
						70AC	10	20	0	306	581	474	123980
						SLURRY	4	14	20	39	466	291	103238

FIGURE 1 Partial list of interventions.

Year	Average values			Totals in mio. DKK		
	PSI	SLS	WLS	Price	Add-work	Spec add
1993	3.64	10.47	4.92	1.5	0.0	0.0
1994	3.61	10.02	5.11	50.0	6.4	26.7
1995	3.57	9.32	4.40	50.0	5.8	28.1
1996	3.54	8.82	4.43	50.0	14.9	15.1
1997	3.51	8.38	4.46	50.0	12.4	9.6
1998	3.55	8.41	5.33	50.0	15.1	0.0
1999	3.59	8.42	5.49	50.0	8.3	9.7
2000	3.59	8.13	5.44	50.0	14.0	12.6
2001	3.62	7.94	5.74	50.0	13.4	5.7
2002	3.73	7.43	5.24	50.0	8.2	19.0

FIGURE 2 Annual maintenance statistics.

within the given budget) are also presented by the system (Figure 3), which gives as an example part of such a list.

By repeating the optimization procedure with different budget levels for future years, it is possible to carry out consequence analysis showing future functional and structural conditions of the road network. This procedure may be used to determine the budget level required to maintain the road network at a given condition level.

Using Data and Results from BELMAN

Data from the condition registration and the measurements plus the results from BELMAN are used in Denmark at both the national and regional level for many purposes. The condition inspection and the routine measurements of the road network give a detailed description of the road condition.

The optimization results are used as a tool for distribution of annual appropriations. These results are distributed in the counties not only to the national road network but are also used for the regional roads. Furthermore, the optimization results are used as a forecasting tool.

Uses of Condition Information

The annual condition inspection registers the scope of damages and repair needs for the entire road network. This information is useful for calculating residual life and repair expenditures for individual road sections, as well as to

Mnt	D	Aut	No-P-S	Frm km/m	To km/m	Year	Solution	WLS	SLS	REF	Effect	Cost	Price	Budget
70	0	0	367-0-0	36/0615	36/0875	1993	NONE	0	0	121	0	0	0	1503
						1994	150GAC+80AC	8	8	23	480	924	721	49992
						1995	80AC	7	7	28	4	220	174	21742
						1996	NONE	6	6	34	0	0	0	9112
70	0	0	367-0-0	36/0875	38/0140	1993	REPAIR	0	6	42	0	22	6	1503
						1994	REPAIR	0	5	47	0	36	11	2895
						1995	REPAIR	0	4	54	0	51	15	21742
						1996	45DBMI	6	6	42	101	640	458	38118
70	0	0	367-0-0	38/0140	40/0460	1993	NONE	2	19	1	0	0	0	1503
						1994	REPAIR	1	18	2	0	33	10	2895
						1995	REPAIR	0	17	4	0	65	19	21742
						1996	SLURRY	4	18	2	98	1047	574	49608
70	0	0	367-0-0	40/0460	41/0700	1993	NONE	9	9	28	0	0	0	1503
						1994	NONE	8	8	31	0	0	0	2895
						1995	NONE	7	7	35	0	0	0	21742
						1996	REPAIR	6	6	40	0	15	4	9112
70	0	0	367-0-0	41/0700	42/0560	1993	REPAIR	1	14	21	0	9	3	1503
						1994	REPAIR	0	13	23	0	21	6	2895
						1995	REPAIR	0	12	25	0	33	10	21742
						1996	SLURRY	4	12	25	52	466	291	47431

FIGURE 3 Plan for analysis period.

- Create an overview of the road networks surface condition;
- Determine a general repair strategy that can easily be adapted to changes in price or improvement of various repair methods;
- Make lists used as the basis for a contractor's bid or directly as worksheets of repairs needed on the road sections and the types of damage that are to be repaired by a certain repair method; and
- Create statistics on the scope of damages and repairs, categorized by damage types and repair methods.

As the list shows, the information from the condition registration is used mostly for short-term planning typically within a year of the registration. It is typically used at the regional level in the counties.

Uses of Routine Measurements

The data from the yearly measurements of the surface condition (e.g., evenness, skid resistance and rutting, and the measurements of the base course) give a complete overview of the development of the pavement condition. This information is used to follow the development on a running basis. Figure 4 shows as an example the average evenness of the main road network for 1981 to 1991.

Distribution of Annual Appropriations

Each year the results from BELMAN are used to back up decisions in the budget negotiations between the Road Directorate and the 14 cooperative partners (county councils). The budget has to be allocated to the counties. It is important to ensure that the money is spent to benefit citizens as much possible.

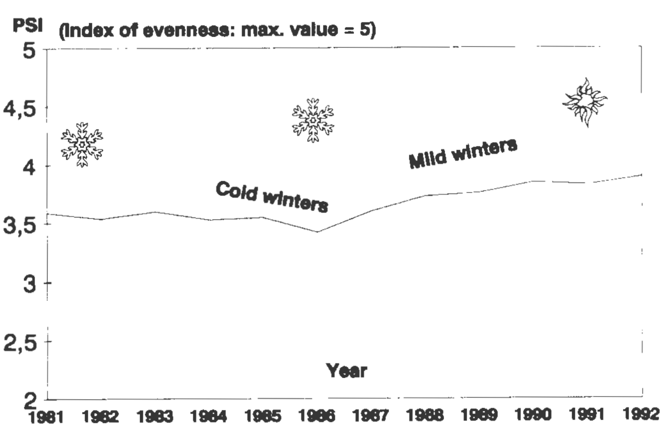

FIGURE 4 Average evenness of the main road network, 1981–1992.

On the basis of the updated BELMAN sections, two optimizations are carried out with a budget corresponding to the appropriations. The first optimization is done only for the road sections the counties have applied for. The second optimization is based on all 2900 road sections.

BELMAN generates a summary report showing the road sections that should be taken into consideration during the budget negotiations. This reports includes

- Information on the current road section (identification, current pavement, life spans, repair costs, and a series of measurement data);
- Any pavement that has been applied for;
- The result of the optimization among applied road sections; and
- The result of the optimization among all the road sections.

The BELMAN system also can determine the types of maintenance treatments that are, on average, most cost effective and otherwise beneficial to use within a given geographical area, based on optimizing over a series of years with the expected future budget. Figure 5 shows the allocation of the optimum use of the budget 1993–2001.

The results from the optimization for the coming year and over a series of years are helpful both for engineers and budget decision makers in the Road Directorate. It is much easier today to precisely and quickly calculate the optimal use of the existing appropriations.

BELMAN AS A FORECASTING TOOL

BELMAN is also used for forecasting by performing a series of optimizations at various budget levels. In these optimizations it is not the individual road sections, but rather the general development of all road sections, as illustrated by the values for a few key parameters, that are of interest. For example, the Danish Road Directorate uses BELMAN to project the expected development of pavement condition over the next 10 years. This is combined with information about the current status of pavement conditions in an annual report on the condition of the national road network. This type of report is also published in some of the counties for the regional roads.

The description of current status, which also is derived from BELMAN, is based on

- Residual life of the wearing course (Figure 6),
- Residual life of the base course, and
- Current values (evenness, skid resistance, and rutting) for key measurements.

The following values are used in projecting pavement condition over the next 10 years:

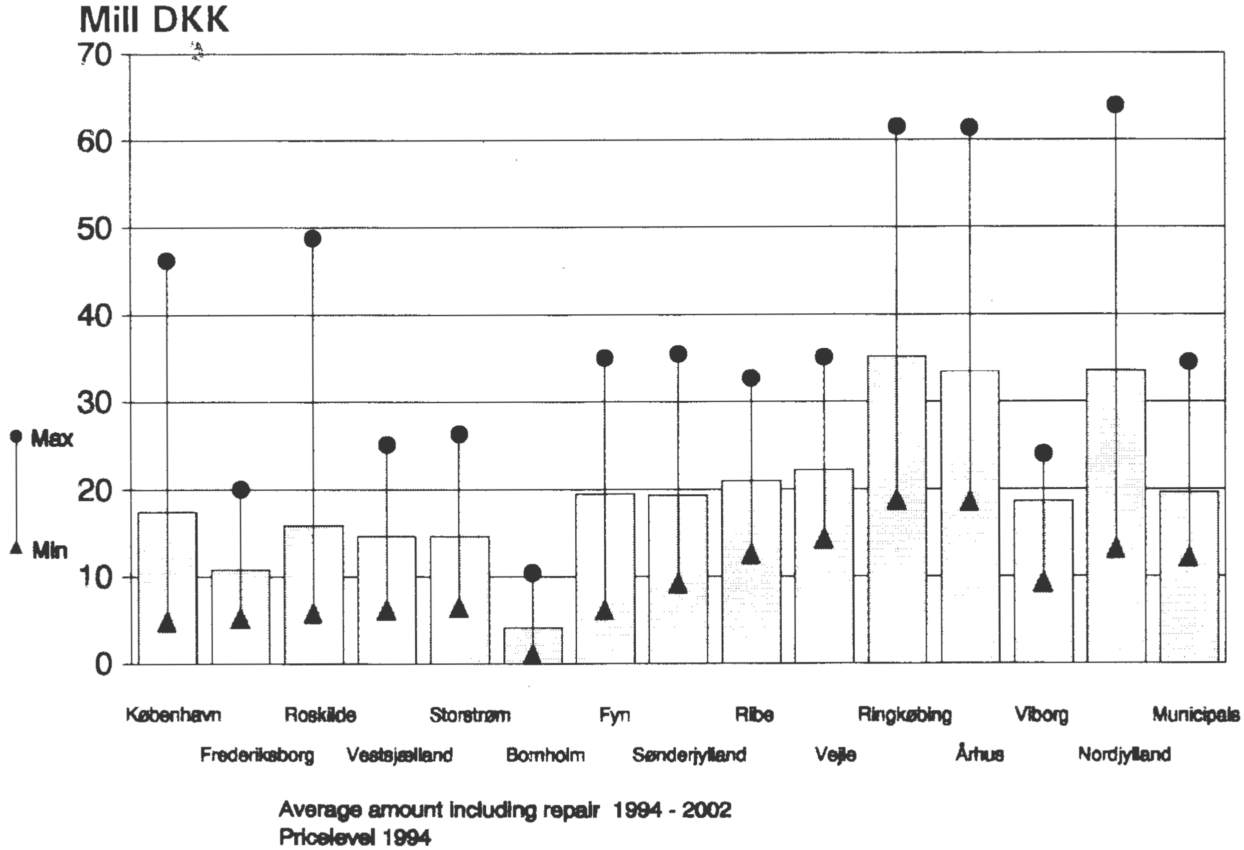

FIGURE 5 Allocation of the optimum use of the budget 1994–2002, including the periods of maximum and minimum values for many county councils and municipalities.

- Change in evenness (Figure 7),
- Change in wearing course residual life,
- Change in base course residual life, and
- Change in distribution of maintenance solutions (Figure 8).

The current status and future pavement condition as a function of the budget are used to calculate the future need for appropriations. In this calculation the value of the wearing and base courses is used. This value is called pavement capital and is a part of the entire road capital.

The current value of wearing and base course on the Danish main road network can be calculated as the costs of laying new wearing and base courses on the approximately 4 600-km-long main road network. The current value is approximately 10 billion DKK (1.5 billion US$).

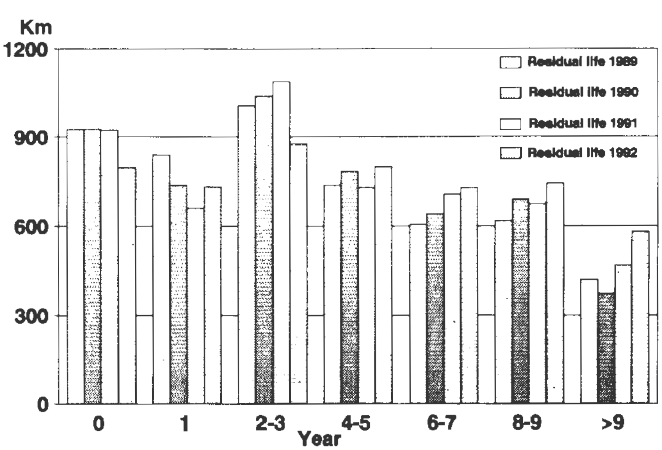

FIGURE 6 Estimated residual life of wearing course.

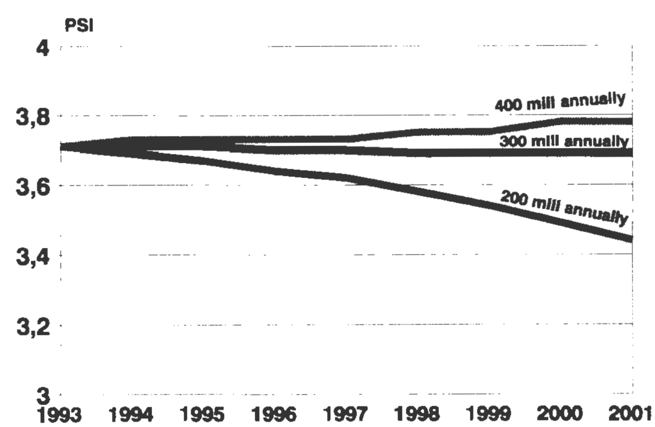

FIGURE 7 Development of evenness of main road network as function of the annual appropriations level.

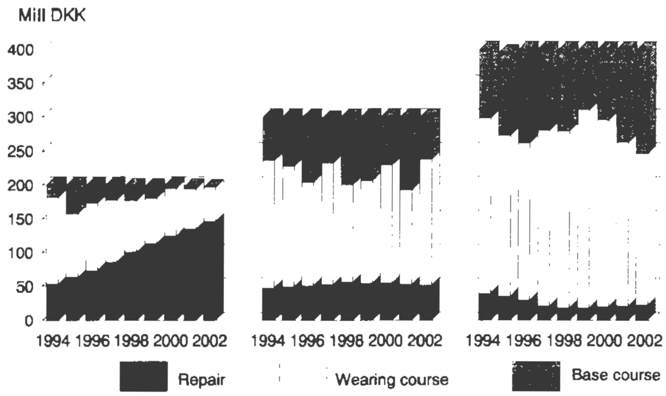

FIGURE 8 Distribution of maintenance solutions as function of the annual appropriations level: 200, 300, and 400 million DKK.

As the pavements deteriorate because of traffic and weather conditions, the pavement capital is reduced. If the pavements of the main road network were renewed on a regular basis, the depreciated pavement capital would have a value of 7.4 billion DKK (1.15 billion US$).

Calculations of the pavement capital in 1992, based on measurements of the present pavement condition, show that the value has been reduced to 7.0 billion DKK (1.1 billion US$). Today there is a capital backlog of approximately 500 million DKK (75 million US$).

Catching up with the existing backlog to ensure that the pavement capital reaches the balance level in year 2000 of 7.4 billion DKK (1.15 billion US$) requires approximately 50 million DKK (7.7 million US$) annually. With BELMAN the future residual life of the base and wearing courses can be calculated. By combining the prognoses for the residual life of wearing and base courses the future value of the pavements and thereby the development of the pavement capital are estimated.

To maintain the pavement capital at the present level an increase in appropriations requires approximately 75 million DKK (11 million US$) annually until the year 2000. The calculation is based on the assumption that traffic will rise by 1.8 percent annually and axle load by 3.0 percent annually. If the increase is larger (e.g., 4 to 5 percent as has been seen during the past few years), a further need for increased appropriations will arise.

Today there is an increase in traffic load resulting from use of super-single lorry tires. This is not calculated in the future needs but is very important for the residual life for the base course. BELMAN calculation has shown that the appropriations must be approximately 50 million DKK (7.7 million US$) higher annually if the now registered use of super-single tires is calculated.

Besides protection of present pavement capital and capital backlog money for old concrete pavements and reinforcement of unstable asphalt base courses is needed. For old asphalt concrete pavements 15 million DKK (2.3 million US$) is needed annually, and unstable base courses require 75 million DKK (11 million US$) annually. Including administration to the cooperators, BELMAN documents that the future need for appropriations from 1993 to 2000 will be 550 million DKK (85 million US$) annually, and the present appropriations are about 310 million DKK (48 million US$).

In the Road Directorate it is known that an annual increase of 240 million DKK (37 million US$) is a substantial amount in a period with very large investment needs in the road sector. Because of that, a low cost strategy to prevent a further deterioration of the pavement is considered. The cost of this strategy will be 410 million DKK (63 million US$) annually. Figure 9 shows the present appropriations and the two strategies.

In the annual report describing the condition of the national road network, changes over the past 10 years, and projections for the next 10 years, the future need for appropriations for pavement maintenance is also described. Without a PMS it would not have been possible to calculate the future need for appropriations.

EXPERIENCE OF USING BELMAN

BELMAN has been used on the main road network in Denmark and on part of the county roads for 5 years. During this period the experience gained by using the system has been very positive at all levels. This can be attributed primarily to the fact that the system has been developed in close cooperation with the users.

At the local level the system was met with scepticism in the beginning, partly because the system was considered very theoretical and partly because comprehensive data collection was needed to obtain the full benefit of it. The scepticism disappeared when it was realized how advantageous it would be to store all data in the system and retrieve them again very quickly for many purposes. Moreover, the models, which are part of the system, have been developed on the basis of Danish experience and improved concurrently with the comprehensive data collection that has taken place. Today, BELMAN's condition data and the objective data from road surface measurements are used as a documentation tool for quality management in the execution of repair works.

BELMAN is an indispensable tool for distributing appropriations between the Road Directorate and the counties. The so-called budget meetings between the Road Directorate and the counties, in which the results of the BELMAN optimization are the essential element, today only take 1 to 2 hr. Previously, such meetings lasted about 8 to 10 hr. Meetings can be conducted much faster now, partly because all necessary data are available and partly because everybody knows the results from BELMAN are

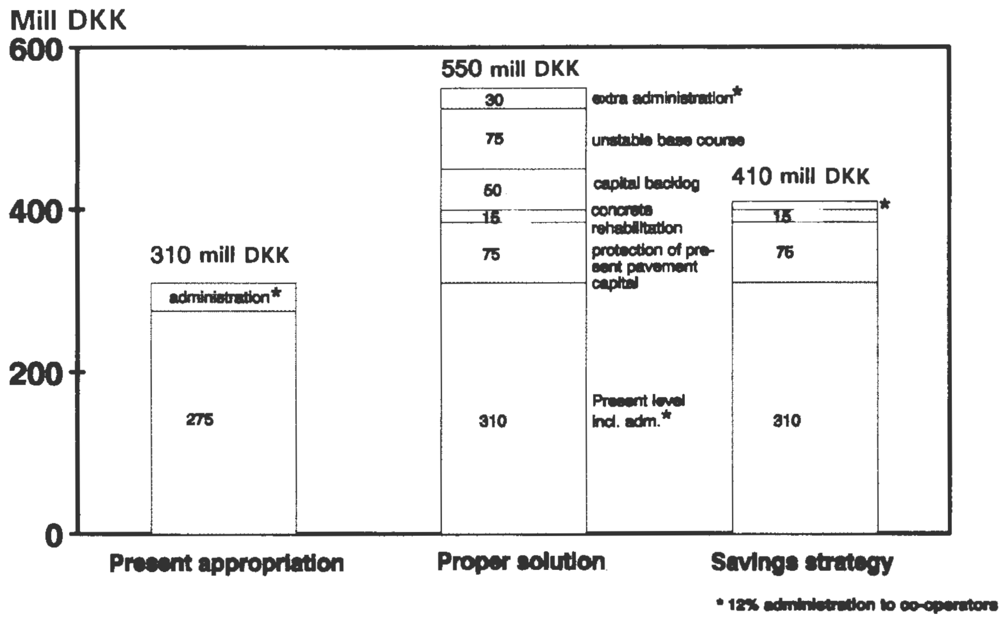

FIGURE 9 Need for annual pavement maintenance appropriations 1992–2000.

reliable. Today weighty arguments are needed to deviate from the recommendations made by the system. Furthermore, there is more confidence that the sections selected by BELMAN are, in fact, the sections for which the best effects on society are achieved.

The application of BELMAN as a forecasting tool for both the national road network and on the county roads has proven to be very important. Today, key figures to make a precise description of the future development of the road condition as a function of the budget can be quickly obtained. This has made it possible to publish an annual report on the national road network in which the future need for pavement maintenance is documented. The report has been positively received by all parties involved—especially by top politicians.

The Minister for Transport now has a collection of material that outlines various pavement condition alternatives as a function of the future appropriation. The Minister should not only grant appropriations for pavement maintenance but should also determine the level of road condition that is desired for the national road network. The same is applicable for the county roads. Several counties have begun publishing reports on the future need. Here the county council will grant the money.

Experience in Denmark shows that extra appropriations will, if possible, be granted, if road administrations are able to document their need for them.

In 1992, the Road Directorate received an increase of 15 percent in appropriations after the report had been published, and the increase has continued in 1993. There is every reason to believe that there will be an improved relationship between appropriations granted and the wear on roads. Figure 10 shows the sharp rise that has taken place in traffic since 1983, whereas appropriations for pavement maintenance have remained on the 1983 level.

All objectives put forward when the development of a pavement system in Denmark was initiated have been attained. Today, there is an extremely effective tool for maintenance at all levels.

Conclusions

BELMAN provides decision makers at several levels with a useful tool for planning future pavement maintenance

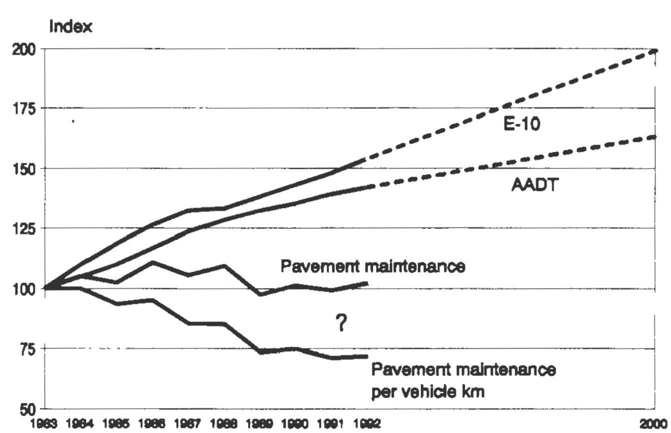

FIGURE 10 Maintenance expenditures and traffic development 1983–2000.

and rehabilitation, on the project level as well as on the network level.

Engineers responsible for the maintenance and carrying out of rehabilitation alternatives can use BELMAN to obtain the maximum benefit possible with the available budget. Top managers can use the system to study the consequences that different budget levels will have on the future functional and structural conditions of the road network and determine the budget level that will result in the highest rate of return to society. Finally, the results from BELMAN are used to tell the political authorities responsible for funding exactly what the need for appropriations will be in the coming years.

It is impossible to say precisely what the effect of using BELMAN is, but in 1992 the Road Directorate received a 15 percent increase in appropriations for pavement maintenance in the state budget. In the opinion of the authors, it is important for the political authorities responsible for funding that future needs be described, and that the consequences of a reduction in the appropriations can be calculated.

Roles for a Regional Transportation Planning Agency in Countering Local Agency Institutional Problems in Adoption and Use of Pavement Management Systems

Paul Sachs, *Metropolitan Transportation Commission*
Roger E. Smith, *Texas Transportation Institute*

A unique support relationship for a local agency pavement management system (PMS) was established in the San Francisco Bay Area. The activities included were developed to address local agency institutional issues that have often led to discontinuing the use of pavement management or to not using it fully. These issues include personnel turnover, overcommitted staff, perceived complexity of PMS, and limited funds for pavement maintenance and rehabilitation. Since 1984 the Metropolitan Transportation Commission (MTC), the regional transportation planning agency for the San Francisco Bay Area, has supported the development and use of PMS by cities and countries in its region. During the past 9 years, 55 jurisdictions, representing more than 60 percent of the street and road centerline miles in the region, have been at some stage in the implementation and use of the Bay Area PMS. MTC trains jurisdictions in PMS concepts, PMS computer applications, and interpretation of PMS budget results. MTC conducts quarterly user meetings at which jurisdictions not only give direction to MTC staff on future modifications to PMS but also work with one another to assist in PMS implementation. If requested, MTC PMS staff presents PMS budget results to participating jurisdictions to emphasize the importance of pavement management. MTC's continued support and facilitation have been major factors contributing to the success of pavement management at the local level in the San Francisco Bay Area. This regional agency involvement is believed to be one of the most important innovations to counter common institutional problems that often prevent adoption or effective use of PMS in local agencies.

Regional transportation agencies are uniquely situated to address some of the institutional issues that have prevented the adoption, implementation, and full use of pavement management systems (PMSs) by local agencies. One of the institutional problems that often leads to discontinuing or less than full use is personnel turnover. PMS knowledge is generally vested in a single person in an agency, and when that person leaves the position, the expertise is generally lost and the PMS is often discontinued (*1*).

Furthermore, in most local agencies in the San Francisco Bay Area, pavement management is only one of several responsibilities of a public works staff member. Such a staff member actively uses the pavement management software for only a few weeks each year, during the inspection and the budget cycles. Otherwise, the pavement management programs are accessed only when a specific piece of data is needed. The responsible person never becomes fully trained in the use of the software, because he or she must start over each cycle. Allocating much time to training is impossible because of the staff member's other responsibilities.

To many potential users, the pavement management process appears to be more complex than they believe they can support. In particular, the software programs and financial analysis are considered complex. Perceived complexity reduces the likelihood of adoption and continued use (*1*). Even agencies that have used PMS for some time seldom use all of the capabilities available in the software.

Most moderate-sized to smaller local agencies do not have the financial resources for the software development, modification, and support or for the training needed to develop and implement pavement management effectively. Their funds are extremely limited even for physical pavement maintenance and rehabilitation, and it is nearly impossible for them to spend any significant portion of their pavement funds for pavement management software development or modification (*2*).

To counter these problems, the Metropolitan Transportation Commission (MTC) of the San Francisco Bay Area developed one of the most comprehensive support programs for local agencies using PMS currently available. This paper looks at three major areas in which MTC found a regional agency role to be important in facilitating the implementation and continued use of PMS in the San Francisco Bay Area and in overcoming institutional issues. These elements are user meetings, user services, and budget analysis. It is hoped that this discussion will serve as a guide to other regional agencies in deciding on appropriate support roles in PMS implementation.

Background

In 1981 the MTC, a multicounty transportation planning agency in the San Francisco Bay Area, began helping several local public works directors document local agency pavement maintenance and rehabilitation needs and shortfalls in the Bay Area. The goal of the study undertaken then was to develop support for requesting additional revenues in pavement maintenance from locally elected officials.

In 1982 MTC released a report entitled *Determining Maintenance Needs of County Roads and City Streets* (*3*), which showed that Bay Area cities and counties were deferring pavement maintenance projects at a rate of $100 million a year. The report also indicated that these local jurisdictions had an existing street and road pavement maintenance and rehabilitation backlog of $300 million to $500 million. In 1982 this report was used in convincing the California state legislature to increase the state gas tax from 7 to 9 cents. Of the 2-cent increase, 1 cent went to cities and counties for use on local streets and roads.

During the next 2 years, MTC continued to work with a committee of local public works officials to help them evaluate and set priorities for their road and street needs. A major recommendation from this work was for MTC to adopt and support a pavement management system for local agencies in the San Francisco Bay Area.

In 1984 MTC began development of a PMS (*2*). Six local jurisdictions (three cities and three counties) formed an advisory group to assist MTC with this effort, and MTC also retained ERES Consultants, Inc., for this purpose. The six local jurisdictions acted as pilot agencies, implementing the PMS components developed in 1984. By 1993 the PMS had been adopted by 55 Bay Area cities and counties. These jurisdictions are responsible for more than 60 percent of the 18,000 local street and road centerline miles in the Bay Area. The PMS has also been adopted by more than 100 other jurisdictions nationwide; some of these are other regional agencies.

Besides supporting the development of the PMS software, MTC has developed programs that assist Bay Area local agencies in every aspect of PMS implementation and operation. This support includes training classes, presentations explaining PMS evaluation results to public works directors, presentations to locally elected boards and councils, and on-call (hot line) support. Such programs are a key to countering the institutional problems discussed earlier, which are prevalent in most local agencies. This support structure is probably the single most important factor in the success of the the MTC-supported Bay Area PMS.

MTC as Facilitator

Since 1984 the Bay Area PMS has expanded to provide procedures and software for local agency pavement management at the network level (*4*) and the project level (*5*), so that local agencies have a full range of decision support tools. The Bay Area PMS software, data collection, analysis procedures, and documentation were designed, developed, and tried under the guidance of users. MTC supported these changes based on the expressed needs of the local agencies. This allowed local agencies with limited funds for pavement management implementation and use to have the software, data collection procedures, and budget tools they need at the least possible cost. The availability of such help is a major factor in countering the institutional problems related to funds for development and implementation of pavement management in local agencies. However, a major factor contributing to the success of the Bay Area PMS is the support activities provided to users by MTC.

As a regional agency, MTC must support all of the agencies within its area. This takes in several types of organizations. In the San Francisco Bay Area there are nine counties, which range from completely urbanized to primarily rural. Of the nearly 100 cities and towns in the Bay Area, about one-third are responsible for fewer than 50 mi of roads and streets, about one-third are responsible for 50 to 150 mi, and about one-third are responsible for more than 150 mi. Members from each of these groups were among the pilot agencies that first implemented the PMS components in 1984. MTC has continued to support agencies in all three groups, which creates a broad range of issues for MTC to address.

User Meetings

One seemingly routine but important support function is conducting regular user meetings at the MTC offices. In the early PMS development stages, the six pilot agencies met monthly. Each of these agencies tried the PMS components, shared experiences, and identified problems. During the meetings it became apparent that those attending were learning from each others' experiences, not only about pavement management but also about other pavement maintenance and rehabilitation matters. On the basis of this experience, user meetings became an integral part of the support structure of the Bay Area PMS.

User meetings are held quarterly. They have become the focal point for identifying changes and enhancements needed for the PMS. At these meetings the users provide direction to MTC on needed modifications or enhancements for the system. The users are surveyed to determine whether new procedures are desired and whether old ones should be maintained or eliminated. MTC has adapted and modified the computer program many times as a result of this process. A number of suggestions and recommendations made by users have been adopted. For instance, the program can now split and combine sections. (This is necessary if a treatment is applied to part of an original section but not the remainder.)

About once a year, users are asked which features they like most about the Bay Area PMS and which they would like to add or modify. The users as a group help establish the priority of needed improvements. In the past the development of the project-level modules and a mapping module were rated as high priorities. The development was then planned and funded by MTC. Such a development is completed under the direction of a subcommittee of users to ensure that it addresses their needs. Subcommittee meetings on the development of major new modules are often held during the week of the quarterly user meetings.

After the initial release of the Bay Area PMS software, many new users were added. At any given time, some agencies are just beginning to implement the PMS, while others are into a third or fourth iteration of the program. Through the quarterly user group meetings, ideas are exchanged not only between MTC staff and personnel from participating jurisdictions but also among the users themselves. Because there are users at all stages of implementation, more experienced users often help newer ones. The user meetings often identify problem areas in which additional training is needed.

While the initial software was being developed, MTC conducted training for the participants. The training sessions included these topics: establishing a PMS work plan and steering committee, collecting inventory data and dividing the network into management sections, distress identification, entering data into the computer, interpreting PMS reports, preparing annual budgets, and computer training. Each year new users within the San Francisco Bay Area need to be trained in these same areas. Such training sessions, though primarily developed for new users, are also attended by new personnel in established user agencies. It is essential that training also be available for the experienced users. Most users in small to moderate-sized agencies only spend a few weeks each year collecting data and using the software. Many agencies experience staff turnover in the departments responsible for PMS and need training for their new staff. Recurring training is especially needed on distress identification, entering data into the computer, interpreting PMS reports, preparing annual budgets, and learning new elements of the system. Training on the PMS components was instituted as a regular part of the user meetings to assist new users in the start-up and to help experienced users become more proficient with the more sophisticated applications.

Technology-transfer seminars were added to the quarterly user meetings to expand the scope of the training. Users had requested assistance in areas beyond using the pavement management elements, and MTC responded with these seminars. The seminars have covered topics such as overlay design procedures, effective use of seal coats, contracting for slurry seals, application of seal coats, utility trench specifications and inspection, and selecting the best treatment. The seminars have been well attended by many public works personnel who had not been involved with pavement management. MTC's support of this exchange of information that is more directly related to the public works staff members' everyday activities improved both the acceptance and understanding of PMS concepts.

The quarterly user meetings now include a wide array of activities. MTC staff generally make presentations on developments that have taken place since the previous meeting. All users attending the meetings have an opportunity to present experiences. Those who have developed new methods to accomplish particular tasks are asked to present them, and many of the more experienced users have made presentations on aspects of pavement management. The meetings also offer ample time for informal one-on-one discussions. In effect, the user meeting has become a support group, with users sharing their thoughts and problems.

All agencies using the Bay Area PMS are encouraged to have representatives participate in the quarterly user meetings. MTC staff members are assigned to stay in contact with specific agencies and to track the progress of the Bay Area users from the time that they begin PMS implementation. Beginning users are assigned the letter "F." As they move through the PMS process, they move up in letters. "E" means that they are breaking their network and conducting their distress surveys, "D" signifies budget development, and so forth. At "A," users have made a budget presentation to their elected board or council and have begun to implement the maintenance program. MTC makes these ratings on a quarterly basis and uses them to help MTC identify users needing special assistance. If an agency fails to progress through the implementation phases or if a representative of an agency misses three quarterly user meetings in a year, the appropriate MTC staff member contacts the agency. This allows the identification of problems, and it is also the way MTC often learns that the person responsible for PMS in an agency has changed jobs.

As PMS use expanded beyond the San Francisco Bay Area, it became clear that not all users would be able to attend the quarterly meetings and training sessions. Thus, MTC videotaped five of the training sessions to provide to jurisdictions at cost. Subjects of the training videotapes include network inventory and section definition, distress identification, and use of the microcomputer as it relates to PMS. The videotapes are also used by agencies within the Bay Area to supplement the training received from MTC staff and to train agency members unable to attend the MTC training.

To communicate with those who miss user meetings and to provide written documentation of some of the more important information developed, MTC publishes a quarterly newsletter. This publication includes computer tips, new maintenance strategies, potential funding sources for street and road programs, and articles on pavement management from outside sources. An article on effective use of the Bay Area PMS written by a user was published in a recent issue. (A goal of the newsletter is to have articles that describe how users have benefited from the Bay Area PMS. Such articles provide impetus for newer users in the program as well as for older users who have not progressed as fast as others.) In addition, notes are prepared by an MTC staff member on the activities of the quarterly user meetings and the technology-transfer seminars; these are distributed to all users.

The user meetings have developed into an extremely valuable method of countering several of the institutional issues in local agencies. As discussed, they are invaluable for addressing the turnover problems in local agencies. They also provide for formal and informal training to reduce the perceived complexity of pavement management. Valuable training occurs through informal conversations among users and through formal presentations by users about their experiences. At these meetings, needed changes can be identified. The meetings are also used to set priorities for modifications and enhancements in the pavement management software that many agencies would not otherwise be able to support. These unique opportunities come about because there is a regional agency to facilitate and promote them.

User Services

In user surveys, on-call and on-site assistance is always rated as having the highest priority. When MTC first developed the PMS software, it became apparent that someone needed to handle computer "hot-line" calls when users encountered problems. Error messages from the computer at inopportune moments reinforce the perception that the pavement management process in general and software in particular are too complex for an agency. A few such incidents lead to loss of credibility and discontinued use of the software. To address this problem, MTC developed a hot-line support system to answer questions for information ranging from how to turn on a computer to how to interpret the PMS results. MTC staff also track all calls to find common problem areas. These areas are then discussed at the general user meetings.

The MTC staff originally believed that good computer user manuals and supporting documentation would meet the needs of most agencies. MTC staff also originally believed that it was not necessary and that it was not their responsibility to train public works department staff in disk operating system (DOS) procedures or in RBase, the data base manager used in the computer program. Through the hot line, MTC staff members found that many questions related to a basic understanding of DOS and RBase. Many other questions were addressed in the user manuals and procedure documentation. However, it was apparent that if the PMS was to be used effectively, several jurisdictions needed basic classes in DOS and RBase. These classes are now given about every 6 months at the MTC offices.

The hot line also helps MTC staff identify user agencies with personnel newly assigned to the PMS or those inexperienced with PMS concepts. When a new person is assigned to the position responsible for pavement management in an agency, the outgoing person often leaves the new person one key piece of information: the MTC hot-line number. When the new user encounters a problem, he or she calls MTC, and the responsible MTC staff member identifies the caller as a new user in an agency with the PMS already implemented. If a representative of the agency has not attended recent user meetings and training, the new person is given information on upcoming training sessions and is encouraged to attend. If appropriate training sessions are not planned in the near future, additional ones will be scheduled or the user will be invited to the MTC offices for individual assistance if that is needed.

The most important feature of the hot line is that it provides immediate answers, which is a key to reducing perceived complexity. In most cases the user can be coached through a problem and can continue using the PMS program. Sometimes the assistance includes referring the caller to the user manual or documentation. On occasion, when an urgent problem cannot be solved on the phone, the user is invited to MTC with the agency data base, or an MTC staff person makes an on-site visit and "recreates" and corrects the problem to get the user back on line. If the problem is not urgent, the user sends the data base to MTC staff for review, debugging, and return. MTC recently started using software that allows its staff to control the user's computer by modem. This facilitates problem solving with less travel and time loss for both MTC staff and the using agency.

When an agency becomes a new user in the Bay Area, an MTC staff member conducts an on-site visit for software installation, distribution of the PMS user guide, and a walk-through of the PMS program. The on-site visit helps MTC staff determine the level of experience of the new user with computers, the type of computer being used, and the types of training the new user needs immediately. Probably most important, the user gets to know the individual on the phone in case a hot-line is required. All of these forms of assistance help reduce perceived complexity for the new user.

As mentioned previously, MTC has developed a method by which users are tracked through their PMS implementation. These ratings help MTC determine if a user needs special assistance. Most of the jurisdictions needing special assistance are the smaller cities with fewer than 50 miles of roads. Their resources are generally very limited, and they often do not have the staff to complete PMS implementation in a reasonable time. If such jurisdictions have adequate funds for consultants, MTC will provide a list of consultants who have helped other agencies implement the Bay Area PMS. MTC has also provided special training for inspectors at the start of the inspection period so that summer hires can be used to reduce the implementation costs.

The user services component of the Bay Area PMS has proven to be invaluable in facilitating PMS implementation and continued use. It has identified agencies where personnel turnover has occurred so that problems can be addressed. It has helped build confidence in using the Bay Area PMS because agencies can call someone if a problem arises, whether the problem relates to software, data collection, data interpretation, or budget formulation. Referring users to manuals and documentation is helpful, but immediate answers on the phone keep them moving so they can meet their deadlines. Without this user service component, the Bay Area PMS would surely have been discontinued in several jurisdictions because of staff turnover or the frustration of users who are not fully trained and do not have time to become fully trained other than through hands-on use.

Budget Analysis

A main goal of network-level pavement management is to determine budget needs and to substantiate the impact of alternative budgets on the future condition of the network, future funding needs, stop-gap funding needs, and backlog. This information is also used to help substantiate the need for funding at the regional and state levels. It is used by local agencies to justify pavement budget requests from public works departments. MTC has developed a program to assist at both the network and the regional level.

Regional and State Level

As each user completes the inspection of its network, MTC requests a copy of the data base. Using the agency's treatment costs, MTC compares their 5-year budget need to expected revenues for pavement expenditures. Expected revenues are projected on the basis of information from the California state controller's reports as modified by the local agency. A regional aggregate of 25 users shows that, on the average, San Francisco Bay Area jurisdictions are currently spending roughly $0.39, when they should be spending $1.00 for maintenance and rehabilitation of pavements.

An earlier version of this regional aggregate estimate was used in 1988 when the California state senate asked regional agencies statewide to develop a 10-year estimate of needs and expected revenues for streets and roads. Using the city and county data bases that it had at the time, MTC produced a 10-year needs assessment for Bay Area streets and roads, showing that the Bay Area needed about $2.2 billion for pavement maintenance and rehabilitation. However, only a little over $1 billion in revenues could be expected. These figures were used by the California state senate to develop the bills that became Propositions 111 and 108. These propositions, passed in June 1990, increased the gas tax from 9 cents to an eventual 18 cents per gallon. This increase is expected to raise $15 billion over 10 years, with $3 billion directed to cities and counties for use on local streets and roads.

MTC staff continues to encourage its users to complete PMS implementation in order to refine and update its regional aggregate needs and shortfall chart, enabling MTC to act as an advocate for additional revenues from a regional perspective. This type of help with funding is almost impossible for a single local agency to accomplish. It has a direct impact on the local agency institutional issues related to limited funds for pavement maintenance and rehabilitation.

Local Level

When a city or county completes the inspection of its pavement network, MTC prepares a budget option report (BOR) for the jurisdiction. This report

- Reviews historical revenue and expenditure levels for street and road purposes;
- Uses historical spending levels to estimate future revenues for street and roads purposes for a 5-year period;
- Estimates a percentage of future street and road revenues that will be used strictly for pavement maintenance;
- Compares estimated revenues for pavement maintenance against actual need, as derived from PMS estimates;
- Documents expected shortfalls and surpluses for a 5-year period based on projected funding;
- Develops other options as a comparison to the estimated level of pavement maintenance expenditures; and
- Offers recommendations on how the jurisdiction might want to proceed with its pavement maintenance program.

A BOR has been prepared by MTC for 25 jurisdictions. One of the first agencies to receive a BOR was the city of San Leandro in Alameda County. In April 1986, its BOR was presented to the San Leandro city council, which informed the council that the city's 5-year need for pavement maintenance and rehabilitation was $11.5 million. Revenues for pavement maintenance and rehabilitation over that 5-year period were estimated to be only $5.5 million. Seven months later the council requested that the Department of Public Works and MTC staff deliver a formal presentation on the needed pavement maintenance revenue.

In the meantime, a ballot measure was placed before Alameda County voters for increasing the county's sales tax by 1/2 cent for transportation purposes. Almost 20 percent of the revenue generated from the proposed increase would go to the city and county public works departments for use on streets and roads. In San Leandro's case the estimated percentage of revenue being returned to was approximately equal to the $6 million pavement maintenance shortfall. The evening before the vote on the referendum, San Leandro public works and MTC staff went before the city council. The council, after hearing the presentation, determined that if the referendum passed the next day, the portion of funds to be returned to the city would be used for pavement maintenance and rehabilitation. Voters passed the referendum giving San Leandro an increase in revenue for pavement maintenance and rehabilitation.

In July 1988 a BOR was presented to the city council of the city of Vallejo in Solano County. It showed a $14 million need and estimated revenues equal to $6.7 million. The year prior to using the PMS, Vallejo had a pavement maintenance and rehabilitation budget of $900,000. The first year after its use, the council devoted $1.4 million to pavement maintenance and rehabilitation. Each year since that time the council has increased the pavement maintenance budget. For FY 1990–1991, the budget was nearly $2 million.

The city of Benicia in Solano County completed its condition survey in late 1989 and received a BOR in early 1990. The BOR showed that the city had a $7-million need over 5 years, and revenues for pavement maintenance were estimated at $2 million. Using the executive summary of the BOR, public works officials were able to secure an increase from $200,000 to $300,000 for pavement maintenance. The city spent this in the first half of FY 1990–1991. The public works department went back to the council to ask for additional funds and was able to secure an additional $400,000. In total, the city of Benicia was able to increase its expenditures for pavement maintenance and rehabilitation by 350 percent in 1 year.

MTC has found that, although preparation of BORs is time-consuming, it remains one of most important services that a regional agency can provide. One of MTC's major interests in developing and continuing support for the Bay Area PMS is to see an improvement in the San Francisco Bay Area pavement network. Staff members of MTC have found that public works staff members in many cities and counties find it extremely difficult to convert pavement condition information into the information needed to support budget requests effectively. MTC offers assistance to jurisdictions to help them interpret the PMS reports and to make presentations to their public works director, city or county managers, and their locally elected board or councils. This assistance helps build confidence in the PMS and helps train local agency personnel so that they can competently complete such activities on their own in future budget cycles. This effort has had a direct impact on problems of perceived complexity and limited budgets.

Does Facilitation Promote Use of PMS?

MTC staff members analyzed data from the state of California to determine if MTC PMS users were increasing revenues for pavement maintenance. Each public works department in California is required by law to report the source of its street and road revenues and to indicate how and where the revenues are spent. MTC analysis included the 9-year period from FY 1980–1981 to FY 1988–1989.

The data for the 9-year period were broken down into two separate analysis periods: (*a*) FY 1980–1981 to FY 1983–1984 and (*b*) FY 1984–1985 to FY 1988–1989. The PMS became available to Bay Area cities and counties in FY 1984–1985. In first period, Bay Area PMS users spent 23.5 percent of total street and road-related revenues on pavement maintenance and rehabilitation, whereas in the second period they spent 37.8 percent, a 62.1 percent increase. In the first period other Bay Area cities and counties spent 35.5 percent of total street and road revenues on pavement maintenance and rehabilitation. In the second period those agencies spent 31.4 percent on pavement maintenance and rehabilitation, an 11.5 percent decrease.

Pavement maintenance expenditures per mile were also analyzed. Broken down into the same time periods mentioned previously, the data show that MTC PMS users increased their pavement maintenance and rehabilitation spending more than nonusers did. From 1980 to 1984 MTC PMS users spent an average of $5,294/mi on pavement maintenance and rehabilitation (see Table 1). From 1985 to 1989, these agencies spent an average of $10,792/mi on pavement maintenance and rehabilitation, an average increase of 103.9 percent. Other Bay Area agencies spent an average of $7,498/mi on pavement maintenance and rehabilitation in the first period. In the second period they spent an average of $8,949/mi on pavement maintenance and rehabilitation, a 19.4 percent increase.

MTC has not been able to develop a method to compare the condition of roads and streets in agencies using the pavement management system with the condition of roads and streets for those that do not. This kind of information would be extremely helpful in documenting the impact of PMS on the pavement network.

Resources Devoted to PMS

During the PMS development period from July 1984 to February 1986, MTC devoted the equivalent of 5.5 person years (PY) to the project. The cost was about $300,000. Since that time, MTC has maintained the program, including all professional and support staff time, at between 3.5 and 4.0 PY for every fiscal year. The cost per year has ranged from $250,000 to $350,000. In addition to the staff time, MTC has hired consultants to perform various tasks. In the development stage the cost to MTC was approximately $180,000. During the past 7 years, MTC has spent an average of $50,000/year on consultant services.

For FY 1992–1993 the cost to support the program was approximately $400,000. Divided among the 55 Bay Area jurisdictions, this amounts to roughly $7,300 each. The cost to develop a PMS at the local level is generally estimated to be from $100 to $300/centerline-mi (6). The 55 Bay Area jurisdictions maintain roughly 11,000 centerline-mi of streets and roads. This would amount to between $1.1 million and $3.3 million if the jurisdictions were to act independently, without considering the cost of long-term support.

This shows that MTC has had an impact on the fund allocation to pavement maintenance and rehabilitation. It also shows that a regional agency can reduce the overall cost of pavement management development, implementation, and support.

Conclusions

Some of the institutional problems that often lead to discontinuing or to less than full use of pavement management in local agencies include these: personnel turnover, overcommitted staff, perceived complexity of PMS, and limited funds for pavement maintenance and rehabilitation. MTC provided the San Francisco Bay Area jurisdictions with pavement management procedures and software that reduced the cost of adopting a PMS, thereby making use more likely. Early in the process, MTC found that to address complexity and turnover issues, training and long-term support were as necessary as the software capabilities in successful PMS application. MTC developed support services that have proved of great value to the successful implementation and use of pavement management at the local agency level. These services, which include user meetings, user services, and budget analysis support,

TABLE 1 Comparison of Revenues and Pavement Expenditures of Local Agencies in San Francisco Bay Area

Expenditures/ Revenue Class	Bay Area PMS Users				Other Agencies			
	1980/81-88/89	1980/81-83/84	1984/85-88/89	% Change	1980/81-88/89	1980/81-83/84	1984/85-88/89	% Change
Pavement Exp. Percent of Total Expenditures	32.2	23.5	37.8	62.1	32.9	35.5	31.4	-11.5
Pavement Exp. $/Mile	8,348	5,294	10,792	103.9	8,304	7,498	8,949	19.4

assist personnel in agencies getting started in PMS with the training and support needed to begin pavement management. They also assist agencies using the PMS by providing the training and support needed by current and newly assigned personnel. They directly address the issues of complexity and personnel turnover. The user meetings are a focal point from which MTC takes direction on improvements and modifications to the software, training, and other support functions. The continued improvements and modifications to the Bay Area software would probably have not been possible if the PMS was supported by individual agencies. This unique relationship has proved successful and demonstrated that success of PMS at the local agency level is as much a function of the support available as it is a function of the software.

This demonstrates the unique role that regional agencies can play in pavement management at the local level. Without this support, many local agencies would spend considerable funds on pavement management only to abandon the process eventually. It is hoped that the MTC's experience can be used as a model for supporting PMS in other regional transportation planning agencies.

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Role of MPOs in Pavement Management

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Metropolitan planning organizations (MPOs) have a role in pavement management that supports local, regional, and state agency needs. The Intermodal Surface Transportation Efficiency Act of 1991 requires each MPO to address six management systems, one of which is pavement management, in the transportation planning process for the urbanized area. A research study was funded by FHWA to address this role and identify a framework for MPO involvement. This framework identified eight major elements for the MPO. Each element has a variety of activities that can be easily implemented by MPO staff. The level of involvement in each activity ranges from low to high depending on the use of the activity in the planning process. The major conclusions from the study are discussed, and a summary of MPOs involved in pavement management around the country is presented. The role of the MPO in overcoming the barriers to using pavement management by explaining the benefits of a system to support increased highway budgets is discussed. There are several methods of improving communications with local agencies and citizens. Effective public relations techniques to communicate future needs are necessary. The participation of MPOs in local pavement management will result in efficient use of limited local resources for the improvement in regional road networks. The overall goal of better managed and maintained highway facilities in urbanized areas can be achieved with coordinated efforts of state, MPO, and local agencies.

The preservation of the existing highway system is becoming a major activity for all levels of government. The goal of maintaining existing levels of service with limited resources is a challenge for everyone; the development of procedures and programs to meet these needs requires significant effort by everyone. Pavement management is one of the programs that is needed at all levels of government: state, regional, and local. The pavement management efforts of all these agencies should be closely related and cooperatively working together to have a system that effectively addresses everyone's needs. There is a role for regional agencies, such as metropolitan planning organizations (MPOs), to be involved in assisting the state and local agencies in this tremendous task. Many MPOs became involved in pavement management by providing a service to their member agencies. Today, the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) legislation requires that MPOs become involved.

Section 1034 of the ISTEA amended Title 23, U.S. Code, by adding Chapter 3, Section 303 (Management

Systems), which requires states to develop, establish, and implement six management systems, including pavement management for federal-aid highways (*1*). It further states that in metropolitan areas, such systems shall be developed and implemented in cooperation with MPOs. Although this requires that MPOs be involved, their role is not defined. This paper will discuss specific actions that MPOs can perform in pavement management, including how they can assist in promoting increased budgets to local finance committees.

Section 134 (Metropolitan Planning) of Title 23 lists 15 factors that should be considered in the urban transportation planning process (*2*). These include the transportation needs identified using the management systems required by Section 303, including a pavement management system (PMS). This means that pavement management shall be considered in the planning process. It is no longer an option; it is a requirement for states and MPOs.

FHWA also has a pavement policy that required states to have a PMS on state-controlled highways by January 13, 1993 (*3*). This policy made it optional for states to have a system to cover local highways. ISTEA now requires states to have a PMS to cover all federal-aid highways regardless of jurisdictional control. This almost tripled the mileage, from 313,000 to 916,000 mi, as presented in Table 1. A review of Table 1 shows that the local mileage is larger than the state mileage in 16 states. Presentations at TRB sessions and FHWA regional pavement conferences conclude that many states are having difficulty maintaining a PMS on state-controlled highways without trying to include highways under local control. How can this need on the local highway system be addressed? This is where the MPOs must have a significant role in assisting local agencies.

Role of MPOs

The role of MPOs is twofold: (*a*) they facilitate development and implementation of pavement management in local communities, and (*b*) they use pavement data in the planning process required by ISTEA (*2*).

Pavement management can be established in local communities by several methods, including consultant contract, existing programs, in-house development, and regional program. The consultant method is expensive to develop and maintain and often requires collection of unnecessary data (*4*). Existing programs use available software that may not meet each agencies' specific needs. In-house developed programs by each agency are time-consuming to develop and implement, and they tend to recreate existing programs. Regional programs are developed, sponsored, and supported by a regional agency such as an MPO or a regional planning agency and are more cost-effective for local agencies (*5*).

MPO Capabilities

There are several reasons that MPOs should be involved in pavement management. The MPO role of providing assistance to member local agencies would encourage the establishment and use of pavement management systems at the local level (*4*). Specific capabilities of the MPO that make it an appropriate agency for this activity include the following:

- Sharing of information,
- Maintenance of data files,
- Coordination of and accessing to various data sources,
- Knowledge of data systems,
- Expertise in computer models and programs,
- Expertise in network and system analysis,
- Experience in data collection,
- Promotion of uniformity,
- Utilization of data on a regional basis, and
- Working relationship with state and local agencies

Framework for MPO Involvement

A study was funded by FHWA to investigate and develop the role of MPOs in pavement management. This study was conducted by the University of Massachusetts and completed in March 1991 (*6*). It developed a framework for MPO involvement that identified eight elements that the MPO can perform with various levels of effort, as shown in Figure 1.

Promotional and educational efforts are aimed at creating pavement management awareness within local communities and convincing communities to participate in the ongoing process. Activities could include public presentations and the preparation of brochures on the concepts, content, benefits, and extent of commitment associated with pavement management.

Policy planning addresses issues pertaining to the formulation of local policies, goals, and objectives. Key issues include assessment of current and past maintenance policies, definition of managerial and physical objectives, and investigation of funding requirements. The local commitments necessary to ensure a continuous pavement management process would be identified.

Network-level analysis or system planning could be executed using one of several computerized network level PMSs available. The MPO and local agency roles and responsibilities would depend on the particular system to be adopted and the development and implementation of goals. This includes data collection, analysis, priority setting, budgeting, and training. MPOs may provide equipment and coordinate hardware and software sharing for those communities that cannot afford the initial capital costs.

TABLE 1 Centerline Miles Under ISTEA for PMSs

STATE	BEFORE ISTEA	ISTEA		TOTAL ISTEA
	STATE	STATE	LOCAL	
ALABAMA	7,684	10,779	11,882	22,661
ALASKA	2,150	4,264	35	4,299
ARIZONA	4,516	5,895	5,483	11,378
ARKANSAS	6,324	15,681	5,104	20,785
CALIFORNIA	13,934	15,115	31,775	46,890
COLORADO	5,428	9,047	5,863	14,910
CONNECTICUT	1,851	3,380	2,385	5,765
DELAWARE	513	1,413	11	1,424
DISTRICT OF COLUMBIA	129	423	0	423
FLORIDA	9,637	11,827	9,761	21,588
GEORGIA	11,179	17,646	11,513	29,159
HAWAII	561	960	385	1,345
IDAHO	3,408	4,939	4,086	9,025
ILLINOIS	11,941	15,987	16,926	32,913
INDIANA	6,488	11,233	9,612	20,845
IOWA	9,324	9,731	15,914	25,645
KANSAS	8,989	10,669	23,121	33,790
KENTUCKY	4,734	13,072	801	13,873
LOUISIANA	4,427	17,443	1,811	19,254
MAINE	2,425	6,105	289	6,394
MARYLAND	2,792	4,517	2,601	7,118
MASSACHUSETTS	2,320	3,074	7,765	10,839
MICHIGAN	8,774	9,535	23,691	33,226
MINNESOTA	10,249	12,070	18,103	30,173
MISSISSIPPI	6,554	10,169	9,721	19,890
MISSOURI	8,542	26,956	3,224	30,180
MONTANA	6,657	6,977	6,451	13,428
NEBRASKA	7,692	9,941	10,234	20,175
NEVADA	2,482	4,668	923	5,591
NEW HAMPSHIRE	1,345	2,703	659	3,362
NEW JERSEY	2,442	2,686	6,801	9,487
NEW MEXICO	4,990	5,336	300	5,636
NEW YORK	9,780	15,000	10,481	25,481
NORTH CAROLINA	6,604	19,550	1,179	20,729
NORTH DAKOTA	6,123	7,605	10,179	17,784
OHIO	8,618	18,283	9,331	27,614
OKLAHOMA	6,641	12,786	18,692	31,478
OREGON	5,857	7,558	8,873	16,431
PENNSYLVANIA	12,266	23,441	3,074	26,515
RHODE ISLAND	543	1,091	547	1,638
SOUTH CAROLINA	6,466	16,773	286	17,059
SOUTH DAKOTA	6,453	7,897	9,878	17,775
TENNESSEE	7,546	13,540	2,319	15,859
TEXAS	21,752	61,837	11,359	73,196
UTAH	3,683	5,658	1,962	7,620
VERMONT	1,404	2,587	1,119	3,706
VIRGINIA	6,884	18,473	1,696	20,169
WASHINGTON	5,755	6,968	10,450	17,418
WEST VIRGINIA	3,038	9,854	273	10,127
WISCONSIN	9,933	11,825	15,459	27,284
WYOMING	3,874	6,071	799	6,870
TOTAL	**313,701**	**551,038**	**365,186**	**916,224**

Project-level analysis includes coordination of preconstruction activities, detailed engineering design, economic analysis, and selection of best alternatives. This type of analysis is usually executed through consultants. The MPO could assist in the hiring or joint hiring of consulting services and the preparation of contract documents.

Programming includes the selection of projects for the transportation improvement program (TIP), development of master plans, and preparation of local improvement programs. This element is aimed at directing and integrating the final products of both the network- and project-level elements into planning programs. The key inputs may include pavement condition, addressed through the PMS, and capacity deficiencies addressed through transportation system management.

Construction includes the contract control, contract scheduling, and traffic impacts of individual projects. MPOs may help communities schedule activities and pro-

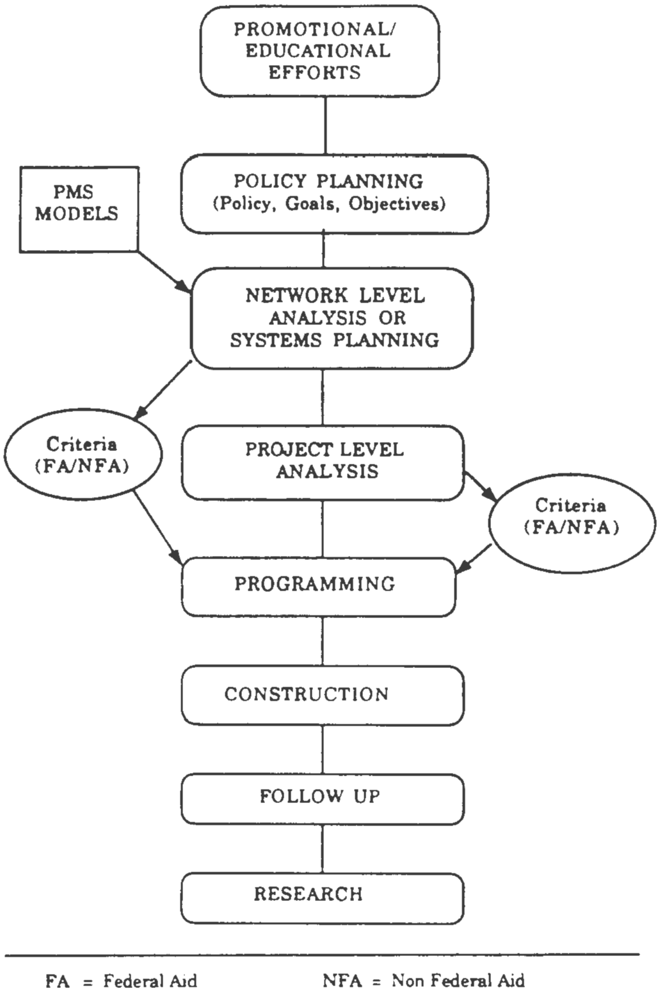

FIGURE 1 Framework for MPO involvement in pavement management (6).

ject construction. They may assist in coordination of joint construction projects and may encourage joint inspection control.

Follow-up includes the data base update, overall process monitoring, and dissemination of local PMS benefits. MPO newsletters may be developed, and Rural Technical Assistance Program (RTAP) center publications advertising success stories would be promoted.

Research includes the pavement performance evaluation, cost-effective strategies, and development of local and regional deterioration rates. Data from the communities could be retained and analyzed to develop representative characteristics on pavement life, treatment costs and effectiveness, and budget needs for the area or region. These characteristics could be used in setting priorities and developing cost-effective programs.

The level of effort in each of these eight elements varies from low to high on the basis of staff resources at the MPO. Those activities with the highest level of effort and the most significant for the MPO are the promotion and education, network-level analysis, programming, and follow-up. The activities with the lowest level of effort would be the project level analysis and construction.

There are three major conclusions from this study.

1. MPOs should play a greater role in the initiation, development, and implementation of local pavement management.
2. The MPO role in pavement management can be achieved through one or more of the eight elements of the framework. Roles may vary according to resources, capabilities, and commitments.
3. Potential use of technical support outside the MPO and local agency is evident. Such support may be sought from state highway departments, RTAP Centers, or consultants.

Examples of MPO Involvement

The combined efforts of various levels of government are working effectively in Massachusetts as presented at the 1992 Annual FHWA Region 1 Pavement Conference. It is the only state in the country where all the MPOs, the state, the Local Technical Assistance Program center, and consultants have all been working cooperatively for the past 2 years. This working arrangement has been facilitated by two significant activities—a user group and a newsletter—which are unique pavement management activities for an MPO. The user group is made up of technical staff from each MPO who meet periodically to discuss various pavement management activities, including support for running computer models. A pavement management newsletter developed by an MPO for the exchange of federal, state, and local pavement activities has been useful.

Many MPOs have been involved in pavement management for several years. They included states in the Northeast (*4,7,8*), Ohio (*9*), California (*10*), and Michigan (*11*). MPOs in these states also include several large urbanized areas such as Boston, San Francisco, and Detroit. Most of these MPOs are in the northern portions of the United States, which are generally older areas that have low growth and where system preservation is more important than expansion.

In Massachusetts, the Department of Public Works issued a Chapter 90 policy for reimbursement of pavement management activities with construction funds. The policy is to reimburse all costs associated with initiating a pavement management program. These include services, training, documentation, and software but not salaries for city and town personnel.

The Metropolitan Transportation Commission (MTC), the MPO for the San Francisco urban area, requires a PMS certification from each city and county desiring to have projects qualify for funding under their state TIP (*11*). This certification provides dates of the most recent inventory, condition, needs, and budget for their pavement management program. The MTC provides technical support to any agency showing interest in pavement management. They have developed their own pavement management software, and they provide training and conduct user group meetings (*11*).

Training

There are several agencies that provide training to MPOs and local agencies in pavement management. The FHWA has National Highway Institute training courses titled "Road Surface Management for Local Governments," available since December 1989, and a new course, "Pavement Management for Urbanized Areas," to be available in 1994 (*12*). The LTAP centers provide specialized training courses on pavement management and technical assistance for unique projects (*13*). Consultants are also available to provide promotional workshops and product seminars.

At the national level, there are TRB-supported activities in local agency pavement management. There are presentations at the annual TRB meeting, and a TRB subcommittee on local agency pavement management has been formed. This subcommittee sponsors sessions at annual TRB meetings and is seeking MPO support and membership.

Budgeting Support

One of the major benefits of a PMS is to provide data for local agencies to support their requests for additional funds for highway maintenance and reconstruction. This is accomplished by providing a documented system containing condition data to support future needs, which assists decision makers in developing strategies and programs for future budgets. Information on project rankings, rehabilitation schedules, and life-cycle cost data is provided, and limited funds can then be spent more effectively. The selection of the most effective maintenance strategy can be based on recommendations from the MPO data base on local pavement treatments. MPOs can increase public awareness of the lack of adequate funds for maintenance and reconstruction through discussions at committee meetings and other public presentations.

Communications

Better communication with local finance and budget committees can be facilitated by use of MPO staff and support activities (*14*). A key to understanding budget needs is the ability to present complete and reliable information in a persuasive manner. If local officials have reliable, quality information about their roads and present that information in a way that the general public can understand, the need for more money and increased budgets can be realized (*15*). Because the history of an agency's roads and problem spots cannot be related to everyone easily and concisely, a road improvement program displaying facts and figures for everyone to view can be useful. The MPO can assist in the development of road improvement programs that show that the local highway official has done his or her job. As a result, what is presented at finance committee meetings can be more believable and reliable.

There are many methods of collecting and analyzing data for road improvement programs (*16*). These range from sophisticated computer models to simple inventories that use index cards. The MPO can assist in selecting the right system that suits the agency's needs and collects only information needed to make proper decisions about managing roads more efficiently. Program data used to develop budgets must consider the costs of various alternatives, the life expectancy of each alternative, and costs of routine maintenance.

The goal of communicating is to convince citizens and local officials that a road improvement program is needed and makes good sense for the community. There are many ways of communicating these data. Communications with planning, zoning, and school boards and elected officials must be carried out to explain the proposed program. The state highway agency and other regional planning agencies should be kept informed that a plan is being developed, and their input should be requested. Performing everyday public relations and listening to citizens on the street and at other meetings is as important as telling people about the plan. Hearing what others have to say is hard work and requires a concerted effort.

Public Relations

Because planning agencies want town officials and taxpayers to support road improvement programs, a public relations effort is necessary. There are many ways to get the message across, and some methods are more effective than others. These methods can be grouped as visual, verbal, written, and media. Visual aids help to tell the story better than words. Most MPOs have experience in developing effective visual aids, including such things as photographs, maps, graphs, displays, and videos. Verbal communications can be achieved at public meetings, press conferences, service club meetings, and community forums. MPOs again have experience in making all these kinds of presentations. Advertisements in newspapers, brochures, and MPO newsletters are effective ways of presenting written programs. Media presentations can be made through radio, television, newspaper stories, and public information messages.

People will support a road improvement program that requests an increased budget if they know the facts and if the facts are presented effectively (*15*). The MPO and local elected officials have to know the subject and use a variety of communication techniques if they want their efforts to be fruitful.

SUMMARY

The pavement management process has gained interest at the MPO level as a result of ISTEA legislation and in response to local agencies' requests for developing programs to improve the overall condition of local roads with limited resources. However, the organization and budgeting process of local agencies varies considerably, which makes it difficult to develop a coordinated regional program. Considering these difficulties and realizing the benefits from a regional program, MPOs should play a greater role in the initiation, development, and implementation of PMSs. The participation of MPOs in local pavement management will result in efficient use of limited state and local resources for the improvement in regional road networks. Data bases at the regional level can enhance and encourage efficient decision making on a regional level. Local agencies can work with MPOs in investigating alternative funding sources and in developing budget proposals for additional resources. The overall goal of better managed and maintained highway facilities in urbanized areas can be easily obtained with a combined effort of state, MPO, and local agencies.

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NEW FRONTIERS

Pavement Management Systems Lead the Way for Infrastructure Management Systems

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Pavement management was first conceived in the mid-1960s as a result of major work done in the United States and Canada. The early pavement management concepts focused on the project level, coordinating improvements in design, rehabilitation, maintenance, and pavement performance modeling. By the mid-1970s pavement management had expanded to primary use at the network level and involved the planning, programming, and budgeting of funds for entire pavement networks of varying sizes. By the mid-1980s the applicability of these same system concepts to bridges became evident to the engineering community, and a major research project was funded by NCHRP to develop bridge management systems. Since then bridge management has become relatively commonplace throughout the world. Work has been performed by others on building management systems, sewage management systems, and other systems for managing the world's infrastructure. All of these infrastructure management systems have many things in common, and everyone benefits from the coordination of the development and usefulness of these management systems. The common elements and the differentiating aspects of infrastructure management systems are summarized, particularly as they relate to the basic concepts of pavement management. Expectations for future development and integration of infrastructure management systems are discussed. Such development includes the application of geographic information systems and other modern technology to all aspects of systems integration.

The management of physical infrastructure is an important ongoing process. Public facilities must be maintained at an acceptable level of service if America is to continue to prosper. Many factors such as safety, protection of public investment, comfort, economics, environmental impacts, aesthetics, and constraints on available resources must be balanced in the managerial process if required results are to be obtained within budgetary limits.

Although public agencies have almost always striven to manage their resources well, the use of systematic processes and automated systems to assist in more efficient infrastructure management really began in the mid-1960s with the advent of pavement management systems (PMSs). The large public investment in pavement structures prompted research into better methods of predicting pavement life and planning maintenance, rehabilitation, and reconstruction. The pioneering work in PMS was accomplished by Hudson et al. (*1*) and Finn et al. (*2*) under NCHRP Project 1-10. Meanwhile, independent research efforts were also conducted in Canada by Haas (*3*) to structure pavement design and management systems concepts.

The term *pavement management system* was first introduced by these researchers to describe the entire range of activities for pavement design, maintenance, rehabilitation, and management. Since 1970 PMS has enjoyed steady growth and development. Because of the proven value of PMS in saving money and maximizing benefits, FHWA mandated the adoption of PMSs in all state departments of transportation (DOTs) by 1993. It could be said that PMSs were created by the "innovators," developed by the "true believers," and implemented by the "champions" over the past 25 years.

The concept of management of asphaltic pavements was first introduced in South Africa in the early 1970s at CAPSA meeting and in further discussions held at the National Institute for Transport and Road Research (NITRR) in Pretoria during the 1970s by W. R. Hudson and others. Pioneering work in this field was done in South Africa by Peter Curtayne, Alex Visser, and others. This work is widely published in various CAPSA, ATC, and NITRR publications.

Many states in the 1970s began early development work on PMS components such as condition evaluation techniques, inventory and condition data bases, deterioration modeling, and network analysis tools. Some agencies succeeded in tying these pieces together into initial integrated systems or PMSs that have also been the initial model upon which other transportation infrastructure management systems could be modeled.

From the perspective of 1994 with every state DOT and more than 200 cities around the United States implementing pavement management, it may seem that the implementation of pavement management was a simple matter. Nothing could be farther from the truth. F.N. Finn and W.R. Hudson (personal communication, 1993) frequently recall the dismay that members of the original review panel expressed when the systems concept was presented to NCHRP during the first year of Project 1-10 (*1*). At the beginning nobody was ready to accept these new concepts. In fact, it was more than 10 years before significant acceptance of the PMS concept was gained.

The original project team was not funded to continue work on the concept after the first phase. In fact, the NCHRP panel seriously considered dropping the idea all together. This is always one of the major problems for innovative concepts in technology. However, a few true believers continued the development of pavement management. Bob Lewis, Chief Engineer of Highway Design for the Texas Department of Transportation, believed in the concept and supported funding for further development in Texas. Alex Kelly and others in the Ontario Ministry of Transport likewise funded the work of Ralph Haas and his team. Subsequently, additional support was provided by NCHRP and AASHTO, largely the authors think, because of the insistence of Harry Smith, who was then a project engineer with NCHRP.

Early implementation of a simple system was carried out by Roger LeClerc in the Washington DOT, and an early useful functioning system was developed in Arizona under the leadership of Chief Engineer Oscar Lyons (*4*). Early conferences sponsored by TRB in Phoenix, Arizona, and Charlotte, North Carolina, succeeded in selling the basic ideas to enough highway agencies to maintain forward motion.

These innovative ideas, this championing by true believers, and the strong support of significant state highway engineers have brought us to relatively strong implementation of pavement management in 1994. Missing, however, at this time, is new research and development effort. No major research activities are under way to improve the process of pavement management at the time of writing this paper (mid-1993). Apparently, new champions and true believers are now needed to advance the state of the art. Implementation is important, but not continuing to improve concepts as well as technology will again lead to failure.

BMS: The Second Step

The collapse of several bridges, notably that of the Silver River Bridge, prompted Congress in the late 1970s to mandate a National Bridge Inventory (NBI) to identify the structural and functional adequacy of bridges on the nation's highways (*5*). A number of states began development of bridge management concepts and techniques using the NBI data and analysis tools adapted from pavement management techniques that were developing (*6–8*). In the mid-1980s, NCHRP Project 12-28(2) was undertaken to develop the initial concepts and framework for broadly applicable bridge management systems (BMSs). This pioneer work resulted in the complete definition of a bridge management system and all of its important subsystems. The research team, headed by W.R. Hudson and S.W. Hudson, was assisted by a team of experts and a panel named by NCHRP. A report entitled *Bridge Management Systems* was subsequently published in 1987 as *NCHRP Report 300* (*9*). Subsequent work was carried out by others, but this original Project 12-28 (2) and the Austin Research Engineers (ARE) research team provided the definitions that serve as the basis for current prototype BMS software packages. A second-generation applications package is under development by NCHRP.

Currently several major efforts are under way to develop improved bridge management. ARE, Inc., is adapting the results of the NCHRP work for the Washington, D.C., Department of Public Works. This major project is similar to the effort that will be needed for infrastructure management for major cities. It also has the dimensions of a management system for a major county or a small state. FHWA also sponsored development of the PONTIS BMS in cooperation with California and several other states (*10*).

The development of PMS and BMS has shown clearly that useful infrastructure management systems can be developed with many things, such as the following, in common:

- Inventory data defining the facilities to be managed,
- Evaluation data defining the current condition and status,
- Location or geographical referencing information,
- Generation of strategies and alternatives,
- Optimization of treatment alternatives by project,
- Analysis tools to analyze needs and develop plans with established priorities,
- Reporting and graphics capabilities,
- Performance monitoring,
- Performance prediction modeling, and
- Funding splits between capital improvements and maintenance.

These elements must be provided in the basic components of any infrastructure management system (IMS) and also for an integrated IMS that ties together several aspects of the problem. A basic integrated IMS would at a minimum include the six mandated subsystems listed later in this paper. Additional subsystems could be added as needed or desired, depending on the modular design of the integrated system.

It seems apparent that the concept of PMS and BMS can certainly be applied to any type of infrastructure facility such as wastewater treatment plants, buildings, water facilities, and airports. However, the purpose here is to show how the various management systems can be tied together on the basis of the knowledge gained in PMS. Efforts have already begun to develop building management systems through the efforts of a committee of the Building Research Board (*11*).

Background of Integrated Management Systems

Given that it is possible to develop a management system for any particular type of facility, it is reasonable to develop an integrated management system for similar types of facilities. The purpose of this paper is to illustrate the validity of this thesis and to show how the innovative concept can flow.

The objective of implementing an integrated IMS within an agency, whether it is in the public or private sector, is to provide decision makers with processed quantitative data for examining the impact of various alternative scenarios and, thus, data organized to assist them in managing the infrastructure more effectively and efficiently.

Several elements of management systems are already in place in many agencies, but they are not coordinated in a comprehensive and systematic fashion. A coordinated set of management subsystems can be used to establish formal procedures for recommending candidate projects and evaluating different strategies for solving problems, correcting deficiencies, and assessing trends of future needs. To tie all these factors together, an integrated management system must incorporate forecasting models to develop trends of conditions, assess needs, and analyze future funding or budget scenarios. This system can help the decision maker in the development of both short- and long-term solutions.

With its 25-year history, PMS shows the way for integrated management systems development in three general areas:

1. State transportation systems:
   –Pavement,
   –Bridge,
   –Safety,
   –Congestion,
   –Public transportation, and
   –Intermodal facilities.
2. City infrastructure:
   –The six subsystems previously listed for state transportation systems, plus the following nine:
   –Water;
   –Sewer;
   –Traffic signals, signs, and markings;
   –Emergency services;
   –Electricity;
   –Garbage collection;
   –Recycling;
   –Drainage; and
   –Park facilities.
3. Major unitized facilities—public and private:
   –Airports,
   –Nuclear power plants,
   –Refineries,
   –Parks and recreation areas, and
   –Other.

Each of these three areas is examined in a separate section after a discussion of the framework for appropriate integrated systems. The new federal requirements for integrated transportation management systems are reviewed in relation to both the current developments and the "ideal" systems framework discussed previously. Finally, implementation issues are discussed.

Framework of Integrated Systems

As the various decision support systems are developed and as they mature with use, there is a need to consider ways in which these systems can and should be coordinated and to consider how the results should be integrated into information for strategic planning as a part of the executive management process using an executive information system (EIS). In general, individual systems (PMS, BMS, traffic monitoring, etc.) have been developed with only informal coordination among the various system developers. Little work has been done throughout the nation to coordinate the efforts among the various systems. Correcting such a major deficiency by using integrated systems would provide policy makers with a tool for investing transportation dollars in the most economically efficient manner. This is particularly important given the new contextual environment for transportation. Transportation policy is no longer developed in a vacuum. Other state and national priorities are directly influenced by transportation decisions, and vice versa.

Multiple-criteria decision problems are best analyzed in an interactive manner, allowing the judgment of the decision makers to be used directly. Such interaction permits decisions based on an assessment of relative allowable trade-offs among criteria in the region of feasibility. Multivariate analysis techniques have been developed to assist in this type of analysis for industry (*12,13*). Sufficient structure and details need to be incorporated into the IMS so that the system represents the physical environment reasonably well but with only enough detail that the burden placed on the decision makers will be minimized.

A general IMS structure based on minimal assumptions will permit decision making via any desired technique on the basis of all of the responses of the total management system or on any portions thereof. Screening or ranking of acceptably good alternatives can be based either on qualitative or quantative responses, depending on the type of information available, the degree of sophistication of the decision makers, and the degree of detail desired in the management system.

Common Aspects of all Management Systems

All management systems have many things in common. These include modular analysis tools, a central data base that is easily updated, compatible benefit-cost analysis models, optimization models, and possibly a graphical interface and a geographic information system (GIS). Also, any facilities management system must allocate resources between capital improvements and maintenance. These common facets of management systems are next considered briefly.

Central Data Base

A good data base and information-handling system are the heart of any management system. A data base is not a management system, but it is required for one. A management system can only operate on the data made available to it. Systems that are set up independently with separate data bases often duplicate many data items, but more important, they have inconsistent location and identification information. An integrated management system operating off of a coordinated central data base, which houses all data needed for any of the management systems or subsystems, eliminates duplication and inconsistencies. Such a data base must be flexible so that when the modular analysis components are upgraded or new components are added, the data base can also be updated or modified to accommodate the data needs for the new subsystems. Such a data base must also accommodate expected additions of new infrastructure types.

Modular Analysis Tools

All management systems must have analysis components that manipulate the pertinent data from the central data base to produce useful information and recommendations for the manager. These analysis tools can generate summary statistics and also can provide graphs, economic analyses, benefit-cost analyses, decision methodologies, optimization routines, statistical analyses, and deterioration rate analyses. An integrated system should have the flexibility to use modular analysis tools that can be easily updated as new technologies are developed. These tools should be consistent across the various infrastructure components that may be managed under the integrated IMS. Such consistency would include common optimization methodologies and life-cycle cost analyses.

Modularity of the system will require that the analysis tools be totally independent of the data base. Unit cost information, deterioration rates, infrastructure types and functional classes, and so forth will be kept updated in the central data base. The analysis tools will be defined relative to the data needs, the models or analyses to be performed, and the outputs to be returned to the management systems. As new modules are developed, each of these three main aspects must be created taking the rest of the system into consideration. The inputs would be extracted from the central data base; the analyses would be performed in modular subroutines; and the control, interaction, and output review would be performed at the user-interface level. Consistency in data needs and interface and output types is important to maintain a seamless integrated system.

Geographically Based Location/Identification

GISs have come of age. Therefore, there is no reason to consider any integrated management system today without using a GIS. Such a GIS will provide a coherent common geographical data base location referencing system that will minimize errors and confusion in collecting, processing, and storing data.

User-Friendly Graphical Interface

Outputs of any management system are critical to its use. Long laborious printouts or tabular data are not easily used by managers in making their decisions. New systems have capabilities that include on-screen push-button controls, a graphical view of the work environment, visual outputs and reports, on-screen photographs and videos, sound, and other usability-enhancing features. Such graphic interfaces not only enhance the use of the integrated management system output, they actually make using the system easy, fun, and more powerful.

Compatible Benefit-Cost Economic Analyses

All infrastructure management systems require a useful benefit-cost or life-cycle cost analysis. There is no reason that such analyses should not be consistent across all infrastructure subsystems within a state, city, private entity, or airport. An IMS will help ensure economic consistency in such areas as unit cost, definition of criteria relating to benefits and effectiveness, interest rates, analysis period, definition of user and agency costs, criteria and goals related to level of service, and other important factors.

Global Consideration and Allocation of Resources

Individual management systems currently allocate an agency's resources separately for individual subsystems. Thus, a budget is set up for pavements, another for bridges, and so forth. This can result in suboptimization of the total budget even though expenditures within a specific type of facility may be made optimal by using its individual management system. An IMS will provide global consideration and allocation of resources. Although certain constraints exist for funding "set-asides" such as bridge improvement programs, these can easily be handled as constraints within the individual subsystems.

Evaluation of Maintenance Versus Capital Improvements

All facilities and infrastructures deteriorate. They ultimately become functionally, structurally, or physically unserviceable. As their demand and use exceed the actual capacity, functional problems occur. Structural deterioration can produce major safety and operational problems. Facilities that are in poor physical condition are aesthetic, operational, and safety hazards. To address these issues, management systems must be able to recommend timely maintenance or needed capital improvements. They must be able to accurately model and analyze the costs and effects of maintenance activities that extend or preserve facilities as opposed to more costly improvements.

Common Aspects of PMS and BMS

It is noteworthy that the team which originally developed much of the pavement management philosophy, particularly the original innovative thinking, was selected by NCHRP to undertake the first definition of BMS. The same concepts and application of system technology apply even though the details vary. Both PMS and BMS involve a change in the way an agency does business. Both systems require a clear understanding of inputs, application models, and outputs of the system. Both require the use of clear models to define the behavior of the system and use of models to evaluate cost. Both systems require a system output function that can be optimized in relation to the costs and benefits.

Current Federal Requirements

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) mandated that all 50 states and the District of Columbia develop and implement six management systems, as follows:

1. Pavement (PMS),
2. Bridge (BMS),
3. Safety management system (SMS),
4. Congestion management system (CMS),
5. Public transportation management system (PTMS), and
6. Intermodal facilities (IMS).

A traffic monitoring system may also be required. In March 1993, FHWA published in the *Federal Register* proposed rules for carrying out the guidelines of ISTEA (*14*). This document covers separate guidelines for each of the six mandated systems and it includes comments from reviewers of the guidelines, including state DOTs, metropolitan planning organizations (MPOs), and other interested groups.

ISTEA is landmark legislation not only because it is linked with other national policy objectives but because it initiates a fundamental change in the evaluation of the transportation system. Importantly, it begins to emphasize that the purpose of transportation is to provide mobility for persons and freight. ISTEA requires the development, implementation, and coordination of six management systems, along with a program for traffic monitoring, by January 1995.

Relevant recommendations of the National Transportation Policy can be summarized as follows:

- That priority be given to maintenance and preservation of the transportation facilities;
- That there be stronger requirements for pavement and bridge management systems and better designs for long-range durability; and
- That management of transportation systems be improved in order to accommodate more traffic and to handle it more safely and efficiently, particularly in areas where congestion already exists.

The management systems concept will favor investment strategies that achieve the highest payoff and are consistent with other national objectives such as clean air, economic growth, and energy conservation. However, the federal guidelines do not address developing the integration of management systems in a consistent or compatible way. The guidelines generally treat each management system individually, simply providing that the state planning process should consider the outputs from each of the systems in the overall planning process.

The next logical step is to examine common boundaries within which the individual management systems should be developed in order to have a measure of commonalty among systems and across agencies. It is especially important that these federally mandated systems be developed consistently within an agency so that eventual integration is possible. A better approach might be to mandate that the individual management systems be developed as compatible modules of a comprehensive public infrastructure management system (PIMS) within each agency. Flexibility should be allowed in designs in order to accommodate the specific needs and sophistication of each agency. However, guidelines should be given to encourage a consistent, integrated package of management subsystems that feed a centralized executive management information system (EMIS). The EMIS then provides a centralized tool for use by the executive team in the statewide planning process, which, according to the federal regulations, must use the results of the individual management systems.

The federal requirements generally address two levels of government: state and metropolitan. The states are responsible for administering funds and directing the implementation of the requirements. MPOs will be involved in coordinating and administering the requirements, in cooperation with the state agency, for cities and metropolitan areas. Therefore, integrated systems for two of the three application areas discussed here are applicable to the new federal requirements.

State-Level Management Systems

State-level IMSs are generally at a higher level of development than are the other application areas. As described previously, pavement management has led the way in both concepts and applications development. As discussed, ISTEA provides guidelines for the framework of each of the individual management systems. An integrated system framework will provide the control umbrella under which thoroughness and consistency can be assured. Each of the six management systems prescribed by the federal guidelines should be subsystems in the overall PIMS framework. They will operate off of a central data base that contains all data for each subsystem in the PIMS.

Sinha and Fwa (*15*) outlined a concept of a total highway management system in which they envision a comprehensive highway management system as a three-dimensional matrix, as depicted in Figure 1. The three dimensions are the highway facility dimension, operational function dimension, and system objective dimension. Table 1 gives the possible elements of each in the three dimensions, according to Sinha and Fwa. The suggested three-dimensional matrix structure indicates that a highway agency has a number of facilities to be managed in the highway system. The overall objectives of the highway agency could be well defined, and the effort for accomplishing these objectives divides the management task into a group of functions. Each facility in the system requires all of the management functions, and through these management functions the overall system objectives are accomplished. Using the framework presented in Figure 1, the highway management process can certainly be viewed as a multiple-objective problem. Although this framework does not address all management systems required by FHWA, the model presented by Sinha and Fwa addresses several of the coordination and interaction issues.

An initial integrated PIMS for states would be composed of the various mandated subsystems: (*a*) pavement, (*b*) bridge, (*c*) safety, (*d*) congestion, (*e*) public transportation, and (*f*) intermodal, plus others that might be added subsequently. The structure should be flexible enough to accommodate changes in the form of the subsystems and in the inputs and outputs of the models as well as the possibility of dividing a subsystem into smaller elements for ease of simulation. Each subsystem or element thereof can be represented by different approaches, such as mathematical models, expert systems, artificial neural networks, fuzzy systems, and so forth, all of which are interconnected by information flows. The inputs and outputs of the subsystems can correspond to normal data or deviations from normality. Uncertainty in the subsystem inputs and outputs could also be included. In addition, decision makers would propose changes in the status quo, and these changes would be used to perturb a subsystem, or the entire system, yielding responses that could

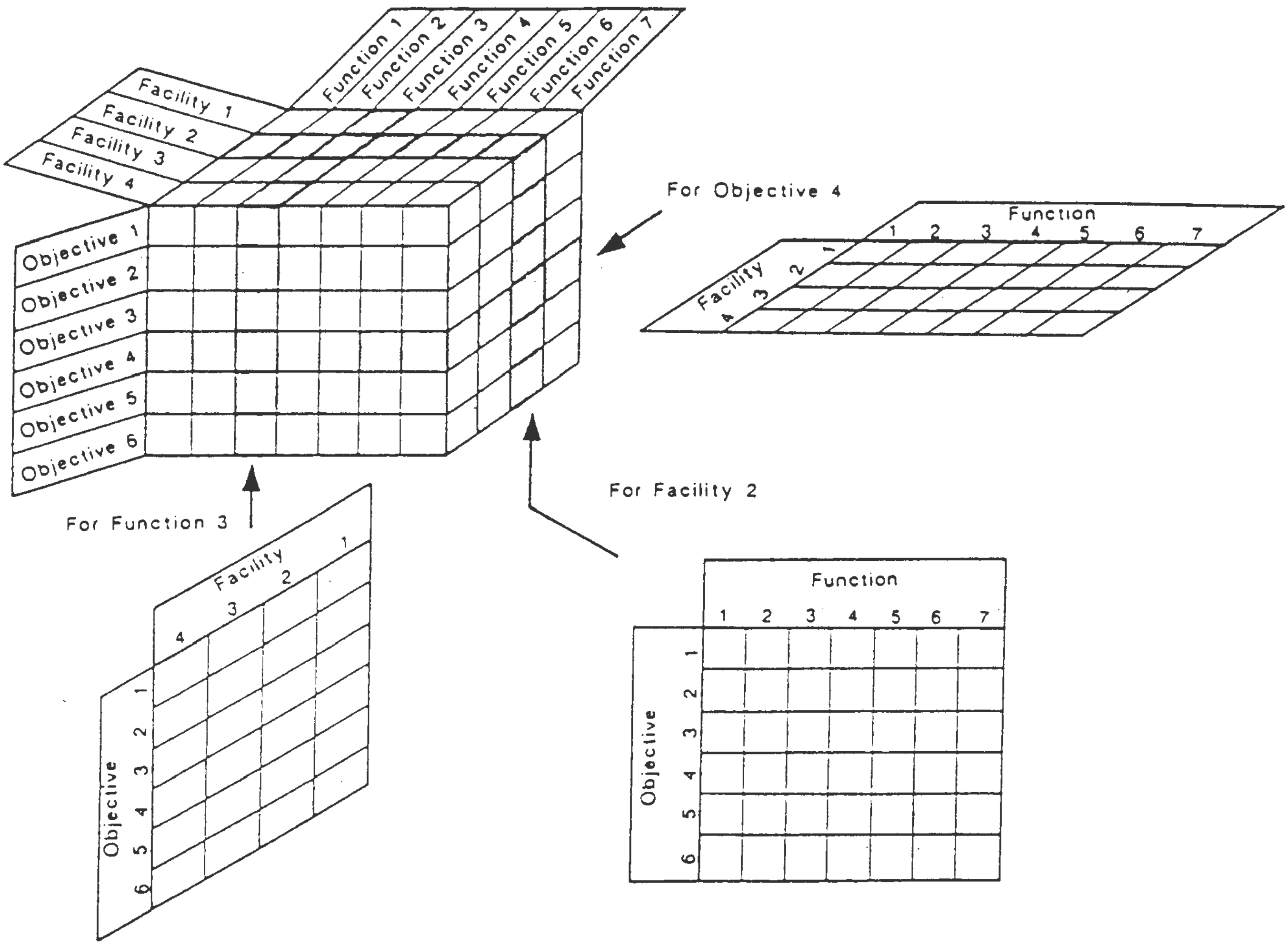

FIGURE 1 Three-dimensional matrix structure of a highway management system (*15*).

TABLE 1 Elements of Highway System Dimensions

Highway Facility	Operational Function	System Objective
Pavement	Planning	Service
Bridge	Design	Condition
Roadside	Construction	Safety
Traffic control device	Condition evaluation	Cost
	Maintenance	Socioeconomic factor
	Improvement	Energy
		Data management

be examined by any of the existing multicriteria decision-making techniques.

The use of artificial neural networks is a possibility for modeling and simulating some of the more complex subsystems in the overall integrated PIMS requirements. These models would be linked via information flow to other subsystems, subsystems not necessarily modeled by artificial neural networks. Figure 2 shows a possible application of neural networks to highway safety.

Municipal Infrastructure Management Systems

An integrated IMS is an important application for the management of municipal infrastructure of a town or city. Given the diversity of services provided within a typical municipality, an IMS would help city administrators and engineers effectively manage and maintain services.

The purpose of this section, therefore, is to develop a first-stage framework for a municipal IMS (MIMS), showing primary municipal subsystems. The system is shown on a conceptual level to provide a widely applicable outline. A more detailed system, including mathematical, economic, and simulation models, as well as specific details germane to particular cities or situations, is beyond the scope of this paper.

One way to visualize at the city level the integration and linkages between the different models required by ISTEA is shown in Figure 3. A representation of model interactions for the different subsystems is presented in Table 2. A strong linkage exists between public transportation and bridge and pavement management. This is illustrated in larger cities where many major streets are

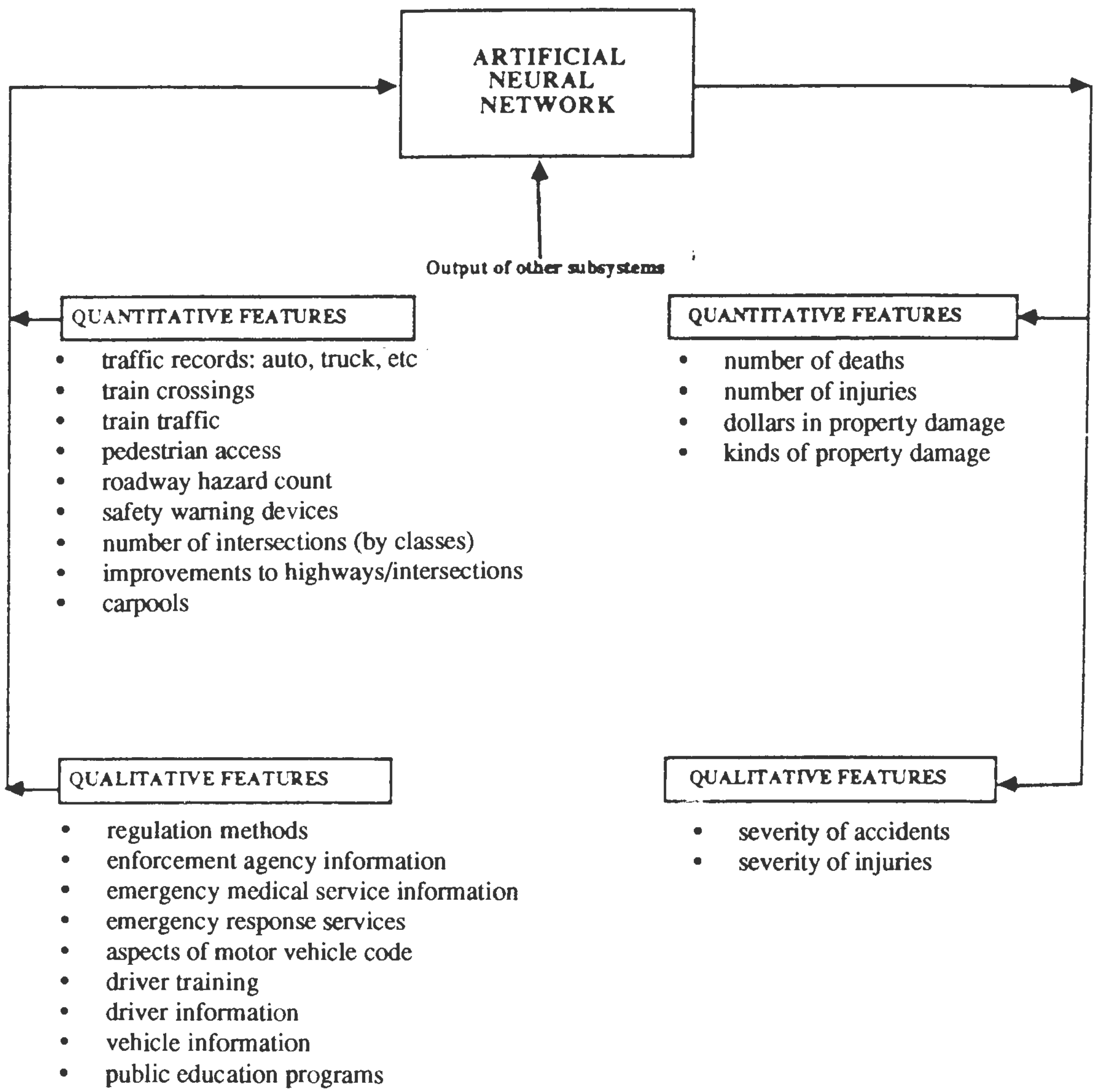

FIGURE 2 Example of artificial neural network for modeling safety management.

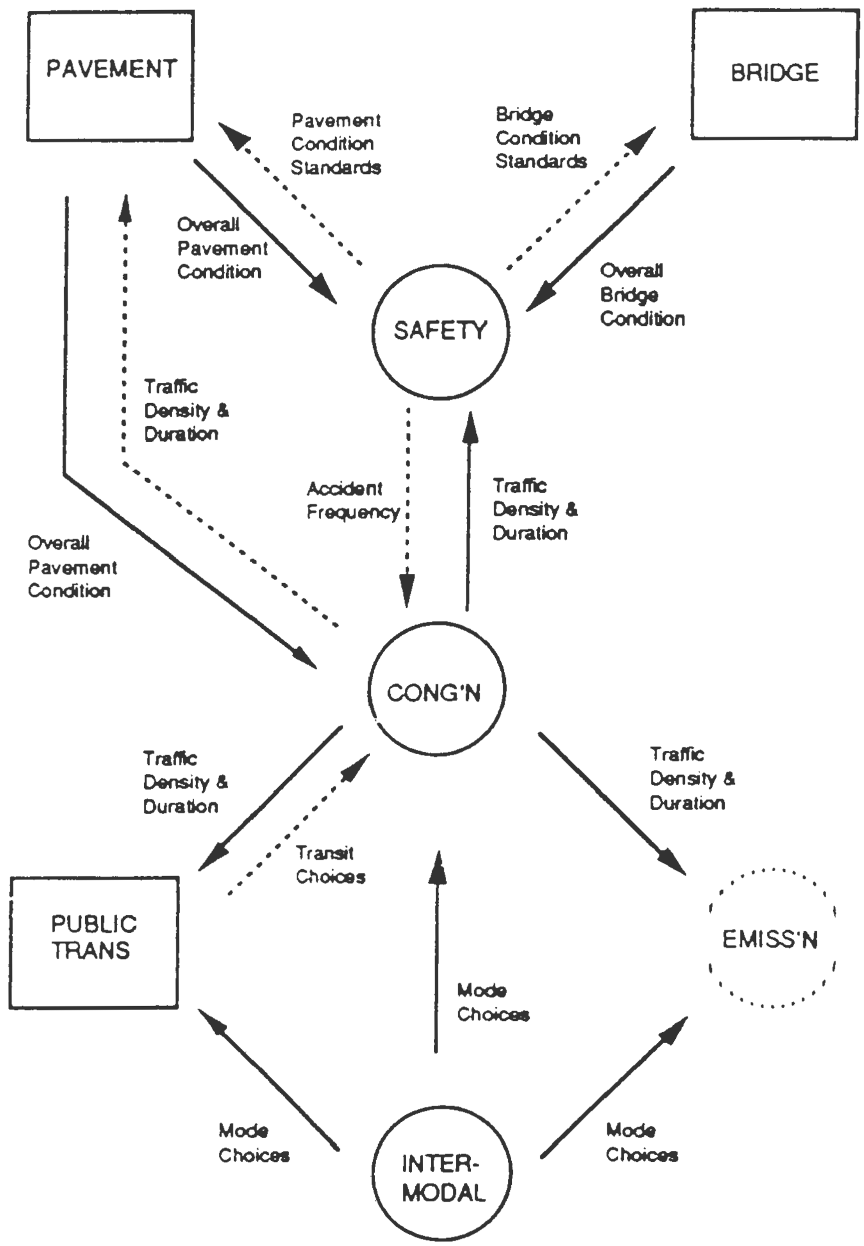

FIGURE 3 Major model integration and linkages (according to Texas Department of Transportation).

being destroyed by heavily loaded buses. Particularly, in the MPO interactions there will be strong linkages between bridges, pavement, congestion, safety, and public transportation.

Systems Definition for MIMS

One definition of municipal infrastructure in terms of "public works" given by the American Public Works Association (APWA) is as follows: "Public works are the physical structures and facilities that are developed or acquired by public agencies to house governmental functions and provide water, power, waste disposal, transportation, and similar services to facilitate the achievement of common social and economic objectives." APWA includes 18 categories of public works and environmental facilities in this definition. Following is a brief list of 6 categories of municipal infrastructure that are clustered together by industry and professional interest group:

- Roads group (roads, streets, and bridges),
- Transportation services group (transit, rail, ports, and airports),

TABLE 2 Model Interactions Among Systems

	Bridge	Pavement	Safety	Pub. Trans.	Congestion	Intermodal
Bridge	--	Major	Major	Major	Minor	Major
Pavement	Major	--	Minor	Major	Major	Minor
Safety	Major	Minor	--	Major	Major	Major
Pub. Trans.	Major	Major	Minor	--	Major	Minor
Congestion	Minor	Major	Minor	Major	--	Minor
Intermodal	Major	Minor	Minor	Minor	Minor	--
Emissions	Minor	Major	Minor	Minor	Major	Minor

- Water group (water, wastewater, all water systems, including waterways),
- Waste management group (solid waste management systems),
- Buildings and outdoor sports group, and
- Energy production and distribution group (electric and gas).

As stated before, since the objective of this paper is to explore the possibility of a comprehensive MIMS, detailed information for each of the subsystems is not considered at this stage. The potential comprehensive system and the identified subsystems are illustrated in Figure 4.

Almost all cities deal with subsystems that are normally owned or controlled by the municipality and that are commonly large enough to require network-level oversight. In this manner the five most important systems should be selected for initial development. It would be hoped that with a true MIMS, all of the categories previously identified would be developed and incorporated into the system.

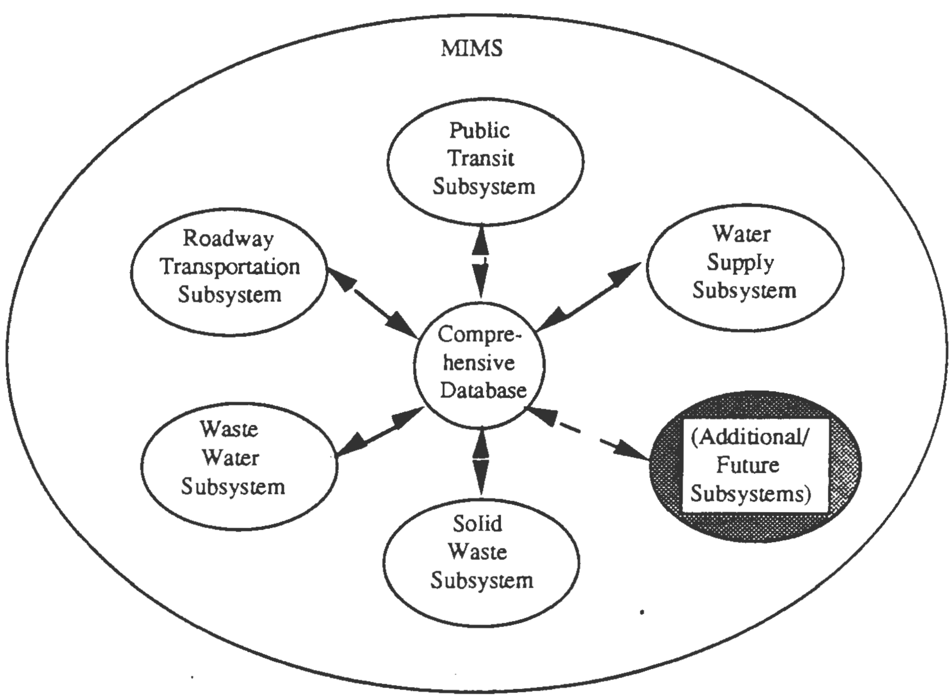

FIGURE 4 MIMS system and subsystems.

Once the system elements and boundaries have been defined, goals and objectives need to be specified. Goals can be defined as the idealized "end-states" toward which a plan might be expected to move. Objectives are operational statements of goals. They are measurable and attainable, where attainability is defined without reference to availability of resources or to budgetary restrictions. By definition, goals are broad and general, whereas objectives are precise statements of what is to be done to reach a goal. One perspective on the goals and objectives of an MIMS can be obtained through the definition of the goals and objectives of each of the subsystems identified, the overall goal being the achievement of "common social and economic objectives."

The next step in the systems development process is to develop system models. This involves the formulation, calibration, and validation of a basic system model. The model is designed to permit the prediction of the consequences of alternative plans without direct experimentation on the real-world system. At this point, the basic requirements for predicting the consequences of various alternative plans should have been developed. However, before alternatives are generated, there must be a set of criteria by which to assess goal achievement of the alternative plans.

To facilitate understanding of the requirements, models, processes, and so forth involved in each subsystem, some kind of basic systems analysis procedure or analysis flow chart should be developed for each of the subsystems shown in Figure 4.

The efficient collection and dissemination of useful and timely information is of critical importance to managing any enterprise. The most important issue for developing an overall IMS is the creation of a centralized data base that allows a flow of information to and from each subsystem and also from each activity, as needed. This results in a more comprehensive, efficient, and timely flow of information for the MIMS as a whole and for each subsystem in particular.

Although the specific information requirements of each subsystem will vary, certain broad information concepts apply to all. Each requires section identification information, in all cases a common system that allows cross referencing between subsystems. Each requires historical data on system performance and system demand and information on system-specific particulars such as design and construction parameters, geometric data, and maintenance records. Each also requires tracking of economic effectiveness and both agency and user costs of service.

Ease of integration into one common municipal data base was a consideration in the design of these data requirement elements. For future development, it is suggested that data should be classified as "required" or "desired."

GIS in MIMS

In recent years a GIS has been used in various management fields such as natural resource management, wildlife protection, and environment protection. In infrastructure systems, GIS has been applied to several areas of transportation systems, including pavements. GIS applications for an urban roadway management system (GIS-URMS) have been investigated at the University of Texas at Austin (*16*). This study demonstrated the strong potential of GIS as a platform for developing an integrated overall IMS.

GIS is a computerized data base management system specially developed for managing spatially defined data, such as shown in Figure 5. As such, its data base contains information on spatially distributed entities that occur as points, lines, or polygons, as well as tools for capturing, storing, retrieving, displaying, interrelating, and analyzing locational as well as nonlocational data. GISs have traditionally been used in natural resource management, land record management, utilities management, and environmental resource management, to name a few areas.

The three elements in GIS are these:

- *Geographical data base.* The geographical data processes three inherent characteristics: position, description, and variation with time. They can be structured in either grid (raster), vector, or triangulated irregular network (TIN) format.
- *Attribute data base.* Attribute refers to all descriptive nongeographical information (variables, names, and characteristics) that identify a geographical feature. For instance, an artificial lake can be identified by its name, water level, water quality, chemical composition, salinity, water temperature, and so forth.
- *Georelational data structure.* One of the main functions of GIS is to establish the relationship between the location of features in the geographical data base and their corresponding descriptions in the attribute data base. GIS performs the linkage between locational and attribute data by means of a georelational data structure.

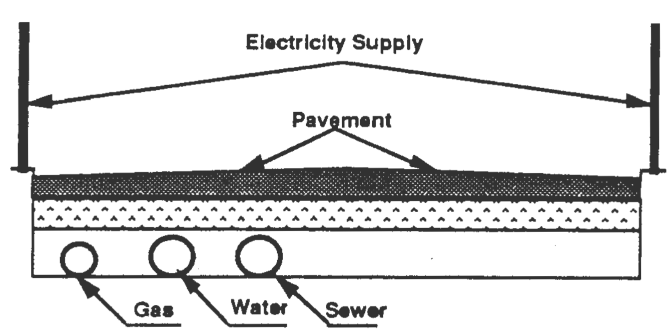

FIGURE 5 Example of common location elements of MIMS.

MIMS Central Data Base

One of the important issues in developing an overall MIMs is the data exchange and communication among the subsystems and with other external systems. The three best-known approaches for data management are the relational approach, hierarchical approach, and network approach.

The relational data base management systems (DBMS) include dBase, FoxPro, Oracle, Rbase, and others. These relational DBMS can effectively perform data exchanges and communications among the proposed subsystems through common data fields such as location ID, segment ID, or other items in the data base. Figure 6 illustrates an example integrated data base for MIMS.

UNITIZED FACILITIES MANAGEMENT SYSTEMS

The third and final area of application of overall infrastructure management is for what are called unitized facilities. These include, for example, an airport, a nuclear power plant, or a major refinery. Each of these facilities fulfills a major function but requires a number of individual, independent subsystems to function.

For example, an airport requires roads and streets, parking facilities, terminal facilities, aircraft parking aprons, taxiways, runways, aircraft control facilities, and so forth. Each type of other facilities has a number of subsystems that must be integrated to produce the required results. In this regard, the main function of an IMS is to keep track of the various subsystems and their relationships to each other. The capacity of an airport, for example, can be controlled by any one of a number of subsystems. If access roads are inadequate, the capacity of the airport suffers. If parking is inadequate, the capacity is reduced. The same can be said for buildings, check-in facilities, baggage handling facilities, the number of aircraft gates, aircraft parking facilities, takeoff and landing facilities, and air traffic control equipment.

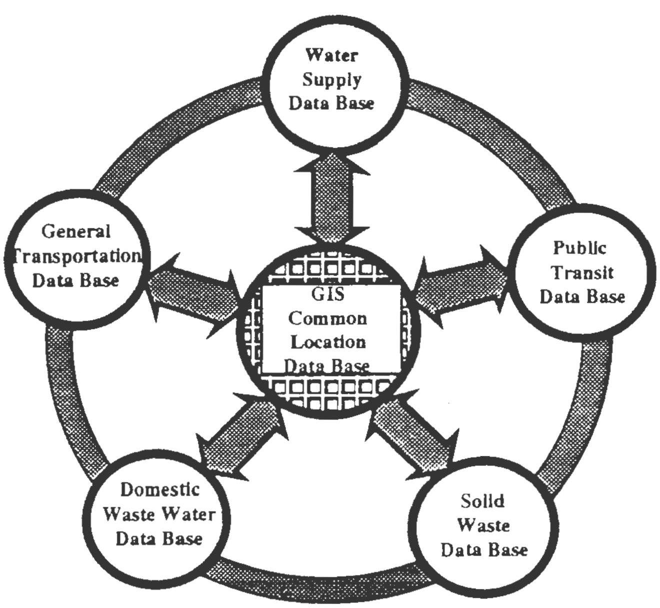

FIGURE 6 Integrated data base for MIMS.

The concepts of infrastructure management can be applied to integrate airport subsystems effectively. The function of these items includes consideration of passengers in most every case so that common data base items include scheduling of takeoffs and landings, related arrival of passengers, traffic delays, weather delays, weather information, passenger demand, and other factors.

Differences and Common Factors with Other Infrastructure Facilities

Unitized facilities are in some ways easier and in some ways harder to handle than other management system applications. Ease in handling arises from the fact that most facilities are located at a common location, such as an airport site. This is confounded when an agency such as the Port Authority of New York and New Jersey has to operate three airports within one municipal area. Nevertheless, the process of handling facilities in close proximity to each other offers a good application for infrastructure management.

Difficult aspects of the problem that differ from pavement management include the broad diversity of functions that must be addressed. In the case of airports, this ranges all the way from traffic access to the airport through baggage handling to the complexity of air traffic control. The scope of this paper does not allow the detailed examination of these common and diverse factors. However, as developers of some of the original concepts of management systems, the authors fully believe that the benefits of unitized IMSs (UIMSs) can be fully realized with a reasonable amount of research and development support.

Major related items in this regard include the potential use of geographical information systems within the facility itself to address the flow of passengers, the proximity of facilities, and so forth. A relational data base tying all of the factors together is also critically important to UIMS.

A major need in UIMS is that for models describing the operation of each of the individual subsystems. However, such models are already required for operating the facilities without a UIMS. In other words, attempts to create UIMS do not increase the difficulty in developing individual models. It does make explicit the need for such models, and it does require the management team to consider the input and output of the individual models and their interactions carefully. However, as previously discovered in bridge management and pavement management facilities, although this explicit requirement tends to make the current operating team uncomfortable and seems to apply a certain amount of pressure, it is very beneficial in requiring explicit consideration of major factors.

In summary, although UIMS is the least developed of infrastructure management systems, it offers the most potential. Private companies such as Wal-Mart have developed, to some degree, a UIMS for handling their inventory of goods and services. They have also used study methods to develop a common store configuration and common training methods so that uniformity will exist throughout their companies over large geographical areas. It is recommended that consideration be given to UIMS development, particularly for public facilities such as airports and for facilities such as nuclear power plants that require extensive public regulation. A UIMS can, for example, consider disposal of waste better than any independent study can. The steps involved include the following: (*a*) apply principals for general management systems as presented herein, (*b*) define all aspects of the facility, (*c*) properly model the system being managed, (*d*) develop a specific data base for the system, (*e*) evaluate the problems that will occur, and (*f*) build in monitoring procedures to evaluate and correct problems in the most cost-effective manner in terms of action and timing.

Implementation, Institutional Issues, and Problems

Considerable effort has been invested in the development and implementation of pavement and bridge management systems. Nevertheless, as pointed out by many authors (*17,18*), the greatest problems associated with the successful implementation of pavement management systems are institutional issues. Many agencies that started development of PMS in the mid-1970s or early 1980s are still ineffective in using their PMS. It is necessary to address the problem of institutional issues and the reluctance of agencies to change, to help ensure that the integrated systems developed in the future are implemented. Space does not permit this paper to address the issue in detail. It is dealt with by others elsewhere. Clearly the systems required by ISTEA cut across all the existing organizational and operational aspects of agencies, making the need for an adequate implementation plan even more critical.

Summary

The development of pavement management began in the mid-1960s. This development took about 10 years to show significant progress. From that point, much implementation has taken place. Following pavement management, bridge management moved forward and has developed to an implementation stage more rapidly.

Current developments, particularly requirements by FHWA to implement as many as seven management systems within a state DOT, clearly point out the need for infrastructure management. The history and knowledge developed from pavement management clearly leads the way to such developments and properly utilized will pay big dividends. These applications can clearly be seen in state DOTs and in municipal infrastructure management systems, as fully discussed in this paper. Less clear but equally applicable, in the authors' opinion, is the use of pavement management concepts to develop UIMSs for application to airports, nuclear power plants, port facilities, and so forth. This is particularly important in public facilities and facilities, such as nuclear power, requiring public supervision.

It is recommended that research funds be made available in the very near future for a research project designed to develop organized integration packages for infrastructure management as outlined in this paper.

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Contract Road Maintenance in Australia: A Pilot Study

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Road maintenance in Australia has traditionally been undertaken directly by the labor forces of the responsible authority. In 1990 the Roads and Traffic Authority (RTA) of New South Wales decided to undertake a pilot study to determine the efficacy and efficiency of contract road maintenance. The innovative features of the pilot project in the Australian context are described. For the evaluation that took place during the 12-month pilot study, the western sector of the Sydney region's main road and state highway network was divided into three parts: (*a*) a network maintained by a contractor under the management of private sector project managers—the contract network; (*b*) a network maintained by the RTA work force under the management of private sector project managers—the works center network; and (*c*) the balance of the network maintained by the RTA work force under the management of RTA personnel—the base network. The pilot project proved the feasibility of contracting the full range of road maintenance activities, demonstrated that the performance of the contractor was at least equal to that of the RTA work force, resulted in a significant improvement (22 percent) in the efficiency of the RTA work force through the application of contractual work methods and the exposure to competition, and demonstrated improvements in maintenance effectiveness through the separation of accountability for road maintenance management and resource management.

Road maintenance in Australia has traditionally been undertaken directly by the responsible authority, with minimal contracting out of services. The contracting out that has taken place tended to be for major items such as asphalt resurfacing, bitumen spraying, or plant hire.

With the need to ensure efficiency and effectiveness in the allocation of road funding in the tightening economic climate, the Roads and Traffic Authority (RTA) of New South Wales called worldwide for expressions of interest to examine the feasibility of road maintenance by contract in part of the Sydney arterial road system. CMPS&F Pty Limited, together with specialist subconsultants, was engaged to undertake the study and subsequently the project management of the network on behalf of RTA. The initial study began in late 1990, with contract maintenance starting on July 1, 1991. The evaluation period ended on June 30, 1992, with contract road maintenance a continuing feature of the RTA maintenance program.

British Columbia, Canada, instituted total contract road maintenance at about the same time that this pilot was conceived (*1*). Lincolnshire County, U.K., is one of several U.K. authorities that has successfully contracted out road maintenance and engineering services (*2*).

This paper concentrates on the applicability, benefits, and costs of contract road maintenance to the pavement management process. It is based on internal CMPS&F and RTA documents.

Pilot Project

In Australia, maintenance of the major road network traditionally has been undertaken by the various state road authorities using their own labor forces. Most of the states are now in various stages of implementing contract road maintenance. The project implemented by RTA in 1990 was the first such project in Australia. It incorporated features that were, at the time, unique in Australia and, as best can be judged, were state of the art worldwide. As the project evolved, the need arose for a comprehensive evaluation of the efficiency and effectiveness of contract road maintenance.

The pilot project was extended to encompass three road networks comprising the whole of the state road network in the western sector of the Sydney region. The pilot project comprised three parts:

1. The contract network: a network (99 km) of classified roads (i.e., main roads and state highways) maintained by a contractor (Boral Asphalt Ltd.) under the management of private sector project managers (CMPS&F), funded from state and federal sources;
2. The works center network: a network (100 km) of classified roads maintained by the RTA work force under the management the project managers, funded from state sources; and
3. The base network: the balance of the classified road network (873 km) maintained by the RTA work force under the management of RTA personnel, funded from state and federal sources.

The networks consisted of a hierarchy from heavily trafficked freeways and urban arterial roads to rural main roads. The road surfaces were either asphalt (urban and heavily trafficked rural roads) or chip seal (spray seal or aggregate seal; rural main roads). RTA's choice of roads for the contract network was based on a shortage of RTA maintenance personnel and an expansion of the road network. The area was chosen to cover the full range of pavement types found in the Sydney metropolitan area. The roads in the works center network were chosen by RTA to mirror those of the contract network as closely as possible.

Innovative Contract Features

The full detail of the initial study, development of the contract documentation, and the evaluation of the bidders are given by Brooking (3). The discussion that follows concentrates on the innovative features of the contract and the rationale behind the bid documentation.

Type of Contract

The ideal bidder would be a lump sum bidder with the contractor responsible for the performance of the network over a 5-to-10-year period. This approach was rejected by the consultant early in the study and before the development of contract documentation. The reasons for rejection of a performance contract were as follows:

- Budget levels were not known and could not be guaranteed;
- Even if the budget was known, the actual level of funds provided could fluctuate depending on available funds and government priorities;
- The pavement conditions were quite variable, and the records of pavement structure, especially after major rehabilitation, were incomplete;
- The inventory of such items as signs, markings, drainage structures, and roadside furnishings was not available at the time of preparation of the documents, although this has since been rectified;
- The detailed maintenance history of the network was unavailable;
- A performance contract should be over an extended period of at least 5 years, whereas the initial contract for the pilot was to be for 2 years only;
- Detailed consideration would have to be given to risk sharing and to the contract conditions to ensure that the network, at the end of the contract, was in appropriate condition;
- The potential for claims for latent conditions was high because the maintenance contractor did not construct the road.

In light of these factors the decision was made to prepare the contract as "a schedule-of-rates contract with provisional quantities." The only work that was guaranteed was the establishment cost, which was a lump-sum item. All other work was to be undertaken only when initiated by the project manager.

Following discussions with the contracting industry, it was decided that a single contract incorporating all maintenance items was feasible, rather than a number of smaller contracts for specific items. This arrangement had the advantage of significantly reducing contract administration costs. The contract would cover all aspects other than the specialized maintenance tasks associated with traffic signals and bridges.

It was decided that the appropriate quality system was a quality assurance system that was in accordance with Category B of Australian Standard AS 2900, which was the standard adopted by RTA in its contract. The contract was, therefore, one of the first major road maintenance contracts in a quality assurance mode let in the world.

Traffic Control

One of the difficulties to be faced with the contract was that of traffic control. The type of traffic control is very dependent on the prevailing traffic conditions and the maintenance activity being undertaken. In addition, the responsibility for traffic flow and road closure resides with the New South Wales police and not RTA. Experience has shown that police officers have, at times, ordered the cessation of maintenance tasks that were causing traffic delays so that a road could be opened. It was decided, therefore, to include traffic control as separate schedule items to allow for different levels of traffic control. It was also decided to place the liability for liaison with external authorities with the contractor.

Project Management

It was deemed that the only way to control costs was to make the project manager responsible for allocating all maintenance tasks. The tradition in Australia is to provide road patrols that travel the network, undertaking routine maintenance tasks as they arise. This means that funds are not necessarily allocated to the highest-priority works.

RTA considered that the most appropriate structure for the engagement of the project manager was via quality assurance terms. This required the project manager to prepare a detailed quality plan for all activities, including inspection, planning, instructions for work, and contract administration.

To assist in project management, a Maintenance Code of Practice was prepared by CMPS&F for the contract network. The code was subsequently developed for use throughout the Sydney region. A modified version was recently adopted throughout RTA, and other Australian state road authorities are also adopting maintenance codes of practice.

A further innovation in project management was the implementation of a detailed inspection and recording system that allowed for detailed tracking and recording of all maintenance tasks and provided a photographic record of the site. This system has meant much greater focus in the technical aspects of maintenance, including attention to the need for long-term rather than short-term solutions. For instance, continual pothole repairs at a site can be readily identified and an alternative, more effective maintenance or rehabilitation treatment such as heavy patching can be specified.

Maintenance Code of Practice

The Maintenance Code of Practice that was prepared ensures that the various maintenance activities are given the appropriate priority. The code bases the assessment of need on road condition and road hierarchy (i.e., traffic volume and importance). It should be remembered that the code of practice is a dynamic document that must be reviewed continually and that must be refined as new information becomes available.

In general, each major asset item was considered under the headings of (*a*) aim, (*b*) work type, (*c*) assessment of need, or (*d*) level of service/level of provision.

Two examples from the contract network Maintenance Code of Practice prepared by CMPS&F are presented here. Table 1 provides the suggested intervention standards for pavement and sealed shoulder rehabilitation. Table 2 provides the standards for assessment of need and

TABLE 1 Intervention Levels for Pavement and Sealed Shoulder Rehabilitation

Road Hierarchy	Pavement Type	Length Affected	Treatment
Freeway	Flexible	> 50% (Note 1)	Pavement Rehabilitation/Heavy Patching
Major Arterial } Minor Arterial } Rural }	Flexible	> 50% (Note 2)	Pavement Rehabilitation/Heavy Patching
Major Arterial } Minor Arterial } Rural }	Rigid	> 50% (Note 3)	Slab Replacement

Note 1 Exhibiting extensive moderate cracking and/or extensive moderate rutting and/or extensive road surface defects and/or IRI roughness greater than 3.4 mm/m.

Note 2 Exhibiting extensive extreme cracking and/or extensive extreme rutting and/or very extensive local surface defects and/or IRI roughness greater than 6.0 mm/m.

Note 3 Exhibiting extensive extreme cracking, stepping and spalling.

TABLE 2 Intervention Levels and Response Time for Temporary Repairs and Emergency Callouts

Road Hierarchy	Defect Type	Limitation of Severity	Treatment	Response Time
Freeway	Pothole	< 30 mm deep	Pothole Repair	28 days
	Pothole	30-75 mm deep	Pothole Repair	24 hours
	Pothole	> 75 mm deep	Pothole Repair	4 hours
All roads other than Freeway	Pothole	< 30 mm deep	Pothole Repair	Only repair if traffic safety problem and then within 24 hours
	Pothole	30-75 mm deep	Pothole Repair	24 hours
	Pothole	> 75 mm deep	Pothole Repair	4 hours
All roads	Local rutting and other defects	Significant effect on traffic or pedestrian safety	Patch	24 hours
Freeway	Local rutting and other defects	No significant effect on traffic or pedestrian safety	Patch	3 days
All roads other than Freeway	Local rutting and other defects	No significant effect on traffic or pedestrian safety	Patch	7 days

the response times for temporary repairs and emergency call-outs. Condition is rated in accordance with RTA standard rating procedures (*4*). Significant changes have since been made in the new codes in light of experience gained with the original Maintenance Code of Practice and through widespread discussion of the principle of a code within RTA. As discussed later in the sections on Effectiveness and Efficiency, the implementation of the code of practice has assisted in moving the maintenance priorities from routine maintenance to structural maintenance.

Initial Evaluation

An initial study, completed in February 1992, assessed performance over the initial 6-month period, up to December 31, 1991, and provided a basis for the final evaluation. Key findings from that study, which are also relevant to the final evaluation, are as follows:

- The "as and when required" nature of the contract ensures that only priority works are undertaken and that organization constraints do not drive the works schedule. As a result, 5 to 10 percent more of available funds were budgeted to structural maintenance of pavements under the contract work practice than under traditional practice.
- A sample of valid work instructions showed the cost of maintenance by the contractor to be approximately 16 percent less than the cost of equivalent work by the works center working under contract conditions.
- There are no historical data that allow the effectiveness of one system to be compared with that of another. However, if the productivity of increasing the proportion of the budget spent on structural maintenance work (conservatively estimated at 5 percent) is added to that of quality management (estimated at 5 percent) and to the base cost reduction of 16 percent, the total cost of maintaining networks in similar condition should be reduced by about 25 percent.

Pilot Establishment

Road Condition

Road pavement condition on roads within the Sydney region is monitored using the laser road surface tester (RST). The laser RST performs a continuous survey of the road pavement, reporting condition parameters of roughness, rutting, texture, and cracking.

Detailed road condition data for the 3 years preceding the beginning of the pilot study (1989 to 1991) and at the completion of the pilot study (1992) are presented in Table 3. The following indicators are used:

TABLE 3 Road Condition Trends

	1989 % Length	1990 % Length	1991 % Length	1992 % Length
Contract Network				
Roughness <150	99.8	99.4	99.2	99.2
Roughness <110	99.1	96.6	95.0	95.6
Rutting < 10	98.6	97.3	97.0	94.6
Cracking < 50	74.9	75.1	77.2	75.1
Texture >0.15	43.2	41.6	49.5	59.9
Works Centre Network				
Roughness <150	99.9	97.7	98.0	98.0
Roughness <110	95.7	89.5	88.5	87.3
Rutting < 10	95.5	90.1	91.4	87.4
Cracking < 50	62.3	62.4	63.3	60.8
Texture >0.15	57.0	64.8	61.0	67.6
Base Network				
Roughness <150	95.9	94.6	95.8	94.7
Roughness <110	85.0	82.4	83.6	82.1
Rutting < 10	97.5	92.6	94.0	90.4
Cracking < 50	50.2	63.2	58.4	57.7
Texture >0.15	72.4	74.3	70.9	73.3
Total Network				
Roughness <150	96.6	95.7	96.4	95.6
Roughness <110	87.4	85.2	85.4	84.1
Rutting < 10	97.4	93.0	94.1	90.5
Cracking < 50	53.8	64.9	61.0	59.9
Texture >0.15	68.1	68.5	67.5	71.3

- Road length with roughness less than 150 counts per km,
- Road length with roughness less than 110 counts per km,
- Road length with maximum rut depth less than 10 mm,
- Road length with mean microtexture greater than 0.15 mm, and
- Road length with cracking index less than 50.

Care must be taken with the interpretation of road condition indicators because of the small size of the contract and works center networks. For example, a 1 percent change in road condition represents a change in condition of 760 m, 1000 m, and 8490 m of road on the contract, works center, and base networks, respectively.

In the year before the pilot project began, road condition on all roads was stable; there had been no measurable deterioration or improvement. When the pilot study began, the contract network was in better overall condition than the works center and base networks.

Budgets

Budgets for the maintenance of each of the pilot networks were allocated to the maintenance managers (for the contract and works center networks) and to the Yennora maintenance unit (for the base network) at the beginning of the project. These budgets were based on a historical analysis of expenditures on the roads in the contract and works center networks; that analysis was supported by another, in which pavement management techniques were used. Through these techniques and an inventory-based budgeting approach, the desirable level of funding was determined for each network. This information provided a guide to the relative level of funding on each network and would account for the different condition profiles on each network.

Comparison of the assigned and desirable budgets indicates that the total assigned budgets on the contract, works center, and base networks were 63, 67, and 74 percent, respectively, of the desirable budgets. Within these budgets the structural pavement maintenance budgets were 69, 79, and 86 percent, respectively, of the desirable structural pavement maintenance budgets.

EFFECTIVENESS

Weather

The most critical environmental factor affecting road maintenance is rainfall. Variation in rainfall over location or time can result in substantial shifts in the nature and extent of road maintenance activity. Rainfall data obtained from the Bureau of Meteorology for permanent stations representing the pilot networks are presented in Table 4.

On the contract network rainfall was 135 mm (15 percent) less than the annual average, occurring over 13 (12 percent) fewer days. However, on the works center and base networks, rainfall was greater than the annual average by 217 mm (27 percent) and 107 mm (13 percent), respectively, occurring over 28 (35 percent) and 9 (8 percent) more days, respectively.

The recorded rainfall profile differed from the average profile, although the period of very high rainfall coincided with the average "wet" period. On the contract and works center networks, the monthly rainfall was below the annual average for 9 and 8 months, respectively. On the contract network 40 percent of the recorded annual rainfall occurred during February, whereas on the works center network 25 percent occurred in December and an additional 35 percent in February.

The impact of rainfall patterns on the performance of a road network is related closely to road condition. Road pavements susceptible to damage from moisture penetration may deteriorate because of either prolonged or above-average rainfall, whereas pavements not susceptible to moisture damage may not be affected. Analysis of pavement types on the pilot networks indicates a high degree of moisture susceptibility on the base network, with susceptibility ratings of medium and low on the works center and contract networks, respectively.

TABLE 4 Rainfall Data for Pilot Networks

Network	Station	Recorded		Average	
		Rainfall (mm)	Days	Rainfall (mm)	Days
Contract	Liverpool	757	95	892	108
Works Centre	Penrith	1026	109	809	81
Base	Richmond	925	120	818	111

Maintenance Responsiveness

As a result of the amount of rain during February 1992, severe flooding of the Nepean/Hawkesbury and Georges river systems occurred. In particular, extremely heavy rainfall was recorded over 2 days. Flooding of the two major river systems was exacerbated by severe local flooding. On the pilot networks, lane and road closures were effected on February 9, 1992.

This flood event demanded a high level of emergency response for the authority; unplanned response was required to handle a large number of problems over an extended period. During the event, control of the situation was assumed by State Emergency Services, which indicated that there was no evidence of any loss in responsiveness by the authority through its use of private sector maintenance managers and contractors. On the base network the authority's work force also responded to similar situations in an efficient and effective manner, to the complete satisfaction of State Emergency Services.

Activity Profile

One measure of maintenance effectiveness is the distribution of actual maintenance expenditures. The primary objectives of road maintenance are measured in terms of road condition and road safety, correlating with the structural and safety subprograms. Effectiveness is therefore increased when the proportion of expenditures on structural and safety activities is increased by means of reallocation of funds from other subprograms.

An analysis of the distribution of the assigned budgets to classes of work was undertaken. The works-scheduling technique on the contract and works center networks allocated resources on an "as and when required" basis, whereas on the base network, the need to utilize dedicated resources fully was a constraint on works scheduling. As a result, on the contract and works center networks, priorities were established for funds for structural and safety works. On the base network, funds allocated to structural activities were rescheduled to lower-priority activities to utilize available resources. This result was consistent with the findings of the progress report, which reported a diversion of funds of about 5 to 10 percent.

Public Inquiries

All public inquiries regarding the region's operations are recorded by the Public Relations Unit at Blacktown. Based on the data the number of "pavement inquiries per lane-kilometer" is 0.10 on the contract network, 0.07 on the works center network, and 0.09 on the base network. This is inconsistent with the measures of pavement condition, but it may indicate a community tolerance that is lower with respect to defects on roads of generally good condition than to defects on roads of poorer condition. Further investigation of this effect is warranted.

The number of inquiries per kilometer of road that relate to the drainage and environmental subprograms is 0.68 on the contract network, 0.78 on the works center network, and 0.59 on the base network. The base network comprises a larger proportion of rural roads, so a lower number of these inquiries is expected because such inquiries generally come from adjacent residents. The recorded difference in the pilot networks supports this expectation and does not indicate a significant difference in community opinion resulting from the shift in maintenance emphasis described earlier. As a result, the level of public inquiries is not a good performance indicator of the success of contract maintenance.

Road Condition

A survey of road condition was undertaken by the laser RST in July 1992, immediately after the conclusion of the pilot period. Analysis of the trend in road condition indicates that no change occurred during the pilot. Minor variations were measured (1 percent improvement on the contract network and 1 percent deterioration on the works center and base networks), but these have no statistical validity.

It is difficult to draw conclusions from this result, given the complex set of variables that contribute to short-term changes in road condition. The marginal improvement in road condition on the contract network may be due to the increased emphasis in structural maintenance, the lower-than-average rainfall, and the lower susceptibility of the road pavements to moisture damage. On the works center network the increased emphasis on structural maintenance may have been offset by higher-than-average rainfall, whereas this effect on the base network, compounded by high susceptibility to damage and decreased emphasis on structural maintenance, may have led to the slight deterioration in road condition.

At this early time there is no tangible evidence that the maintenance practices used during the pilot study have contributed directly to the recorded road condition. Logically the long-term effect of an increased emphasis on structural pavement maintenance would be an improvement in road pavement condition.

Work Quality

During the term of the pilot study the works center did not introduce a quality system for work on the works center or base networks. For this reason a comparative evaluation of the work quality of the contractor and the works center is not possible.

The quality of work on the contract and works center networks was monitored by the maintenance managers. On the contract network, for which the contractor established an approved quality system, the maintenance manager performed audits of the system, conducted ad hoc inspections of work in progress, and did random sampling of the finished product. The maintenance manager also responded to designated hold points in the system. On the works center network the role of the maintenance manager was limited to inspection and sampling of the work.

Under these arrangements the contractor and works center accepted and corrected nonconformances noted by the maintenance managers. There is no evidence of any short-term difference between the quality of work provided by the contractor and that of the RTA work force. In the longer term the emphasis on structural maintenance and design of repairs should lead to an increase in the quality of the contract and works center networks.

EFFICIENCY

Overhead

A comparison of costs between road maintenance agencies must be equitable and must ensure that competitive neutrality is retained. It is therefore important that overhead be brought to account against both the contractor and the authority's work force.

The contractor submitted a bid of scheduled rates for each of the pay items in the contract. All of the contractor's operating overhead is recouped through income; hence it can be assumed that the rates bid include allowances for operating overhead. Failure by the contractor to adequately allow for overhead in the rates bid would mean a loss of potential profit or the higher loading of rates on other works, in turn decreasing the chance of a successful bid.

The contract schedule of rates makes provision for some activities of an overhead nature, specifically, the provision and operation of the project quality system. These items, however, are project-specific and, being paid as contract items, avoid duplication of overhead.

There is no provision within the contract for the payment of overhead costs such as job site charges and idle plant outside of the bid unit rates for specific road maintenance tasks. Hence, the payments made to the contractor for each item of work are the full costs to the authority for that item of work.

The total real cost to the authority for any item of work includes the overhead applicable to that work from all levels of management within the authority. However, for the purpose of a comparative evaluation of work methods, it is only necessary to consider those overhead costs that differ when applied over the organizations being compared.

A detailed analysis of the corporate, regional, operations, and works center overhead was undertaken, concentrating on the differentials between contracted work and direct control work. Actual costs and elements of costs were adjusted to take account of all overhead so that a true comparison could be made.

Direct Cost Comparison

The comparison of the efficiency of the contractor and the works center was achieved by comparing the actual cost to RTA for undertaking works with the contract bid rates for that same work.

Site instructions were issued by the maintenance management team for all works on the contract and works center networks. On the works center network these instructions were implemented by the works center, and hence it was possible to compare the actual works center cost with the value of the site instruction at the contractor's bid rate.

On the issuance of each site instruction, a unique cost heading was established in the authority's costing system. The form of the cost heading was a concatenation of the activity code and the unique site instruction number (e.g., "12310726" for site instruction number 726 for pavement patching work). All costs associated with that instruction were then collated by the system using the time sheet information supplied by the work gangs and the overhead costs applied in accordance with the preceding analysis.

At the completion of each site instruction, the maintenance manager and the works center formally agreed on the actual quantities involved in each item of work under the site instruction. Using the agreed-upon final quantities costed at the contractor's bid rates, the contractual cost of the site instruction was determined and was compared with the works center costs.

Table 5 presents the actual RTA and contractor costs as bid for the valid and matching data sets from the measurement of work information and the costing system, listed by activity, and summarized by maintenance subprogram. Only those activities actually used on the works center network are shown. These data represents performance over the second 6 months of the pilot study, from January 1, to June 30, 1992.

Table 6 extrapolates the cost differentials reported in Table 5, representing the valid data sample, over the actual 1991–1992 maintenance program expenditure on the works center network. It indicates that the total delivery cost of that program by the RTA work force was 6 percent less than the equivalent delivery cost by the contractor.

TABLE 5 Comparison of Costs

Sub-Programme	Activity	Contractor Cost $	RTA Cost $	% Difference
Structural	1200	92320	55801	- 40
	1210	3525	3013	- 15
	1230	47850	54037	+ 13
	1231	505025	477566	- 5
	1232	19951	13068	- 34
	1250	4150	2247	- 46
	1260	3122	1871	- 40
	Sub-Total	675943	607603	- 10
Drainage	1500	3120	8422	+170
	1510	723	2201	+204
	1990	149	456	+206
	Sub-Total	3992	11079	+178
Safety	1610	134244	76080	- 43
	1630	3808	4078	+ 7
	3100	1441	7123	+394
	3120	1644	3990	+143
	3130	2157	7581	+251
	3200	1684	387	- 71
	Sub-Total	144998	99239	- 32
Environmental	1560	2221	1409	- 37
	1570	35154	16919	- 52
	1930	15281	20177	+ 32
	Sub-Total	52656	38505	- 27
TOTAL:	ALL	877589	756426	- 14

Note: + Difference means contractor cost less than RTA cost.
- Difference means RTA cost less than contractor cost.

As indicated earlier, the initial evaluation found that the cost of work by the contractor was 16 percent less than that of the same work by RTA under identical work practices over the initial 6 months of the pilot study. As indicated previously, over the second 6 months the cost of work by the contractor was 6 percent more than the cost for the same work by RTA. This indicates that the RTA work force improved its productivity by 22 percent through improved management and refined work practices, directly resulting from the exposure to competition under the pilot study.

Prospects for Future Change

As indicated, the RTA work force recorded an improvement in productivity through changes directly related to the

TABLE 6 Expenditure Comparison, Works Centre Network

Sub-Programme	Total Expenditure (%)	RTA/Contractor Cost	Adjusted Proportion (%)
Structural	56	0.90	50
Drainage	7	2.78	19
Safety	31	0.68	21
Environmental	6	0.73	4
TOTAL:	100	-	94

exposure to competition. The contractor's cost were at rates bid in January 1991, 6 months before startup of the pilot study and were based on the contractor's expectation at that time of the budgetary position, management of the network, and site difficulties. Given that RTA, highly experienced in road maintenance work, was able to improve productivity by such a substantial amount, it is reasonable to expect that contractors will also be able to refine work practices to improve productivity, although an assessment of that improved productivity is not possible at this time. The experience and knowledge gained by the maintenance contractor would be significant. Competitive market forces should see these gains being passed on to the authority in future bids.

Ongoing contracting of road maintenance will create a competitive environment and result in improved productivity for all maintenance work. Continued evaluation of the performance of internal and external maintenance service organizations is required so that the appropriate mix of organizations is established on a geographic or activity basis.

Impacts of Contract Maintenance in Sydney Region

The road maintenance contract pilot study has had short- and long-term impacts on the operation of the Sydney region. It was apparent that the management and staff of the Yennora works centre responded to the pilot study by critically assessing work practices and making adjustments to improve overall efficiency, resulting in the reported improvement in productivity of 22 percent. In addition, the increased emphasis on structural maintenance works resulting from the adoption of contractual maintenance management procedures reduces the amount of amenity works. Structural works, by their nature, demand a greater use of plant and materials than labor-intensive amenity works.

Arising from the pilot study, the combination of increased productivity and the shift to less labor-intensive activities has resulted in an initial reduction of RTA staff, with 35 employees being granted voluntary redundancy in September 1992. This represented an 18 percent reduction in the road maintenance work force of the Yennora works centre.

At the time of preparation of this paper, the Sydney region was in the process of implementing an organizational review designed to improve the efficiency and effectiveness of its operations, focus the region on its core business, eliminate activities that can be undertaken more cost-effectively by the private sector, and eliminate duplication of activities. The road maintenance contract project has had a significant impact on that review.

The maintenance organization in the new regional structure is completely based on the contractual structure and relationships implemented for the pilot study. Three distinct organizational units have been established, emulating the roles of the region's Road Asset Unit, the private sector maintenance manager, and the contractor. This will ensure that the region's maintenance operations are managed in a competitive manner that provides for the ongoing evaluation of performance. Private sector and public sector resources will be placed on a similar operational basis so that the appropriate mix of private and public sector resources can be established, monitored, and reviewed.

The Future

The performance of the road network is complex. Road condition reflects interrelationships between budgetary, environmental, quality, structural, and management variables. The structural variable represents the nature and age of the asset, and is fixed, although not entirely known, and in the case of the networks it is not well documented. The environmental variable cannot be reliably predicted, but it can be modeled in the longer term. Therefore, for a given style of management there is a relationship between the maintenance outcome, road condition, and budgetary input. Improved understanding of this relationship would lessen the risk to the authority in terms of liability for road defect and conditions.

The retention of total budgetary control by the authority within the contractual arrangement adopted for the pilot study has not allowed RTA to share any of its liability for road defects with the contractor. However, the maintenance manager and the contractor are liable for events resulting from negligence on their part.

A more desirable arrangement would be RTA and the contractor's sharing of the risk and liability for road condition and defects over a number of years. This would necessitate the transfer of a degree of the budgetary control from the authority to the contractor or project manager. An appropriate mechanism for this style of arrangement is the performance-based contract, by which the contractor and the authority agree on a budget/condition relationship, with the contractor accepting the risk of maintaining the defined condition within the agreed budget over a period of 5 to 15 years.

For such a project to be successful, it is essential that as much information on the network as possible be available in order to control the contractor's risk. Information on the following should be collected:

- Pavement condition,
- Pavement structure,
- Maintenance history, including routine maintenance, and
- Traffic history.

This information is quite incomplete for the Sydney road network.

Conclusions

The pilot project achieved the following:

- It proved the feasibility of contracting the full range of road maintenance activities.
- It demonstrated that the performance of the contractor, previously inexperienced in large-scale works of this nature, was at least equal to that of the authority's work force.
- It resulted in a significant improvement in the efficiency of the authority's work force through the application of contractual work methods and the exposure to competition.
- It demonstrated improvement in maintenance effectiveness through the separation of accountability for road maintenance management and resource management.

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Future Directions and Need for Innovation in Pavement Management

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Research costs money, innovation saves money, but good research produces innovations. That is our theme. When we speak of research needs, we need to think of the innovation that can result from research well done. Emphasis in highway research and particularly pavement management research for the past 20 years has been on short-term needs and implementation. Lack of support for intermediate and long-term efforts has left the industry, in 1994, facing many of the same problems it faced in 1970. Pavement management has progressed from a concept in the 1960s, to a working process in the 1970s, to a significant degree of implementation in the 1980s. The principles have been formulated and much has been learned from implementation experience at the federal, state or provincial, and local levels in various countries. By the year 2000 many more agencies will have adopted pavement management systems (PMSs). But the improvements in application and implementation have not been matched by improvements in the component technology of pavement management. For example, good, long-term performance prediction models are still unavailable at the time of writing. A substantial amount of innovation is necessary if we are to realize a standardized pavement management process with widespread or universal applicability. Such a PMS must have comprehensive technical underpinnings, but sufficient flexibility for tailoring to individual agency needs and resources. The required innovation and research should range from short-term problem solving to strategic efforts for technology and application improvements. An outline for a program of research to develop innovations that can achieve the desired improvements is presented. The changing nature of pavement research and the associated needs are reviewed; a standardized structure for pavement management is described within which the component activities, and research toward their improvement can be incorporated. The major types of research that must be carried out for a successful program of improvements in pavement management technology and application are described, the major elements of successful pavement research are defined, and some of the opportunities for innovation and major advances in pavement technology and application of the process are identified.

Research costs money, but innovation properly implemented saves money. Good research produces innovations. The key term may be research, but we should think of the resulting innovation and vice versa. In essence, speak of research needs, think of the innovation that can result from research well done and implemented. Once good research is formulated and carried out, the key is implementation. Good research involves at least four levels of activity.

1. Long-term research required to solve problems that cannot be dealt with in any other way,
2. Intermediate-term research requiring 5 or more years to solve problems of some depth,
3. Short-term research to get quick answers, and
4. Problem solving and technology development.

All of these levels of research have a training and implementation aspect. Any good finding must be implemented and that involves technology transfer and training issues.

The emphasis of pavement management research for the past 30 or more years has largely been on short-term needs. The AASHO Road Test was the premiere major research effort with long-term emphasis and adequate funding to actually solve the problem it undertook and define the limitations of the results. Defining the limitations of the results of research is also critical to good implementation. Lack of support for intermediate and long-term research implementation in recent history leaves the industry facing, in 1994, many of the same problems it faced in 1972.

The increased number, size, and weight of vehicles operating on U.S. highways today have significantly increased pavement maintenance and rehabilitation (M&R) costs. Construction practices and materials used in most existing highways may not provide adequate performance in the presence of modern heavy loaded vehicles. This is especially true if legal load limits are allowed to increase even further. The M&R needs of existing pavements must be reevaluated with respect to proposed loading and the economic effects of those changes.

This paper reviews implementation for pavement research. More specifically, it reviews the implementation required to make pavement management effective and provide a better mechanism for implementing research. We firmly believe that pavement management is the best mechanism for putting pavement research results effectively and quickly into practice.

Pavement management and implementation of pavement research have the same objective (i.e., better pavements and better benefits to the riding public that uses those pavements). Furthermore, true pavement management is the best possible framework for implementation of pavement innovation through feedback to improving the working methods. Properly defined and used pavement management requires a feedback loop to ensure that new innovations and new knowledge developed as a part of the process are retransmitted to the process to improve it. This is one of the basic tenets of systems engineering and the basic concept that makes most systems function effectively. This is no less true for pavement management systems (PMSs) than it is for missile guidance systems or any other system.

Effort Needed to Properly Implement Pavement Management and Research

Pavement management has progressed from a concept in the 1960s, to a working process in the 1970s, to a significant degree of implementation in the 1990s. The principles have been formulated and much has been learned from pavement management implementation experience at the federal, state or provincial, and local levels in various countries.

Improvements in application and implementation have not, however, been matched by improvements in the fundamental technologies of pavement management, and the quality of pavement performance has not increased. Many of the same problems that existed in 1970, such as the lack of good, long-term performance models, still exist in the 1990s.

A substantial amount of research and innovation is necessary to truly implement a productive pavement management process with universal applicability. Such a process must be technically sound and have comprehensive underpinnings. The innovation and research required range from short-term problem solving to strategic efforts for technology transfer and application improvements.

An important set of institutional issues must be resolved for pavement management to flourish and function effectively. Existing agencies are slow to change as is well documented in management practice (*1-3*). Only a completely integrated pavement management process will yield the full consideration of total life cycle costs in highway decisions and actions. Agencies must consider all aspects of the pavement life cycle, including user costs and benefits. Research and interaction are needed to bring pavement management into the mainstream of the highway agencies and change administrative attitudes in the direction of organizational change.

Encouraging highway agencies to fully consider operations, including vehicle operation and M&R activities, during design will increase the benefits derived from any PMS. Maintainability is a key concept to be examined for pavement and bridge structures. By making highway structures easy to inspect and maintain, M&R and vehicle operating costs can be reduced. Designing M&R activities early can reduce the cost of protecting agency personnel, time required to perform activities, and need for special equipment. Well-planned M&R activities can also reduce the increase in vehicle operating costs caused by related congestion. Considering these factors during the design process reduces the likelihood of building a pavement that is difficult to maintain.

Needs and Benefits of Coordinated Research Plan

Many state and federal agencies have prepared statements of pavement research needs, research plans, and programs of technology transfer. These are necessary and a large amount of useful research has been carried out. However, what is often lacking is an overview of what is required for a successful program of research and the associated long-term benefits or payoff.

To achieve such success, the following four major types of research should be incorporated into the overall approach:

1. Solutions to short-term problems and applications (1–2 years),
2. Intermediate-term research and development (3–6 years),
3. Strategic or long-term research (5–25 years),
4. Implementation, including technology transfer and the development of research capabilities (continuous).

Emphasis in pavement research for the past several decades has been on items (1) short-term research and (4) implementation. Lack of support in intermediate and long-term efforts leave us facing in the 1990s many of the same problems faced in 1970. On the positive side, Strategic Highway Research Proposal (SHRP), which began in 1987, provided a focal point for reevaluation of some overall pavement research needs (although it does not address PMS research needs per se). Of particular importance to pavement management are the SHRP Long-Term Pavement Performance (LTPP) Study, the asphalt studies, and the maintenance studies. Unfortunately, deficiencies in data collection and processing are hampering the LTPP results.

Because of the predominant short-term focus, however, some of the problems identified in previous decades still limit the use of current research findings, including the development of new models. In addition, because there is not a truly universal PMS available, much of the knowledge gained from past highway experience is being lost as staff retire. The experience gained in the 1950s, 1960s, and 1970s is rapidly disappearing from the scene with continued retirement of senior staff in many public agencies.

It is important to have an overall, coordinated plan to guide future funding and address future needs. Benefits that can be derived from such an overall plan for PMS research include the following:

1. Provide the means for seeking and organizing results of research that is performed both nationally and internationally,
2. Provide direction for future research funding and enable personnel to tailor research to future national needs,
3. Provide a coordinated avenue to implement innovation more readily,
4. Limitations and shortcomings of existing and historical methods can be more rapidly identified and lead to the recognition of important research topics, and
5. Current knowledge, data, and research results can be integrated into a coherent strategy consistent with long-term needs of standardized PMS.

Elements of Successful Research

Among the elements of a successful program of research are the following:

1. Having an overall plan for short-, intermediate-, and long-term research;
2. Top-level commitment and support plus sufficient funds;
3. Continuity of funding, not stop and start;
4. Allowing the flexibility and freedom for innovation;
5. Developing true research capability (people, facilities, etc.);
6. Cooperation between practitioners and researchers; and
7. Dissemination of the results of the research (publications, conferences, workshops, seminars, short courses, etc.).

Overall Plan

An integrated, overall plan covering short-, intermediate-, and long-term research is particularly essential for state or provincial and federal agencies. The issues of current concern might carry the primary focus but a "macro" approach allows for better interaction between projects, permits better identification of priorities, preserves the long-term integrity of the research, and permits more efficient overall program management.

Commitment and Funding Support

Successful PMSs at both the state and local levels have had, with no known exceptions, strong top-level commitment and support in the organization. Similarly, pavement research programs must have such commitment and support, in addition to the commitment of the researchers themselves.

Sufficient and consistent funding with a reasonable degree of flexibility is also necessary. This is not to say that justification for funding and identification of expected payoffs are not necessary. If these payoffs are to be realized and the opportunity for innovation to exist, such funding support and flexibility are essential components.

Organizational support, in terms of facilities, staff, opportunities to interact with practitioners and researchers both within and outside the agency, and encouragement, is also important to successful research.

Continuity of Funding

To be successful, research funding must have reasonable continuity. This does not mean a blank check but rather the opportunity to meet real breakthroughs with adequate support and funding. Innovation does not occur on a precise schedule, it happens in unique and unexpected ways and should not be restricted.

Flexibility and Freedom for Innovation

A common thread of successful, innovative research has been the degree of flexibility and freedom provided researchers. Innovative results cannot be mandated. They come from hardworking, innovative people who are not placed in a bureaucratic straitjacket of administrative control. Particularly constraining is a detailed, procedural environment where more time is spent in progress reporting than in actually doing research. A research management team should select researchers in whom they have confidence. A level of good administration, not control, is the key to good results. The AASHO Road Test is the prototypical example of such effort in which W. Carey had the authority and the freedom to fulfill the project mandate.

It must also be recognized that research may carry a considerable degree of risk and that the payoff in terms of implementation may be some distance in the future. Thomas Edison tried more than 100 combinations of materials before he succeeded in producing the first electric light bulb. He "failed" his way to success.

Developing Research Capability

Research capability resides in universities, institutes, consulting organizations, state, and federal research groups. Although some of this capability has been acquired on-the-job, the basic source lies in universities. Many persons who are active in good pavement research have post-graduate degrees and learned the basic concepts of statistics, analysis, and so forth required for research success from their university training.

Development of research capability requires dedicated, competent students, research support, coursework, and direction from professors. If one looks at the highly regarded pavement researchers in the United States, Canada, and abroad, in the public agencies and in the private sector, a substantial number of them come from universities with an extensive track record of educational excellence and research accomplishments.

Not everyone is a good researcher. Good training and analytical ability are essential. The research team must apply proper methodology in their work.

It is essential that continued regeneration of research capability occur, with universities playing an integral part, and that there be a strong interaction among the public and private sectors and the universities.

Cooperation Between Practitioners and Researchers

Successful innovation can best be implemented if the sponsor or practicing engineer is involved from the beginning as a partner, not as a supervisor. A PMS makes this possible because the feedback loop for new innovation hinges on the results of field use and upgrading of the PMS. It is important for practitioners and research sponsors to recognize that there is such a thing as appropriate research methodology that must be used to produce the best results.

Dissemination of Research Results

Research results need to be disseminated within organizations and externally for peer review. Of course, much internal success is in terms of implementation and improved efficiency or cost-effectiveness, but external judgements are also important to follow-up work and its long-term success. There are many new techniques for dissemination of results (e.g., videotapes, multimedia presentations, and user-friendly computer software programs).

The forums for dissemination of research results include journal publications, conferences, workshops, and seminars. The latter two forums are also often applicable to internal dissemination. Another important type of forum is represented by the "Advanced Course in Pavement Management Systems" of FHWA, which was held in a number of U.S. cities in 1990 and 1991 and incorporates both up-to-date practice and recent research results. (*4*).

Collective Opinion of Research Needs

Two recent studies have been made of research needs as defined by practicing engineers (*5,6*). A synopsis of these study results is given here but the reader is urged to read the papers in full.

Hudson-FHWA Study

During 1990 and 1991, a survey was made of priority research needed to better implement pavement management. This survey included over 200 practicing engineers from the United States and 20 other countries.

This survey produced over 400 research problem statements related to the short-term (4- to 5-year time frame) needs to implement better pavement management, and also the long-term (15- to 20-year time frame) needs to develop better pavement management.

A compilation, summary, and evaluation of these research needs statements has been described by Hudson and de Solminihac (5). Included is a formulation of a rational research program to improve pavement management as envisioned by a large group of engineers practicing in all aspects of pavement management and at all levels of application. The items shown in Table 1 are those that received high-priority responses among a significant number of practicing engineers. They are listed by category, as summarized by Hudson and de Solminihac (5).

There were 204 responses with 101 unique responses describing long-term opportunities for innovation and research needs within the pavement management area of study. The top priority items are given by category in Table 1. There is no priority among categories, but the topics within each category are listed in priority order.

Summary

For Inputs and Data Collection, the main interest of the respondents in the survey was the development of automated pavement condition data collection methods and the use of new technology in data collection, such as weighing in motion and geographic information systems. Some interest was also shown in other areas of the data collection process, specifically traffic, deflection, and roughness data.

For the category of Implementation and Institutional Issues, the concern changes from short term to long term. In the short term, the respondents identified the need to fully implement comprehensive PMSs and establish training programs for technical personnel and decision makers involved in PMS. On the other hand, the main concerns were for the long-term deal with integration of all infrastructure management systems within the highway agency and the standardization of PMS and reference systems to permit better communication among the different systems.

With respect to Output and Performance Models, the main concern for both the short term and the long term was the development of improved models to predict pavement performance histories as a basis for year-to-year improvement of PMSs, and then to relate them to design, construction, and maintenance variables. In addition, some concern was shown about the need to correlate performance models to user cost and the distribution of funds within the agency.

In the area of Economic and Cost Analysis Issues, the respondents expressed a concern for better understanding of the full economic and life cycle cost over the life of the pavement, particularly including a better understanding and integration of user cost. Other concerns were expressed about the quantification of the benefits of pavement management and particularly the benefits of developing a PMS and of improving the budget optimization subsystem of a PMS.

In the category of Pavement Management Systems Concepts, the main concern in both the short term and the long term was the need to standardize the definitions and concepts of PMS. The need for better information exchange between various systems and among agencies using PMS was expressed as well as the need to improve quality management to yield more reliable results.

In the Materials and Behavior category, there was no consensus on the most critical need or element of innovation. There was a concern for developing alternative materials rather than asphalt for resurfacing and building pavements in the future, particularly in the long term. Other concerns expressed in this area deal with developing longer lasting materials and improving laboratory testing procedures to better simulate field conditions.

In the Design category, the main interest for both the short and long term was in developing accurate, comprehensive methods of pavement rehabilitation design. There was also interest in improved mix design procedures to better relate materials properties to actual pavement performance. Additional concerns were expressed about the ability to make better use of PMS feedback to upgrade the design phase of future pavements and develop performance-related specifications.

In the Maintenance category, the main concern in the short term is to develop better maintenance materials and techniques to repair and rehabilitate pavements. In the long term, the main interest expressed was related to the development of long-term performance models for rehabilitated pavements and the provision of improved performance models for various rehabilitation techniques.

Finally, because not all responses fit a specific category, several individual responses were lumped in the "Other" category. The main concern in the Other category was education within the agency about the use and adaptation of pavement management and the information resulting from pavement management. The respondents believed that there remains a need to emphasize the benefits of the use of a PMS within their agency.

Haas-ISAP Study

The Futures Committee of the International Society for Asphalt Pavements (ISAP) was formed in 1990 to provide information that would aid in considerations of future directions of asphalt pavements.

A draft report was prepared in August 1990 entitled "Focus on the World Future for Asphalt Technology" by

TABLE 1 Summary of Results of Pavement Management Research Needs

Pavement Management System Concepts (10 responses)

1. Standardize PMS concepts.
2. Establish methods for better exchanging data between relational databases for integrating design, inventory and PMS data.
3. Implement a total quality management within PMS.
4. Develop a better understanding of and define a life cycle of pavements.

Inputs and Data Collection (37 responses)

5. Develop automated distress surveys.
6. Develop the use of Geographic Information System (GIS) to integrate vast amounts of PMS data.
7. Develop a rapid, automated system to determine the pavement structural capacity.

Output and Performance Models (27 responses)

8. Develop improved performance curves.
9. Correlate pavement performance to pavement design, construction, maintenance strategies and other factors.
10. Relate pavement performance to truck damage and user cost.
11. Evaluate and improve existing pavement performance or life cycle prediction techniques.
12. Develop better distress prediction models.

Materials and Behavior (23 responses)

13. Develop alternatives to asphalt derived from crude oil for use as resurfacing materials and to build pavements.
14. Produce pavements with longer life using better materials.
15. Quantify the effects of overloading pavements.

Pavement Design Consideration (14 responses)

16. Develop an accurate, comprehensive method of pavement and rehabilitation design.
17. Develop mix design procedures that can relate laboratories properties to pavement performance.

Maintenance and Rehabilitation Subsystems (15 responses)

18. Determine the performance of rehabilitation measures under varied and combined environmental conditions
19. Evaluate the effect of maintenance strategies on pavement life and behavior of all pavement structures.

Economic and Cost Analysis Subsystems (24 responses)

20. Improved economic and user cost analysis and interaction of PMS with priority construction projects.
21. Simplify, emphasize, and improve the budget optimization in PMS's.
22. Determine the total return on investment from pavement management system development.

Implementation and Institutional Issues (40 responses)

23. Standardize PMS use in order to group regional and national PMS, and develop the ability to communicate between different PM's.
24. Integrate all infrastructure management systems into one central management system and standardize the use of data.
25. Interface PMS and GIS with performance prediction models.
26. Include highway engineers' experience into PMS through expert systems.
27. Better market PMS.
28. Make more efficient use of PMS's.
29. Evaluate effectiveness of available PMS's.

Others (14 responses)

30. Improve education of executives (e.g., municipal administrators, policy makers) in the purpose and benefits of PMS.

C. Freeme, J. J. Gray, R. Haas, R. McComb, and W. Phang. It examined forces shaping our future environment, identified key political, economic, social, and technological issues, and discussed the strengths, weaknesses, opportunities, and threats to the future.

In support of this effort, and to garner consensus around the world, the authors prepared a questionnaire survey on many of these key issues and circulated it among members. The responses provide guidance to assist in the development of research priorities (6).

The key issues in the questionnaire were classified into Environmental, Social, Public Policy/Political, Technical, and Economic categories. The issues posed required a yes or no response, a determination of priority (high, medium, or low), and the respondent's assessment on a scale of 1 (low) to 10 (high) of his or her degree of knowledge on the issue. The identity and address of the respondent was requested.

For each issue the percentage of yes responses is given in Table 2. In Table 2, yes responses are expressed as high-priority responses to the various issue categories.

The top seven issues were identified by more than 90 percent of the respondents, with more than 50 percent of these indicating a high priority. Three other issues were identified by 80 to 90 percent of the respondents, and still with more than 50 percent indicating a high priority.

The Future of Pavement Management

Learning from the Past

We have learned a lot in the 25 years during which some form of PMS has been available. The use of a sound technological base plus good data; a staging requirement for implementation; and the fact that alternatives, deterioration models, and life cycle economic evaluation are essential elements are some of those things. Table 3 gives some of the key things learned for 25 years of pavement management experience (7).

Of major interest is that the generic form noted in Table 3 can be applied to other infrastructure components, such as water, sewer, bridges, and so on. The basic

TABLE 2 Summary of Top 10 High-Priority Issues

	Overall %	
	Selecting	High Priority
1. Structuring end-result specifications so that the contractor can be held accountable for performance	98	75
2. Benefits and costs of adding reclaimed materials to asphalt mixes	93	91
3. Establishment of the conditions under which clear advantages can be gained by the use of modified, engineered, or premium asphalt cement binders	96	71
4. Speeding up the introduction and client acceptance of innovative materials, equipment, or procedures by the construction industry	93	67
5. Communicating the economic importance of pavements to the public	98	66
6. Development of specifications for long-term performance guarantees of paving work	96	58
7. Premature asphalt paving failures in new construction or in maintenance interventions combined with a lack of education or training	91	54
8. Availability and extent of education or training in the asphalt paving field	89	61
9. Fumes from asphalt plants or asphalt mixes and their possible effects on the health of the public or to workers in the paving industry	85	59
10. Maintenance of and/or increased industry productivity combined with improved quality and performance of asphalt pavements	83	56

TABLE 3 Results of 25 Years of Pavement Management Experience

1.	The framework and component activities for PM (the PMS process) can be described on a generic basis.
2.	Existing technology and new developments can be effectively organized within this framework.
3.	The process allows complete flexibility for different models, methods, and procedures.
4.	PM operates at three basis levels: network, project selection and project.
5.	A sound technological base is critical to the process and its effective application.
From using PMS:	
6.	Development and implementation of a PMS must be staged.
7.	Staging allows for understanding and acceptance by various users.
8.	Options almost always exist; they should be evaluated on a life cycle basis; this means we need models for predicting deterioration of existing pavements and rehabilitation maintenance alternatives.
9.	PM can make efficient use of available funds but it will not "save" a network if funding is below some threshold level.
10.	Good information is essential to the effective application of a PMS.

structure involved needs to remain reasonably stable as future technology is developed. This does not hamper progress. Instead, it provides a consistent philosophy for identifying technology improvement needs and realizing the benefits of such improvements.

The Future

Several issues and needs must be resolved for PMSs to continue to progress.

- Resolve the effects of different organizational structures,
- Identify the requirements and direction of local PMSs versus state or federal systems,
- Establish benefits of PM in quantitative terms, and
- Integrate PMSs with maintenance management and other areas or levels of transport system management.

There are pavement management process-related issues to be resolved, too. They are to

- Establish relationships between pavement management and other facilities or infrastructure management systems, with methods for comparing results;
- Effectively use automation in data acquisition and processing, decision making, construction and maintenance operations, etc.;
- Develop better interfacing of network and project levels of pavement management;
- Develop better methods of estimating existing pavement deterioration, as well as the required maintenance and rehabilitation treatments; and
- Develop better ways to evaluate the impacts of different vehicle weights, types, and dimensions.

Clearly, good implementation and application must continue, but new ideas and new innovation are also badly needed. No innovative, open-ended PMS research is currently under way anywhere in the world. It is badly needed. The essential elements of renewing innovation in pavement management are

1. A source of funds in reasonably sized chunks; say, \$500,000 over 3 years;
2. Dedicated zealous researchers, small interdisciplinary teams of three or four including those devoted to research on pavements, economics, and statistics;
3. Reasonable flexibility and freedom for the research teams to be innovative;

4. A sponsor willing to accept apparent "failure" as an outcome because innovative research is risky;
5. An open-minded, small group of advisors to interact and advise the direction of the team, but not dictate or control; and
6. Trust to be placed in the teams of researchers; neither the teams nor the results should be manipulated.

Changes to Expect

Advances in PMS will come from incremental improvement in current technology and changes in the process, greater use of PMSs, new equipment and methods, and application of new technologies. New equipment and methods, along with their automation, offer some very promising opportunities. They can improve pavement management technology, particularly in pavement construction and maintenance.

Pavement evaluation, for instance, currently uses laser, optical, and acoustical methods to measure profile or roughness. Automated, image-analysis–based methods to measure surface distress are coming into the market, too. High-speed deflection-measuring methods are somewhat further off but should be available for productive use in the 1990s.

Promising technologies for construction and maintenance should involve robotics for equipment and microelectronic–based automated control procedures. An example of a promising new technology in construction is a different method for accomplishing asphalt compaction.

Among the new technologies that are being considered, none has received more attention than the application of knowledge-based expert systems. These afford the opportunity to encode the accumulated experience of experts in various areas.

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INNOVATIONS IN PMS IMPLEMENTATION

Long-Term Cost-Benefit Analysis of Pavement Management System Implementation

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Many agencies in the United States, Canada, and other countries have implemented pavement management systems (PMSs) over the past two decades. Although the technology and implementation have developed rapidly, the costs and benefits of pavement management have generally been assessed only on a qualitative basis. A major reason for this is the difficulty of quantifying benefits to both authorities and users. The qualitative costs and benefits of developing and implementing a PMS, including those of a general and specific nature, are defined and classified. General benefits include better chances of making correct decisions, improved intraagency coordination, and better use of technology; specific benefits, such as justification of programs, would accrue primarily to elected representatives and senior management. It is suggested that the true, quantitatively based indicators of PMS cost-effectiveness involve the ultimate savings in real highway expenditures plus user cost savings. If these "secondary benefits" of user cost savings can be quantified and if they indicate a substantial degree of PMS cost-effectiveness by themselves, then the basis exists for quantitative justification of the PMS. On the basis of data from pavement management implementation in the province of Alberta, it is demonstrated how user cost savings can be calculated for an increase that actually occurred in average network serviceability, even though the budget remained constant. (In real terms it decreased. Consequently, the analysis was conservative.) The ratio of these user cost savings to PMS costs [i.e., cost-benefit (C/B) ratio] ranged up to about 100:1 or more for a variety of scenarios and assumptions. Although it does not represent an exhaustive economic analysis, the case application illustrates that it is a quite sound way in which to look at the value of a PMS. Moreover, it has been found to be a very effective tool for senior administrators with which to justify implementation of a PMS. A second state-level evaluation was carried out on the Arizona PMS on the basis of available data. It was intended for comparison and for verification of the approach used. The C/B ratios are not as high as those for Alberta (partly because of differences in the data and because of the assumptions that had to be used), but they are still substantial and support the general principle of the analysis techniques used.

In light of tougher current economic realities, public administrators faced with the need to implement a pavement management system (PMS) must first prepare the business case or financial justification. Senior administrators and elected officials have become aware of the need for cost-recoverable programs that can return to the public real dollar savings. These savings are in terms of better use of funds and rates of return on the initial investment that result in the program's paying for itself within short periods. In some agencies, however, the initial PMS implementation costs can take a large portion of 1 year's annual rehabilitation budget. Consequently, a frequently asked question is "Why should we spend that much of this year's budget when we could use it to pave many miles of road?"

The implementation costs for a PMS can be estimated on the basis of the industry standards for data collection, software acquisition, consultant services, and in-house staff time required to monitor the project. It is more difficult to determine the benefits (short, medium, and long term) that will accrue to the agency. The initial costs can seem frighteningly high by comparison.

This paper presents an analysis framework for public administrators to follow when preparing the business case study for justification of pavement management implementation. It is based primarily on the analysis of an existing pavement management system in the province of Alberta, Canada. Also, an analysis of the PMS in Arizona is carried out for the sake of comparison.

Cost-Benefit Analysis of PMS

Many agencies in Canada and the United States have established formal PMSs to assist their staffs in maximizing the investment in roadway facilities. As of January 1993, every state in the United States must have a PMS in place if the state is to continue to qualify for full FHWA funding allocations. This alone has hastened the development of PMS technology.

The technology of pavement management systems has developed rapidly over the past two decades, but the quantification of costs and benefits has lagged.

Currently under way in the United States is an FHWA project to collect data and case studies with the objective of quantifying the actual benefits realized through pavement management implementation. One of the first products arising from this project was a report by Hudson (*1*), who identified two primary areas of costs associated with pavement management. They are as follows:

1. The cost of developing a PMS, including the cost of obtaining the necessary and appropriate data for using the PMS and keeping them current, and
2. The true costs of the highway pavements.

The ultimate savings in real highway expenditures are the true indicators of the cost-effectiveness of a PMS. Actual pavement investment and related costs must be considered along with savings and benefits that can be realized from effective PMS implementation. Many problems exist in documenting the true costs associated with the highway investment because accounting procedures (such as the inclusion or exclusion of overhead or indirect costs in unit costs) vary from agency to agency. Obtaining cost information may also be impeded because few if any agencies have fully implemented a PMS over a long term. Also, actual highway investment may be difficult to assess if construction costs occurred over a long time span without a common basis for comparison. Similarly, it is difficult to obtain accurate maintenance cost information particularly tied to pavement location.

An NCHRP Synthesis (*2*) summarized the findings of a questionnaire on pavement management practices sent to all state and provincial highway departments. Respondents were asked to identify benefits received by their agencies through PMS implementation. Fifty-three descriptive benefits were identified by respondents under the headings of budget funding requests, legislature, prioritization, improved project selection, rehabilitation strategies, data collection and pavement condition data, understanding of the value of the highway system, data storage and analysis, uniformity of approach, communications, and dollar savings. Regarding the dollar savings, only potential savings were discussed, because sufficient long-term data were not yet available. A common thread throughout the list was that of a "better understanding or perception of the highway cost-benefit relationship."

A review of the list of benefits to be realized, as summarized by Hudson (*1*) and essentially reiterated in the NCHRP Synthesis (*2*), suggests that the quantification of benefits will be difficult. Of the 13 benefits listed, only the savings in user costs can be calculated with some confidence, based on the results of the Brazil United Nations Development Programme (UNDP) study; those results were updated for U.S. conditions in a study for FHWA by Zaniewski et al. (*3*).

The Brazil UNDP cost study, undertaken by TRDF under the auspices of the World Bank between 1975 and 1981, endeavored to develop vehicle operating cost (VOC) and pavement deterioration models for the economic evaluation of alternative highway investments. This work and the FHWA study previously noted have made it possible to quantify user cost savings as a result of rehabilitation (*4,5*).

If sufficient historical data are available, there can be some measure made of the effectiveness of dollars spent on the system, as well as an assessment of the improved serviceability level of the network.

Another benefit may be quantified as the savings attained through PMS implementation within a fixed rehabilitation budget. These agency savings reflect the improvement in the strategic selection and timing of projects that deliver "a bigger bang for the buck" to the agency.

Case Studies

The Ministry of Transportation and Highways of British Columbia requested that a cost-benefit analysis be performed to assist the ministry in its decision to proceed with pavement management. As discussed in the previous section, the quantification of costs and benefits is difficult, and so, to assist in this quest for evaluation of potential

PMS expenditure, case study data were sought. The province of Alberta was extremely helpful in this search. It is the implementation of Pavement Information and Needs System (PINS) and Rehabilitation Improvement and Priority Programming System (RIPPS) in Alberta between 1986 and 1990 that forms the basis of this cost-benefit study. A secondary discussion of the state of Arizona's PMS cost savings is also presented to support the basic study.

ALBERTA PINS/RIPPS

In 1980 the Alberta Transportation and Utilities Department began a three-phase project to develop and implement a provincial pavement management system. Two phases of the system were completed and implemented by 1985. Those were PINS and RIPPS. The third phase, which includes project-level analysis and life-cycle costing, is at the preliminary design stage as of 1993.

Alberta was chosen as a case study for two reasons. First and most important, the Alberta system has been in operation for 5 Fiscal Years, and accurate data are available on its beginning condition and costs. Second, although partial data are available on systems implementation in Idaho, Minnesota, and Arizona, it was felt that a sister province and next-door neighbor to British Columbia would be more pertinent to the analysis.

Summary data on the primary highway network are presented in Table 1. Between 1986 and 1990 the paved network length increased 7.2 percent, from 11 909 to 12 767 km of two-lane-equivalent highway. This was largely due to a provincial program to upgrade the primary highway network using a combination of capital and rehabilitation funds. The increased length reflects the addition of asphalt concrete surface to existing asphalt concrete base pavements as part of a stage paving and construction program.

The condition of the primary network expressed using the composite performance measure of pavement quality index (PQI) in 1986 was 6.3 on a scale of 0 to 10, in which 10 is perfect. PQI is a combined function of the strength [structural adequacy index (SAI)], roughness [riding comfort index (RCI)], and surface distress [visual condition index (VCI)]. By 1990, the average primary network PQI had risen to 6.8. What is remarkable about this increase in performance is that through two 5-year periods during which the funds available for rehabilitation were fixed at $40 million/year (with no adjustment for inflation), and in spite of a larger, aging network, a 7.9 percent improvement in overall network condition occurred during the second 5-year period. The only difference in the two periods is the use of PINS/RIPPS and the addition of 11 000 km of new pavement.

Using this information, a cost-benefit case is made, as presented in Table 2. Several assumptions made in preparing the evaluation are as follows:

1. The 1986 PQI is a reflection of the prior expenditure of $40 million/year [Canadian (Cdn)] for the previous 5 years, and the 1990 PQI is the result of the expenditure of $40 million/year (Cdn) for the 1986–1990 period.
2. Although maintenance costs are part of an overall pavement management system, no value is assigned to them because of the following considerations:
   –Accurate data on pavement-related maintenance costs are difficult to obtain;
   –PINS/RIPPS address rehabilitation needs only; and
   –Maintenance costs are relatively small in relation to rehabilitation costs, so they can reasonably be assumed to have stayed constant.

TABLE 1 Summary Data on Primary Highway Network, Province of Alberta

Period	PQI Primary	Length Primary
1982	-	-
1986	6.3	11909
1987	6.3	12226
1988	6.6	12519
1989	6.8	12693
1990	6.8	12767

TABLE 2 Summary of Cost-Benefit Case Study, Province of Alberta (Canadian dollars)

Description	Road Needs 1981 - 1986		PINS/RIPPS 1986 - 1990
Rehabilitation Funds	$200 million		$200 million
PQI	6.3 (1986)		6.8 (1990)
Length	11,909 km		12,767 km
Savings on Vehicle Operating Costs		$492 million	
Replacement Value - adjusted for PQI	$5.38 billion 3.39 billion		$5.80 billion 3.94 billion
Increase in Value (Agency Savings)		$550 million	
Total Savings		$1.042 billion	
Costs			
PMS Development		$650,000	(1)
Operating Costs (5 years) a) $42/km (including road bans/strength) b) $25/km (excluding road bans/strength)		 $5,000,000 $2,900,000	 (2) (3)
Equipment costs @ $60,000 p.a.		$300,000	(4)
Total Costs a) 1 + 2 + 4 b) 1 + 3 + 4		 $5,950,000 $3,850,000	

3. No value is assigned to salvage although it could be as high as 20 percent of original materials, because the percentage of the network requiring full reconstruction is not known.

4. The number of registered vehicles in Alberta is estimated at 1.8 million vehicles that travel an average of 20 000 km/year. The actual number of vehicle-km traveled is calculated from Statistics Canada data on fuel consumption; however, the translation of this number into vehicle-km traveled is difficult because of (*a*) change in the average fuel consumption of vehicles and (*b*) the fleet mix in the province. Data were obtained from the Canadian Automobile Association (CAA) and from the Provincial Division of Motor Vehicles.

5. Pavement data acquisition equipment purchases are included in the calculation as one-tenth of the original purchase price plus a debt value. This is because the equipment will be used over a 10- to 15-year period, and the costs should be shared equally over the period.

User Cost Savings

The VOCs were calculated on the basis of an adaptation of the Brazil UNDP study to Canadian conditions, as follows (6):

$$\mathrm{VOC}_j = (a + b\,\mathrm{PQI}_j) \times (\mathrm{VMT}) \times \mathrm{IF}_j \times \mathrm{DF}_j$$

where

VOC_j = VOC for year j,
PQI_j = PQI for year j,
VMT = vehicle miles traveled,
IF_j = inflation factor,
DF_j = discount factor,
a = 0.31182 (assuming 1986 is base year) and
b = −0.02735 (assuming 1986 is base year).

The VOC savings is the difference between 1.8 million vehicles traveling on a network with a PQI of 6.3 and the same number of vehicles traveling on a network with a PQI of 6.8. The VOC savings or user savings are estimated at $492 million (Cdn) as a result of the improved network condition.

The Brazilian UNDP user cost model is very complex and takes into account the following variables: vehicle speed (constrained by vertical gradient, engine power, braking capacity, horizontal curvature, road roughness), fuel/lubricant consumption, tire costs, vehicle maintenance costs, depreciation and interest, occupancy and cargo delay, and administrative overhead.

Agency Savings

To determine the agency savings, a calculation was made to find the protected value of the network expressed as savings in value. The network value is estimated by Alberta Transportation in 1990 dollars to be $5.8 billion (Cdn). Discounting the value for the 1986 length results in a 1986 value of $Cdn 5.38 billion. An attempt was made to adjust this "replacement" value for network condition using the following logic. If replacement value equals a PQI of 10 (i.e., all roads in the network are new), then a PQI of 6.8 represents an adjusted system value of $3.94 billion (Cdn), and a PQI of 6.3 represents an adjusted system value of $3.39 billion (Cdn). The difference between these two values is the savings in value. It is equal to $550 million (Cdn). This increase in value was achieved by the expenditure of $200 million (Cdn) in rehabilitation, $35 million (Cdn) in new construction, and $5.95 million (Cdn) for the PINS/RIPP system. The return on investment is, therefore, $310 million (Cdn).

System Costs

With respect to cost, the PMS development cost in 1980 is calculated at $495,000 (Cdn) using the following figures:

	Cost ($Cdn)
Consultant cost	450,000
In-house engineering	45,000
Total	495,000

This was adjusted to 1986 dollars, for an adjusted total cost of $650,000 (Cdn).

Annual operating costs for the system in 1989 were $980,000 (Cdn), which includes all staff and equipment time (including outside contractors) and equipment operating costs for field and office data collection and entry. These costs equal $42/km. The entire primary network is tested on a 2-year rotation for surface distress and roughness, and on a 2-year rotation for strength. The field data collection costs also include skid resistance, frost probes, and spring load ban monitoring. Using a unit cost of $42/km (Cdn) for all costs, the 5-year operating cost of PINS/RIPPS is $5 million (Cdn). If the road ban program, skid monitoring, and strength programs were deducted, the unit cost would be reduced to approximately $25/km (Cdn), or a 5-year cost of $2.9 million (Cdn).

The implementation costs for the pavement management system can also be compared to the total value of the road network or to the total rehabilitation investment or to both over the development period. In Alberta the PMS development and operating cost over 5 years equated to 2.5 percent of the rehabilitation budget [$5 million (Cdn)/$200 million (Cdn)] and 0.08 percent of total value of the road network [$5 million (Cdn)/$5.8 billion (Cdn)]. By comparison, the annual rehabilitation budget equates to only 0.69 percent of the total value of the road network [$40 million (Cdn)/$5.8 billion (Cdn)].

Cost-Benefit Ratios

The cost-benefit ratios for the Alberta case can be calculated using the user cost savings, the agency savings in values, or both, as summarized in Table 3.

It should be stated that not all of the cost savings (user or agency) are solely the result of the PMS implementation and that some savings would have occurred as a result of the expenditure of $235 million (Cdn) in rehabilitation and new construction. The exact percentage of the savings directly attributable to the PMS is impossible to calculate.

However, to reiterate an earlier point, it can be said that in the 1981–1985 period the province spent $40 million/year (Cdn) on rehabilitation and ended up with PQI of 6.3. As a result of a change in the way in which rehabilitation decisions were made with the introduction of PMS, the expenditure of $40 million/year (Cdn) over the next 5 years resulted in an increase to 6.8. This increase occurred in spite of an aging network and decreasing value of the dollar.

Arizona Case Study

The state of Arizona case study is included to illustrate the potential savings that may be generated within the rehabilitation budget as a result of a PMS. These savings are real dollar savings achieved through selection of less costly rehabilitation strategies before a road becomes irreparable.

The state of Arizona implemented a pavement management system in 1980–1981 on its 7,400-mi (11 840-km) network of highways. The system replacement value is estimated at $6 billion, which is similar to that of Alberta, and the state rehabilitation budget of $52 million (Cdn) had doubled since 1975 as a result of the increased needs produced by a reduction in pavement condition. The PMS was developed in conjunction with a consultant to address the rehabilitation budget (or preservation budget, to use Arizona terms) specifically (2).

The main objective of the system was to develop a decision-making tool to maintain the network in its "most desirable condition within the available budget." A secondary objective was to provide statewide consistency in policy and level of service and to protect the state's road investment. The actual cost savings as a result of PMS implementation are given in Table 4. In 1980–1981 the state highway budget was set at $46 million (Cdn) on the basis of the previous 5 years' pavement data and in an attempt to maintain the 1975 condition. Using the PMS to generate the entire rehabilitation program and following through on its generated recommendations, the same level of service was reached with only $32 million (Cdn). This was a real dollar savings of $14 million (Cdn).

Two reasons were cited for the cost savings:

1. The PMS selected rehabilitation strategies that were preventive rather than corrective, and it selected roads for rehabilitation before they became irreparable.
2. The strategies selected were less conservative (and therefore less costly) than the pre-PMS strategies because of the refinement of the performance prediction models that occurred during system development. The state was fortunate to own a good data base on which the models could be developed. For instance, where 5 in. of asphalt overlay would have been used previously, 3 in. was selected with the PMS. The models indicated that for Arizona conditions, there was no difference in the rate of deterioration between 5 and 3 in. Hence, the latter was selected, at considerable saving. Not all of the technical decisions reflected this large a saving, but the overall savings added up.

Using the PMS to select the rehabilitation program for the 1982–1987 period and maintaining the same standard resulted in a potential saving of $101.3 million (Cdn). Cost data on the system development and operation are not available in the literature (2). However, given that the Arizona highway system is approximately the same size as that in Alberta, similar costs are assumed for this comparison. The cost-benefit ratios would be as shown in Table 5.

TABLE 3 Cost-Benefit Ratios for the Alberta Case: 1986–1990 (Canadian dollars)

Cost		User Cost Savings $492 million	Agency Savings in Value $550 million	Total $1.04 billion
1.	Including Road Bans Monitoring $5.95 million	1:82	1:92	1:175
2.	Excluding Road Bans Monitoring $3.85 million	1:132	1:142	1:271

TABLE 4 Cost Savings: The Arizona Case Study (millions of dollars) (2)

Interstate	Funds Needed * Interstate	Funds Needed * Non-Interstate	Funds Available ** Interstate	Funds Available ** Non-Interstate
1980 - 81	$32		$46	
1982 - 83	13.2	23.1	17.0	23.1
1983 - 84	18.5	30.3	28.3	36.7
1984 - 85	19.0	36.6	37.1	43.0
1985 - 86	20.0	38.3	37.1	44.7
1986 - 87	21.0	40.9	48.0	47.3
Sub-Total	91.7[a]	169.2[b]	167.5[c]	194.8[d]

Surplus (c-a) Interstate 75.8
Non-Interstate (d-b) 25.6

Total Savings $101.3

* Funds needed as a result of the rehabilitation analysis

** Funds available through FHWA formula

TABLE 5 Projected Cost-Benefit Ratios: Arizona Case Study (Canadian dollars)

	1980 Savings $14 million 1 year	1982 - 87 Savings $101.3 million 5 year
Cost including Road Bans $5.95 million	1:14	1:17
Cost excluding Road Bans $3.85 million	1:18	1:26

Note: Road ban monitoring involves weekly deflection at control sites throughout the province to determine load restrictions during spring thaw.

Although it is not as high as the Alberta ratios, it should be noted that the 1980 ratio resulted in a 1:14 benefit in the first year; it should also be noted that no accounting is made for user costs or savings in value that would increase the total benefits.

SUMMARY

The costs of pavement management implementation can be expressed as a percentage of the total value of the road network or the total rehabilitation budget or both. The actual implementation costs can be readily estimated from industry standards for data collection, software, consultant fees, and in-house staff time. However, the monetary benefits directly attributable to the implementation of a PMS are difficult to estimate. A portion of the savings in both user cost and increased network asset value can be attributed to the rehabilitation expenditure regardless of the system used to program the improvement. However, based on some reasonable and conservative assumptions, for the Alberta and Arizona PMSs, cost-benefit ratios demonstrate that even if a small percentage of the savings is attributable to a formal PMS, the benefits far outweigh the cost.

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Using Innovative Management Techniques in Implementing Pavement Management Systems

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Over the past 10 years, awareness of and familiarity with computerized pavement management systems (PMSs) has increased greatly in organizations of all sizes. Realizing the benefits made possible with these systems, many agencies have initiated steps to put PMSs in place. The development of PMSs is an agency-specific endeavor: the systems must be tailored to each organization's climate and structure. Agencies developing systems in the 1990s can readily benefit from lessons learned in the 1970s and 1980s. A review of some early implementations reveals that, for one reason or another, many early systems are not in use today. Reasons cited include their reliance on mainframe computers, unreasonable demands for updating the systems, lack of continued training and user support, inability of the systems to address the needs of those throughout the organization expecting to use the results, and the failure to integrate the PMS into the decision-making process within the organization. The last two issues, which can be categorized as unresponsiveness to internal institutional issues, have emerged as the major obstacle that must be overcome for any system implementation to be successful today. If these issues cannot be resolved, the use of management systems within an organization are negatively affected. It must be recognized that systems developed within one division of an organization, or in a style contrary to the organizational environment, are no longer addressing the needs of an organization as a whole. Businesses now examine the way their daily functions are performed to determine whether there are more effective and efficient management styles for running their organizations. Many of these organizations are evaluating the use of the concepts of total quality management (TQM) as a new way to approach the processes within their organizations. Similarities between the implementation of a TQM system and a pavement management system could help address many of the institutional issues that hinder successful PMS implementation. A TQM approach to a pavement management implementation process is introduced.

As the benefits of pavement management systems (PMSs) become more evident to agencies responsible for the maintenance and rehabilitation of pavement networks, many agencies are developing and implementing such systems. FHWA has greatly influenced the increased acceptance of these systems by issuing its mandate that all state highway agencies (SHAs) use pavement management techniques for their pavement rehabilitation programs by January 1993 (*1*).

The development of PMSs is an agency-specific endeavor: they must be tailored to each agency's unique organizational climate and structure. However, agencies developing systems in the 1990s can benefit from the lessons learned in the 1970s and 1980s. A review of some of the early implementations reveals that, for one reason or another, many of them are not in use today. Reasons cited include their reliance on mainframe computers, unreasonable demands for updating the systems, lack of continued training and user support, the inability of the systems to address the needs of those throughout the organization expecting to use the results, and failure to integrate the PMS into the organization's decision-making process.

The last two issues, which can be categorized as unresponsiveness to internal institutional issues, have emerged as the major obstacles to be overcome if system implementation is to be successful today. This matter has been an important topic in FHWA's Advanced Course in Pavement Management, and it continues to be discussed at conferences on management systems. It is believed that if these institutional issues cannot be resolved, the use of management systems within an organization is negatively affected. It must be recognized that systems developed within one division of an organization or developed in a style contrary to the organizational environment are no longer addressing the needs of the organization as a whole and may be destined to fail.

In analogous developments, businesses are examining the way their daily functions are performed, and they are implementing new management styles aimed at increasing their overall effectiveness and efficiency. Many of these approaches are geared toward improving the overall satisfaction of customers through increased attention to their needs, improving processes in the development of a product or service, and increasing employee participation in decisions that affect the organization as a whole. It is believed an organization can achieve these results through total quality management (TQM).

Currently several transportation agencies are striving to improve the quality of their services to the public, elected officials, and other external customers. This desire has led directly to the consideration of TQM concepts, which have worked well in industry. The National Quality Initiative is an example of the increased commitment to improving the quality of services by SHAs.

The desire to improve the quality of services leads quickly to the desire to improve management of the largest infrastructure element: pavements. Although every agency that owns pavements has been "managing" them for years, it is recognized that improved management of the pavement infrastructure could lead directly to improved quality of the highway system for the public and elected officials as well as to the better use of the limited resources available.

Understanding the concepts and philosophy involved in effectively managing this improvement through TQM permits better understanding of PMS as a process that affects the way an organization serves its customers. From this vantage point, it appears that the principles of TQM, which are aimed at improving the process that compose the system that provides services and products to customers, could be applied to the implementation of a PMS and could help address the organizational issues that often preclude success. This concept is supported through a discussion of the main principles of TQM and examples of organizations in which some aspects of the principles have been used.

TQM Philosophy

Many business organizations throughout the world are beginning to recognize the management approach that was first put in place by Japanese industry more than 20 years ago to improve the quality of products and services. Through intensive attention to the needs of customers as a product is developed, the Japanese have revised the image of the business world with respect to the quality and workmanship that go into everything the Japanese produce. Words that used to represent a cheaply made product—"made in Japan"—now represent some of the finest products in the manufacture of electronic and automotive equipment.

This turnaround was made possible by the attention Japanese businesses gave to the radical new way of thinking presented to them by W. Edwards Deming. Deming's teachings led them to view business in a new light that gives primary attention to the satisfaction of customers' needs. Although originally oriented toward the manufacturing environment, TQM has expanded into the service sector in recent years.

The TQM philosophy views the development of a product or service as a series of processes. Each process can be viewed as a step that receives a product from the process that immediately preceded it and that serves a customer who is responsible for the next step. Internal customers receive most of the services produced within the companies; external customers actually purchase the product. This very different point of view allows one to view each of the steps as an important part of development, and by improving each of the processes, the end product is improved.

A key internal factor must be established for TQM to succeed: namely, an environment in which employees believe they are part of a team contributing to overall company goals and objectives. It is critical that this sense of teamwork be established to reduce the internal competition that typically takes place within a corporate environment. In the desired environment, people are free to make suggestions for continuous improvement, work more effectively as a system, and take risks through innovative thoughts and ideas. The goal of TQM is to get people to work smarter, not harder (2).

PMS as a Process

Over the past 10 years, pavement management has been promoted as a tool to assist planners, engineers, and others responsible for the maintenance and rehabilitation of pavement networks. PMS implementation requires a series of steps so that the system can provide the type of guidance necessary for the identification and timing of future rehabilitation needs, the budgeting of necessary funding levels, and the impact of trade-offs between competing priorities. As a computerized tool, PMS has the potential to provide benefit to individuals throughout a transportation agency; these benefits help top-level administrators who need what-if scenarios to justify spending levels; engineers who must design and construct the rehabilitation treatments identified; and research engineers who evaluate the effectiveness of various design approaches over time.

The decisions that make up the steps in pavement management require input from various divisions. Those decisions also affect the work of people in the divisions. If the objective of pavement management is viewed as a method that can be used to manage a pavement network more efficiently and effectively, the steps of data collection, capital improvement planning, needs justification, and maintenance scheduling can all be viewed as products developed from this method. Thus, pavement management can be viewed as a process that, like any other organizational process, must be managed. Implementing pavement management is very similar to implementing a TQM process, because it requires a total commitment from top levels of management, it affects individuals throughout the organization, and it greatly affects the "traditional" way of accomplishing the objectives of the organization. Because of the similarities in the way the PMS and TQM processes affect an organization, it is possible to study recommendations from those implementing TQM (this constitutes a fairly large data base) to see what benefits they can provide those desiring to successfully implement a PMS process.

Applying TQM Philosophy to PMS Implementation

W. Edwards Deming has developed 14 points that are critical to the successful transformation of an organization into one with a quality-based philosophy (*3*). Whether applied in a manufacturing firm, a for-profit company, or a transportation agency, Deming's 14 points can help create a quality-based organization and provide guidance in implementing any process in an organization. The points provide insight into how to introduce change within an organization and successfully transform the organization to the new philosophy of, in this case, pavement management. Each of Deming's 14 points is presented, with a brief explanation of the relevance of point for PMS implementation (*4*). Examples of agencies in which these points have been adopted in some manner are provided where possible.

Statement of Aims and Purposes

Point 1: Create and publish to all employees a statement of the aims and purposes of the organization. The management must demonstrate constantly its commitment to this statement.

The fundamental importance of management support for PMS development and implementation if it is to be successful is recognized by the pavement management community. The importance of this factor is emphasized as the first point in Deming's strategies for a successful implementation.

Recent legislation mandates, today's SHAs to use a pavement management approach for the rehabilitation and maintenance of the federal-aid system (*1*). Other agencies, including cities, counties, airports, and private agencies, believe in the benefits provided by the implementation of PMS and are building the support needed from the upper levels throughout the organization.

Whether the support for pavement management is mandated or develops from a belief in the benefits it can provide, upper management within an organization must support the development and implementation of the system through words, actions, and resources. The goal of transportation agencies is the maintenance of their infrastructure to accommodate the needs of the traveling public in a manner that is efficient, cost-effective, justifiable, and flexible. For a transportation agency to accomplish these goals, managers and engineers look to tools such as pavement management. Like TQM, pavement management is not meant to be an additional responsibility placed on engineers and planners. It is supposed to be a tool that lets them perform their work better.

For successful adoption of the PMS philosophy, those at the top levels of transportation agencies need to define the reasons that pavement management is being supported within the organization as well as the goals for the system. Many agencies establish steering committees as soon as they decide to adopt a PMS approach. These groups are assigned to define the agency's pavement management needs. A steering committee may decide that its goal is to develop and implement a system that allows pavement-related decisions that are efficient, effective, objective and that reflect the changing rehabilitation needs and goals of the agency. The committee may decide to achieve this goal by using a computerized system to simplify or speed up the agency's ability to achieve these goals and objectives. It may assign itself a role as the group responsible for the design, implementation, maintenance, and promotion of the system within the organization.

It is important for management to respect the rehabilitation recommendations of the agency's PMS once it is implemented and to demonstrate their commitment to this philosophy constantly. In other words, management must make decisions consistent with the logic of the PMS;

sometimes this requires decisions that are not popular or the reasons for which may not be initially obvious. This may mean making decisions that result in higher initial cost alternatives with lower maintenance requirements or catching pavements before they deteriorate to a level at which repairs cost much more. It may also require the commitment to the PMS with necessary resources such as computer equipment, manpower, and data collection equipment. This commitment must be consistent over time and throughout changes in the directorship of the organization.

Many agencies have been able to win the support of their top managers and are benefiting tremendously from the support. The state of North Dakota, for example, had its chief engineer on the steering committee so that he was involved and informed throughout the development process. The state is using the recommendations from its PMS for its project programming and gained enough support for its system to be able to purchase automated condition evaluation equipment.

New Philosophy

Point 2: Learn the new philosophy: top management and everybody.

As emphasized in the discussion of Point 1, for a PMS to be truly successful, it needs the support and commitment of top management. PMS requires a new way of looking at things and a fresh approach to addressing the competing priorities within a transportation agency. For the PMS philosophy to be truly adopted within an organization, people throughout the organization must be trained: people at all levels and within all functions that will be affected by the change PMS brings about. As with TQM, PMS requires a commitment to making decisions that best represent an agency's philosophy. The "same old thing" is no longer satisfactory. Today's public requires transportation officials to be more accountable than ever before. The public requires that agencies using public funds be accountable for all expenditures of tax-supported dollars. People within the organization and even the public who support the agency need to understand and support this new approach. Educating people is a continual process.

Inspection

Point 3: Understand the purpose of inspection: to improve processes and reduce cost.

TQM holds that quality does not arise through a process that relies on inspections once a product is completed. The TQM philosophy does not state that inspections should not be performed but rather that an organization should evaluate the processes being used to build the final product and should build quality into the product instead of relying on inspections to catch inferior products. The belief is that by building quality into the processes used to develop a product, the quality of the end product improves at the same time that development cost are reduced.

As an example of this concept, imagine an organization that builds widgets. Each takes 3 weeks to build, after which time the widget is inspected. If it does not meet specifications, it must be sent back and fixed. Not only is this process expensive, it places all the responsibility for quality on the inspector. If that individual does not catch the faulty product it is delivered to a customer.

The TQM philosophy evaluates and continually strives to improve each step (or process) throughout the development of the widget. Individuals building the widget would evaluate the results of each stage of development, determine the variation that occurred in the development, and determine methods to improve the process to reduce variation in future developments. By fixing or improving each process, quality is built in, the cost of reworking is reduced, and the responsibility for quality rests with individuals throughout the developmental stages.

The successful development and implementation of a PMS could also focus on building quality into the system rather than on spending large quantities of resources on development only to find the system does not do what it was intended to do. Several transportation agencies have suffered the consequences of such a situation by turning over system development to a consultant and not being involved in the developmental process. Several months after the consultant begins, the agency sometimes finds that it has an expensive computerized system that does not conform to agency needs. The agency must then face the decision of redoing the system it has already paid for or accepting delivery knowing there is little chance the system will be used.

Many such problems can be prevented by taking the time at the beginning of the system development to outline carefully what the client expects from the system, whether the system is developed in-house or by consultants. It is important to spend time on the design of the system before the programming stages. It is also important to ensure that the programmers understand how the processes work within the organization and that they know of any changes to take place in the near future. In addition, it is important for them to understand who will be receiving what information from the system and in what format that information will be required. Finally, it is also important to outline a feedback loop to ensure that the system is continually updated and remains reliable.

To ensure that the needs of the agency are being met, it is strongly recommended that agency employees from various divisions be involved with any consultant hired to develop and program a system. Additionally, the agency may want to consider integrating decision points or reviews into the developmental stages as a control measures to ensure that each stage of the development is appropriate and is leading to a system that bases its recommendations on the philosophy and practice of the implementing agency.

Delaware's state highway agency emphasized the importance of design in its development. The consultant's work on the project was in two phases—the design of an appropriate system and the development of the system. This approach works well for two reasons. First, the contract for system development can be negotiated more accurately once the system design has been completed. It is often the case that contracts for development are negotiated before the system design, possibly resulting in miscalculations in the costs. The second benefit in this approach lies in the ease of the agency in releasing a contractor after the first phase if it appears the contractor cannot complete the work as requested.

Contract Awards

Point 4: End the practice of awarding business on the basis of price tag alone.

Government agencies are frequently caught in the trap of awarding contracts to the lowest bidder. Under the Brooks Act, consultant services are exempt from the bidding requirement, so an agency may make a selection on the basis of consultant qualifications rather than cost. This is important for helping ensure the development of a quality PMS. Experienced consultants who have successfully developed working systems in the past are less likely to experience the pitfalls novices might encounter.

There are two major issues with respect to this point. First, it is important to continue to select consultants on the basis of qualifications rather than of price. Consultants hired for system development need to demonstrate their experience and provide references. The system implemented must truly represent the goals outlined by the steering committee at the beginning of the implementation process.

Second, it is important to support pavement management system development as a consultant-based process rather than considering it a software purchase that goes out to bid. This is a critical point in ensuring that the end product satisfies the needs of the agency acquiring the services. In most situations pavement management is a service customized to fit unique organizational needs and requirements. There are few opportunities to take a standardized system, with no customization, and expect a successful implementation. Experience has demonstrated that the most successful case studies have occurred in agencies that recognize that their own decision process differs from that of other agencies. This does not mean that new systems must be developed for each agency but that systems which are flexible enough to be tailored to the organization's needs will be most economical and successful.

Production and Service

Point 5: Improve constantly and forever the system of production and service.

Throughout a pavement management implementation, it is important that the developers and agency personnel keep in mind that the actual implementation of the system is never really complete. A process is being put in place, not a one-time action that is completed when certain steps are done. The PMS process needs to be continually updated in order to continue making effective recommendations to its users. To be most effective, the PMS process must take into account each aspect of pavement engineering including design, maintenance, construction, and so on. In addition, it must be recognized that pavements are just one part of the total transportation system being managed by the agency.

An important component of implementation and system design is to outline processes that allow for continual feedback into the system and periodic reviews of system components to make sure that they still reflect original assumptions on costs, conditions, and organization policies. Questions should be asked regularly by the PMS coordinators to find out whether the rehabilitation treatments considered in the system are still applicable, whether new contractors have entered the market making a previously unused technology available, or whether the rehabilitation costs are still appropriate, for example. The decision process used by the PMS should be reviewed at least annually to determine, for example, whether it is still meeting the agency's goals effectively, whether the services provided to the public have improved, whether the network condition has improved over time, and whether the available funding is being used more effectively than before. By addressing such questions, the system can continue to improve with time and use.

For this continuous improvement to take place, it is important that there be an environment that supports input from the entire organization and that honest assessments of system capabilities are performed. It becomes important for people to be committed to improvement rather than to their own egos and for people not be criticized for generating ideas, no matter how farfetched they may appear at first. The steering committee should be kept in place following the actual implementation of the computerized system so that new capabilities for the system can continually be evaluated.

It is also important for employees to continue to learn and to keep up with the latest technology. In the past 20 years, there have been great changes in the computer industry. Mainframe computer systems, available in the 1970s when PMS began, have been replaced by personal computers (PCs) or networks. Users do not want to discard the many years of data stored on their mainframes and may not be aware that today the information can be uploaded to a PC for pavement management purposes. It is important that they keep abreast of such developments.

It becomes the steering committee's responsibility to see that the pavement management process continues to improve. Money must be budgeted for continual improvement of the computerized system to keep up with new technology and new ideas. In addition, implementation should not be considered complete once a system is in place. If left alone, it will quickly become ineffective, outdated, and unused. Pavement management must be regarded as a process that is being put in place, not just a computerized system. The computerization is only a step within the total process.

In one SHA, a large mainframe data base was developed to store the pavement condition information collected annually for its non-interstate highway network. Additionally, pavement design, maintenance, and rehabilitation information was input into the data base. The structure, however, has not kept pace with today's technology, and because of the significant delay between asking for and receiving information, the system is simply avoided by staff. The state is now hiring a consultant to rectify this situation; additional funds are being spent on a system thought to be complete. The agency is not alone in this predicament. Many agencies have managers who remember allocating resources for pavement management years ago and who fail to understand the need to update their capabilities. They must be taught, and the improvements must be demonstrated.

Another SHA depended on a champion to get the PMS process in place. This individual was able to direct the efforts of enough people within the organization to improve the condition of the state's network. This success was promoted throughout the organization, and increased support for the PMS followed.

Training and Education

Point 6: Institute training. Point 13: Encourage education and self-improvement for everyone.

As mentioned earlier, training and self-improvement are important components of both PMS and TQM. Individuals want to do their jobs well. They generally want to continue learning and improving the way they do their jobs. This may be especially true of individuals who work in the area of PMS because of the continuing advancements made in the field. Technology continues to improve through research supported by TRB, FHWA, universities, and other agencies. In addition, computer technology continues to change, allowing new capabilities every year. If learning stops and new information is not sought out, how will the systems that were implemented continue to meet the changing environment in which they must serve?

Because people learn in different ways, training can be done in many different ways. Some individuals learn best by reading, some by listening, some by watching, and others by tinkering. When training agency staff on the pavement management system, it is important to orient the training to the best learning style of each of these individuals; just because one approach makes sense to the trainer, it may not be effective with all participants.

This lesson is especially important as the benefits of a pavement management philosophy are taught to city council members, legislators, and other government officials and managers. Although many of the people involved in pavement management are engineers who tend to think logically, many of the individuals to whom PMS presentations are made do not have a technical background. Those who have to be convinced of funding level needs may not be swayed by technical arguments. Therefore, people from different backgrounds and different ways of thinking should work together in order to learn new ways of presenting information.

Training can take place through the many PMS conferences and courses available. Conferences such as the Third International Conference on Managing Pavements are important sources of training for individuals hoping to implement a system as well as for those who have had operational systems for 10 years. Attendance at conferences and training courses needs to continue after a system is implemented so that people can learn about the new technology available and talk with other agency implementors about how to deal with certain issues. FHWA offers several courses on PMS, and universities are adding it to their civil engineering curriculums.

User groups provided by software vendors are other sources of training. Although all participants in these events have implemented the same type of software, learning opportunities may include a new aspect of the software or a new way to handle a troubling issue. In addition, agencies can assist the vendors in their future system development to ensure that the system in place continues to address users' needs.

For training to be effective, it must be thought of as more than a response to a problem. In most situations, training is recommended when something has gone wrong or when someone lacks skills. PMS requires a new look at training as a source of continuous learning. Employees are the most valuable asset of any organization. It is important that management provides these assets regular opportunities to stay involved and continually improve the jobs they perform.

The Metropolitan Transportation Commission (MTC) in the San Francisco Bay Area is an excellent example of an organization that has a demonstrated commitment to training. MTC, a regional planning organization, developed a PMS in the mid-1980s for the local agencies within its jurisdiction. Today that system has been implemented throughout the San Francisco area and throughout much of California and the West Coast. To continually provide improvement to the agencies that have implemented the system, MTC has begun providing training courses on various facets of pavement maintenance, rehabilitation, and design in addition to their regular users' group meetings. MTC recognizes the need for continuous improvement and is instrumental in providing affordable training opportunities for the agencies it oversees. Agencies that may have stopped using MTC's PMS have kept active through the continued training of new staff by MTC.

Leadership

Point 7: Teach and institute leadership.

Leaders develop the vision of an organization. Many PMS initiators have been leaders within their own organizations, people with the vision to see the effectiveness of new ways of thinking and the efficiency with which things could be done. PMS steering committees must now take on the role of leaders as they define and express their vision for PMS within their organization. The more the vision reflects the collective vision of representatives from every department, the more committed each individual and department is to implementing and supporting the system.

Managers of PMS departments can best assist their staff by considering themselves coaches or mentors. They need to provide the resources needed for PMS to continue as a way of demonstrating their ongoing support for the PMS process, as addressed in Point 1. Necessary resources may include training, hardware, direction, and manpower, but they may also include the knowledge and authority to remove barriers to the implementation process.

In addition, leaders must instill in workers the sense that their work is important and has meaning and need to allow them to develop pride and joy in their accomplishments. At times, a leader must energize staff members and inspire them to follow the new processes and procedures that come from PMS implementation. They must help show the staff that this new approach works and practice the philosophy in the things they say and do. This is especially important because a leader is usually visible to many and typically influences the activities within an organization.

In some agencies, a leader is the champion who gets the entire PMS in place. The leader has the ability to see the long-term benefit of a PMS and focuses on the possible outcomes from such a system as motivation. Of course, there are risks involved for such a leader in a typical government agency, but it is important to have an environment in which this kind of thinking can exist and thrive and to develop others who begin to think in these innovative ways. In some organizations this may be the only way to introduce change. This approach can be effective, but it is often slower and more frustrating for those involved. It must be undertaken with the objective of winning over rather than of fighting top management.

Climate of Trust

Point 8: Drive out fear, create trust, and create a climate for innovation.

In an organization where there is fear, people can not perform at their best. When there is fear, people do not talk freely or express themselves openly about what is wrong or how things could improve. They do not feel comfortable suggesting changes for fear of being fired, laughed at, or viewed as criticizing the boss. What managers today need to do is to develop an atmosphere of trust in which staff can feel free to offer suggestions, tell people they are wrong, and know that their opinions are valued.

A steering committee is very important in this realm. When individuals feel threatened, they are often defensive or critical of any change because they are not sure how it will affect them. They are often focused primarily on preserving their jobs, rather than on feeling secure enough to look at the larger possibilities. Long-term focus and teamwork become impossible under such circumstances.

Also important with respect to a steering committee is for employees to know that organizational rank or position is meaningless while discussions occur. This is especially important if a lower-ranking employee is to recommend a process change—especially if the process was put in place by a boss who is also on the committee. Many people fear that something they say may come back to haunt them. They may not be fired, but they may get passed over for a promotion as a result of their criticism in discussions in the steering committee meetings. Each individual on the steering committee must do his or her part by affecting the things each one can control to avoid increasing fear. Honest and open communication are probably the two strongest factors in eliminating fear.

Optimization

Point 9: Optimize toward the aims and purposes of the company the efforts of teams, groups, and staff areas.

Pavement management is one way to assist an agency in optimizing its staff toward the highway agency's aims and purposes. Within a PMS, the aims and purposes of many different departments can be optimized collectively because they serve as a tool that can assist each department. People within these departments are not trying to accomplish different goals but simply perform different functions aimed at maintaining the infrastructure in an efficient, cost-effective, justifiable manner. Why then, does each group within an organization often have its own barriers? How many times have PMS implementors heard that they do not understand how another group does its job or that they do not do things the right way?

This is one of the primary reasons that the idea of forming steering committees evolved. These committees allow organizations to focus on a team approach to system development so that a PMS can be a tool that is used by each group. The primary purpose of this group's getting together is to address the concerns of each group, increase the credibility and appropriateness of the recommendations coming from the system, and improve the flow of information within the organization. It is important that enough people are involved so that each division or department owns the work being done and the improvements being made within the organization. These people must have a stake in the success of the organization and its ability to meet the needs of the public.

Staff Goals

Point 10: Eliminate exhortations for the work force.
Point 11: Eliminate numerical quotas for production—instead, learn and institute methods for improvement; eliminate management by objectives—instead, learn the capabilities of the processes and ways to improve them.

The *American Heritage Dictionary* (5th Edition) defines exhortations as strong warnings. In Points 10 and 11, Deming is referring to the setting of slogans, work targets, or productivity goals at arbitrary numbers that may or may not be achieved through no fault of the workers. Deming's theory is that not attaining even unattainable goals can be demoralizing to the staff, even if it is something over which they have no control. Instead, he stresses working toward meaningful goals and objectives that people throughout the organization believe can be achieved. For example, if a steering committee sets a target of a fully implemented system within 6 weeks, the committee needs to be clear that everyone involved believes this is a realistic target. All committee members should be involved in developing the goals and objectives for the implementation.

It is important in today's organizations to recognize each individual's desire to do a good job and to continue to improve and receive increased responsibility. When management sets some kind of numerical target as the measure of success, the employee switches focus from improvement to beating the target. This point may also be linked to the other points that discuss eliminating fear within the organization. Where fear is not present, exhortations may not be present either.

The focus of these two points is to look at long-term investments as the way to improve our organizations and systems. In this case the investments are made in people's self-respect, knowledge, and interest in their jobs. It is important to be sure that as PMSs are designed and implemented, there is real understanding of the jobs being done by different departments within the organization and clear identification of the needs of the system. There must be a combination of asking questions, listening to the answers, and taking necessary action.

Barrier Removal

Point 12: Remove barriers that rob people of pride of workmanship.

The main emphasis of Point 12 in Deming's work is the abolition of the typical personnel evaluation systems that are in place. Deming believes that these systems are demeaning, lack necessary consistency between individuals, have no real meaning, and set people off against each other. People often do not put the time into them that is necessary.

Although this point does not directly relate to PMS design and implementation, it does emphasize the importance of regular feedback and communication with people on their performance. A steering committee could learn from this and regularly assess its own performance as well as the effectiveness of the system it is responsible for to see that it is addressing the needs of the organization as a whole. The committee should develop and implement its own mechanisms for discussing ways to do a better job and identify creative ways to continue to improve the processes already in place.

Corrective Action

Point 14: Take action to accomplish the transformation.

Through knowledge and understanding of the issues behind each of Deming's 14 points, people become prepared to successfully accomplish the transformation within their organization. Deming suggests an approach that is depicted through a cycle of four steps that are repeated through continual improvement. The four stages of Deming's cycle include the following: plan, do, study, act.

The first stage is to plan the work to be done to achieve the goals and objectives. In pavement management, there must be an approach planned for obtaining the collective wisdom of people from various departments, the most efficient approach for implementing a computerized system must be outlined, a training program must be designed, a feedback loop for regularly updating the system must be outlined, and an approach for introducing this new approach to the entire organization must be developed.

Once the planning is completed, which often takes more time than the other steps, the plans can be executed, the group can study the effect it is having on the entire organization, and any necessary corrective action can be taken. This entire cycle can be repeated over and over, continually improving everything the committee does.

A successful PMS implementation must have strong support at the top of the organization. The person with the most power must be committed to the endeavor and be convinced it will work. They must believe that the end result is worth the effort. A quality PMS implementation must not be an extra job placed on individuals, nor can it be a one-time operation that is dumped on an organization. It is a way of thinking and a way to more successfully accomplish our PMS implementations for long-term survivability.

Conclusion

To be most effective, pavement management should be viewed as a process that is implemented within a transportation organization to help manage this one aspect of its infrastructure system effectively and efficiently. Pavement management involves adopting a new philosophy within the organization, and it involves a commitment from people throughout the organization to make decisions that support the new philosophy. The computerized systems, most commonly thought of as the pavement management tool, are only one way of using a pavement management process.

Viewing pavement management as a process provides valuable insight into the implementation of a new way of thinking from the implementors of TQM. This TQM movement, which has been gaining momentum throughout business and within transportation agencies, discusses the institutional issues that must be addressed for the implementation of a new process to be successful.

This paper considered the 14 points that W. Edwards Deming developed as the most important factors to be addressed if the TQM process is to be successful. Applying those 14 points to a pavement management implementation gives insight into the issues that have hindered the use of pavement management in many of today's transportation agencies. It is only through the recognition of the importance of these points and the desire of managers to improve the quality of services they provide that the mandates issued by FHWA for the use of PMS will be achieved. Without the strong desire of managers and others throughout the organization to improve the quality of services, the development and implementation of a PMS will have no impact on an agency.

The key concepts of TQM can be very helpful in the development and implementation of a PMS for a transportation agency. Many of these concepts have been discussed. There are also several strategies that can be adopted by an organization to enhance its chances for effective implementation. They include the following:

1. Improve communication throughout the organization.
2. Identify and listen to the needs of the external and internal customers. In a transportation agency, the external customers are the traveling public and legislators. The needs of these customers must be fully considered.
3. Encourage risk taking within the organization so that new ideas and continual improvement can occur.
4. Practice creative problem-solving.
5. Evaluate existing PMS practices continuously and look for areas of improvement. All significant quality improvements must be supported by top management.
6. Create an environment in which people enjoy what they are doing and take pride in their efforts.
7. Cultivate a team approach to a PMS implementation through the use of an active steering committee. Use the committee throughout the design, implementation, and use of the system. There is strength in numbers.

Many of the early implementors of PMS failed to recognize these institutional issues as factors needing to be addressed as part of PMS implementation. Few of the early implementors are still using the systems that they spent thousands of dollars to implement. To avoid the continuation of this dilemma, today's agencies are recognizing the need to address these issues at the beginning of the implementation process. Although it is too soon to be proven beyond doubt, early indications are that agencies in which several of these issues have been addressed are more successfully using their PMSs within their organizations. Organizations that have learned from new management strategies have developed and implemented systems that are used across the organization for a comprehensive management strategy. Recognizing pavement management as a process, similar to TQM, will successfully help a transportation agency to achieve its pavement-related goals and better satisfy the public it serves.

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New Approach to Defining Pavement Management Implementation Steps

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Most implementation guidelines are prepared under the assumption that the decision to implement pavement management has been made. They generally do not address the problems of an individual in an organization who must convince the management structure that pavement management is something that should be adopted and implemented. In addition, many guidelines stop after the pavement management system has been adopted, pavements inspected, and information is in the computerized system. A new approach in pavement management implementation guidelines is described. It addresses five phases of pavement management adoption and implementation that cover the full range of implementation. The first phase is for individuals within agencies who are interested in finding information about pavement management to determine if they would like to pursue implementation. The second phase is for the pavement engineer, maintenance supervisor, or other persons trying to get their agency to adopt pavement management practices. The third phase is for personnel in an agency who have decided to implement pavement management but who have not selected the pavement management process, pavement management decision support software, and data collection procedures. The fourth phase is for agency personnel after the third phase, has been completed and the system is being implemented in the agency. The final phase is for agency personnel after the initial implementation is complete and the agency is trying to make pavement management a routine part of the management process. When the fifth phase is finished, implementation can be considered complete, because the pavement management process becomes the standard method of managing the pavement system in the agency.

Most guidelines for implementing pavement management are a series of sequential steps that were prepared under the assumption that the decision to implement pavement management has been made (*1–8*). They generally do not address the problems of an individual in an organization who must convince management that pavement management should be adopted and implemented. Pavement management is being mandated in state highway agencies in the United States (*9*). However, among local agencies, only those that have federal-aid roads and streets are required to adopt a pavement management system (PMS). Many federal and airfield agencies still have a choice. Even if pavement management is being mandated, there is a big difference between having and effectively utilizing such a system. There is still a need to convince management that the pavement management concepts and components should be used effectively. Implementation is not complete until the PMS has an impact on decisions being made in the pavement management process.

This discussion of pavement management implementation addresses several phases of pavement management adoption and implementation that cover a much broader range of implementation activities than most earlier guidelines do. The first phase is for individuals within agencies interested in finding information about pavement management to determine if they would like to pursue implementation or more effective use of an existing PMS. The second phase is for the pavement engineer, maintenance supervisor, or other persons trying to get a decision from the agency management on implementation and effective use of pavement management. The third phase is for personnel in an agency who have decided to implement pavement management but have not selected a PMS, pavement management decision support software, and data collection procedures. The fourth phase is for agency personnel after the PMS, pavement management decision support software, and data collection procedures have been selected, and the system is being implemented in the agency. The final phase is for agency personnel after the initial implementation is complete and the agency is trying to make pavement management a routine part of the management process. When the fifth phase is finished, implementation can be considered complete, because the pavement management process becomes the standard method of managing the pavement network in the agency.

This approach to implementation is heavily influenced by diffusion of innovation and technology transfer studies (*10–13*). A set of steps based on these concepts is being developed as implementation guidelines by ASTM Committee E17.41. This document gives much more of the reasoning behind each step, whereas the guidelines being developed for ASTM are the primary steps.

Although this set of guidelines uses five phases with subsections in sequential order, an agency may start with any phase and at any point, depending on the status of its own pavement management implementation. For instance, if pavement management is mandated, the first phase is not needed. On occasion it may be necessary to back up and repeat previous steps or phases. The time required to implement pavement management varies among agencies depending on information and procedures already in place, the size of the network, and the resources available. It is impossible to define the amount of time required without a thorough investigation of the current situation of an agency and of the resources available for implementation.

Some agencies need assistance in some phases, because of staff shortages, lack of experience, or other factors. Assistance is available from several sources and is appropriate at different times for different agencies.

Phase 1: Deciding That Pavement Management is Needed

Phase 1 is directed at the potential pavement management "champion" in an agency. A champion is a person or small group of advocates in the agency who recognize the need for and benefits of pavement management and works to get it adopted and implemented in the agency. The champion must first be convinced that pavement management concepts should be adopted and then must convince the agency to adopt pavement management (*13*). The champion may be responding to and have the support of a counterpart champion in an influential external agency. The following is a series of steps the champion must generally complete to reach a positive decision about pavement management adoption and implementation.

First Knowledge

The champion in the agency recognizes a need to change or enhance the manner in which pavement design, maintenance and rehabilitation planning, and programming are conducted. This can occur as a result of a perceived need to improve the process when the person encounters a problem that is difficult or impossible to address with the current system. It can occur when the person learns about pavement management and its capabilities from other personnel, technical publications, professional association meetings, or other professionals. It can be identified by members of the agency administration as a management objective that they perceive to be needed in the agency. It can also occur through legislative or other outside-agency mandates for use of the process.

Attitude Formation

The champion must have the knowledge necessary to decide if pavement management will be good for the agency. Knowledge of the principles of pavement management are important at this stage in order to ensure that the pavement management process is relevant to the agency's particular situation.

The "how-to" knowledge is critical at this point. The champion must determine the information that is desired by potential agency users, ways in which the pavement management procedures will be used, the answers that must be provided, the costs of implementing the system, the benefits provided, and the changes that will be required in the existing agency. The champion must be able to compare advantages and disadvantages of the systematic pavement management procedures with current procedures.

New approaches to public works management create uncertainty in those affected with respect to ways in which their jobs, authority, and responsibility will be modified. The champion must have enough information to reduce that uncertainty to the point where the champion believes that adoption of the pavement management is appropriate for the agency. Demonstrations of an operating pavement management system, case studies, formal training sessions, and discussions with peers using pavement management are effective means of obtaining this information. Paterson and Robinson (*14*) include a set of criteria for evaluating PMSs to determine if the systems fit the needs of an agency.

Decision To Pursue Implementation and Adoption

The agency champion decides to pursue adoption of pavement management in the organization or to reject it. Documented information on the benefits and cost associated with pavement management are important at this stage. Information on how the costs of implementation, the benefits it will provide, and the changes that will be required in the existing agency are very important at this point. Implementation efforts by other agencies using pavement management can be used to demonstrate the costs and effects. Many times the decision point is not a single instant in time but is reached over a period of time during the forming of attitudes, as discussed in the previous step.

Development of Alliances

Pavement management usually crosses several traditional divisions of authority within an agency, including those departments responsible for pavement design, maintenance, rehabilitation, planning, programming, and construction. PMSs are also only one of several infrastructure management systems in most agencies and so must interface and harmonize with other systems. Pavement management normally crosses functional lines and their associated management processes: design, utilities, traffic control, traffic capacity planning, budgeting, information management, maintenance management, work management, and others. The information management aspect is particularly important because it has a central role for all management processes. Members of each agency and subagency that must interact with the pavement management process could conceivably prevent or retard its adoption. Therefore, a very important step is the development of an alliance of key individuals from each affected department that is in favor of the adoption of pavement management. These individuals should generally formulate an initial set of goals that they hope to achieve with pavement management.

Getting Pavement Management on the Agenda

In most agencies, innovations that affect the management efforts of several departments, such as pavement management, must be approved by at least the agency director and often by elected officials. These officials must be convinced that the current process needs to be changed and that pavement management can provide the needed help. Before they will be convinced, pavement management must become a part of the agenda, formal or informal, from which the decision makers work. Getting pavement management on the agenda focuses the attention and energy of the agency on pavement management as a topic to be addressed. Many times this is the most difficult step, and it may require considerable effort and time for the pavement management champion. The alliance of department managers with established preliminary goals is helpful, and sometimes absolutely essential, in getting pavement management on the agenda for discussion with the leaders who must approve changes to the management process and structure.

Phase 2: Obtaining Corporate Decision

In Phase 2 the agency management commits to implementing pavement management. One of several decision-making processes is normally used to reach the decision. The type of process used depends on the type of agency, organizational structure, and personalities of the managers in the agency. Normal decision-making processes include the following types:

- Optional decision: choices to adopt or reject are made by an individual independent of the other members of the agency.
- Collective decision: choices are made by a consensus of the members of the agency.
- Authoritative decision: choices are made by relatively few in the system who have the power, status, or technical expertise.
- Combination decisions: various elements of the choices may be made by some combination of the decision processes described here.

In many agencies, some combination of all of the different decision-making types is used. The decision to implement pavement management may be authoritative because it is forced on the agency by policies of outside agencies or the agency administration. The actual selection of the PMS may be based on collective decisions. Some groups within the agency may have the option of being involved.

Decisions can also be contingent on previous decisions. A previous investment in expensive data collection equipment may force the use of that equipment in the pavement management processes being adopted or developed. Decisions may also be conditional. For instance, the decision may include a provision that pavement management will be implemented for a small portion of the pavement network on a trial basis. At the end of the trial implementation, an evaluation would be made to determine whether to continue, modify the selected approach and try again, or discontinue implementation.

In this phase, the pavement management champion must convince the agency's management that pavement management is appropriate for the agency. The method of decision making within the agency will affect on how the pavement management champion organizes the information, gets the topic on the agenda (formal or informal), and develops support for the pavement management decision, but the method of decision making has little impact on the information needed. The champion must guide the agency through the same steps that the champion went through to make the decision to adopt pavement management.

Agency Persuasion

The champion must have adequate knowledge to demonstrate that the pavement management approach is better for the agency than the current management approach. Knowledge of the principles of pavement management are important at this time so the champion can explain the concepts to the decision makers. The pavement management champion must show that some problems are difficult or impossible to address with the current system and must persuade the decision makers that pavement management can help the agency achieve its management objectives.

The "how-to" knowledge is critical at this point of presenting the advantages and disadvantages of pavement management processes as compared with the way that current procedures work. The champion must know what information is needed, how the system is used, what answers it can provide, how much it will cost to implement, what benefits it will provide, and what changes will be required in the existing agency. All new management approaches create uncertainty about expected consequences, and the champion must have enough information to reduce that uncertainty to the point where the agency decision makers can see that the pavement management process would be helpful to the agency. Demonstrations of operating pavement management processes, case studies, formal training sessions, and presentations by other agencies using pavement management are effective means of providing this information.

Agency Decision

The agency decision makers decide to adopt (or reject) formalized pavement management for the agency. This is the culmination of the persuasion stage previously described. In some instances, the decision is made to reject pavement management, but no such decision is final in most agencies. The decision to reject forces the champion to start over with the collection of information and other steps described. The decision can be conditional on using a trial implementation, with the final implementation decision to be made later.

Formation of Steering Committee

A steering committee should be formed; it should be composed of upper-level management personnel and possibly should include elected officials. All departments affected by or involved in the implementation of pavement management should be represented on this committee. The committee should provide the support needed to facilitate any changes created by the pavement management process that cross traditional lines of authority. The committee should prepare goals for the implementation committee or champion and should provide the resources to achieve the goals. Although the committee meetings may be time consuming, it is essential to have the interaction of all affected groups; their "buy in" of the pavement management support software and procedures selected is critical. Otherwise, some of them will undoubtedly erect barriers to full implementation and use of pavement management.

Gaining of Commitment for Funding

Real commitment is achieved in most agencies when funding is committed. The steering committee should ensure that adequate funding has been allocated to support pavement management implementation. The available funds may control the rate at which implementation can proceed. Funding can be allocated incrementally to provide for a pilot implementation and then staged implementation for the remainder of the network.

Formation of Implementation Group

In small agencies the implementation group may be a single person, preferably the pavement management champion. In larger agencies, the group can consist of a separate pavement management work group. The group must convert the goals prepared by the steering committee into a work plan that details the tasks and resources required to adopt and implement pavement management in the agency. The group is responsible for the day-to-day efforts throughout the implementation period. It should be responsible for completing the remaining steps described subsequently; however, this group must work closely with the implementation steering committee. The working group should include representation from all of the major user groups. However, one person must be in charge and have authority to make day-to-day decisions.

Selecting and Testing of Pavement Management Processes

So far, the decision to adopt or at least to complete a trial implementation of pavement management has been reached by the agency. The pavement management approach, the software, and the data collection processes have not been selected. This phase normally includes matching and restructuring processes. The agency must find the PMS components, data collection methods, pavement management software, and management procedures that meet the needs and constraints of the agency. In many cases this requires adopting existing components and processes and modifying them to meet the special needs of the agency. This is the first phase within the guidelines when pavement management is actually being used in the agency.

Organizational Analysis

The implementation group compares the pavement management process with the existing process to determine how the new process can be used to facilitate pavement decisions or alleviate perceived problems. The group must review the existing organization, methods, and procedures to determine how the pavement management process will support decision making within the agency. The decision support provided by the adopted pavement management process must match agency needs. Location of the person or staff responsible for pavement management in the agency is often a difficult decision. A PMS that matches the methods and procedures currently used by the agency has a much better chance of being fully adopted and used than one that requires major changes in the organizational lines of communication, chain of authority, data collection procedures, and data storage processes. However, the opportunity to improve the efficiency of management within the organization should still be considered, because duplication of functions such as data collection might be avoided. Changes in organizational structure, processes, or lines of communication should be developed carefully in the context of all pavement management processes and should be planned rather than allowed to happen in isolation.

The organizational analysis should include a review of agency structure, communication flow, data collection processes, existing data bases, other affected infrastructure systems, data flows, and decision-making processes. The implementation group must have the information to demonstrate the problem and show how available pavement management support software and processes provide the needed solutions. Accurate, reliable information on the costs and benefits of the various PMSs, software, and data collection procedures are critical at this time. Generally the implementation group must provide information and show how similar agencies have used the selected procedures, approaches, and software. To reduce the anxiety of others in the agency, the group must demonstrate the relative advantage provided by PMSs and the compatibility with existing procedures.

Selection and Design of System

Systems design must follow organizational analysis. The activities should include selection or development of the decision support software, determination of the data to be collected, definition of the data collection processes, and decisions about data storage processes. Of special importance in designing the pavement management process to fit the needs of the agency are the central and common aspects of information management as they affect data processing and storage. The information management system architecture must be developed with attention to harmonizing data standards, definitions, and reference systems. The data to be collected, the cycle of data collection, and the updating of the data base must be defined. In this step, basic decisions must be made about the division of effort between network and project-level pavement management processes as well as the interface between network- and project-level management. This step will determine where the pavement management support software and staff should be located and who will be responsible for ensuring that data are collected on a timely basis. The step should include development of requirements for training resources and software support. It may also include purchase of hardware and associated software.

This step can be time consuming, and it should involve the working group, with several reviews by the steering committee. Those selecting the system should ensure that the data collection requirements of the process selected can be completed or supported. They should make sure that the system addresses all of the network-level questions required by the agency, that it can interface with the desired project-level system, and that it supports the existing management structure of the agency.

Modification of Selected Pavement Management Process

Staff of every pavement agency think their organization and its problems are unlike those of any other agency. They always see a need to modify any system to make it fit their perceived unique situation and problems. Many times the modifications are minor changes to reports and data collection procedures, but these are important so that acceptance of the PMS is ensured. Thus, adaptability is important at this time. However, the system must still be perceived as appropriate and affordable to implement while also being compatible with current management procedures. Thus, the systems, processes, and methods selected in the previous step are modified to fit the needs of the specific agency.

Preparation of Staged Implementation Plan

The implementation should be planned in as much detail as possible, even though it will probably be changed at a later date. The planning is normally done by the implementation group and approved by the steering committee. It is generally not possible to implement pavement management for a large network in a short time. However, each data collection process, software system, report, and data storage method must be tried to determine if each matches the needs and constraints of the agency. Changes will be needed on the basis of trial use of the software considered and selected. Those changes need to be planned for and identified early to avoid costly revisions. Using a pilot implementation in the phased implementation facilitates these adjustments. It also provides information to permit a more accurate estimate of the time and resources needed to complete implementation.

Staged implementation is also often necessitated by available funds and time. It is important to provide adequate time for the training needed for all of those involved in using pavement management during the implementation. Pavement management is not just software—it is the management process that includes all of the decision makers involved. These decision makers generally must make some adjustments to accommodate the new information that will come from the pavement management decision support software. They must be trained to use the information from the pavement management process effectively. Training is generally most effective when real information is available from the agency's own pavement network.

Implementation Through Trial Operation

The system selection is normally followed by a pilot or trial implementation. A small percentage of the network is used to test the PMS, decision support software, data collection processes, data storage, and other activities. The trial implementation should go through every management step in the pavement management process. This allows the agency to try the system, and it permits the identification of the elements that require modification to meet agency needs. It also serves as an aid in training the various users of pavement management; training needs to be a major part of the implementation efforts. The costs and results of the system should be thoroughly documented to help define the implementation resources and training needed for full implementation. Feedback from pavement management users should be programmed into the implementation process from the start so that users have an investment in the system and are more likely to assist with adoption rather than develop barriers.

Documentation of Results

It is crucial to document the findings of the trial implementation as they relate to the goals and work plans established earlier. Documentation will improve the identification of the resources and time needed to complete information retrieval. It will help determine if the current plan can be followed or if it must be modified on the basis of this more complete information. The documentation should include recommendations for modifications of the adopted PMS software, data collection processes, and continued implementation. The results often must then be presented to the steering committee before implementation continues.

Phase 3: Final Agency Decision

The agency decision makers make a commitment to continue with full implementation, to revise pavement management concepts, or to reject pavement management at this time. Before continuing into full implementation, the agency may decide to repeat a few previous steps because of problems encountered during the pilot implementation. Rejection may be a temporary setback, or it may result in years of delay before pavement management will be considered again. That makes it imperative that every effort be directed at successful trial implementation.

Documented information on the current and future costs of the selected system is important at this time, as is information on expected benefits. Results of trial implementations must show that the recommended system can provide the support needed by the agency and fit within the agency's constraints. Information from other agencies can be used to help demonstrate the benefits, but costs should come from the pilot or trial implementation within the agency. The steering committee or implementation group need to present the results from the preceding steps to the decision makers and convince them that pavement management processes should be continued through full implementation.

Revision of Goals

After the pilot implementation, the original goals developed by the steering committee should be thoroughly reviewed. On the basis of the organizational analysis and the information gained from the pilot implementation, goals should be revised to match the agency needs to the constraints, especially the available resources needed for full implementation and use. It is particularly important to consider training and support plans in the goals and funding needs at this point.

Revision of Implementation Plan

The pavement management implementation group should review the work plans, resource requirements, and time requirements. To revise the implementation plan, the implementation group should work from the revised goals using the information learned during the pilot implementation. The PMS, the software, and the data collection methods should be thoroughly reviewed. At this point it is possible to make major changes fairly easily; after full implementation, major changes are almost impossible for a number of years.

The revised work plan can still be staged. The staging can be by area, system, or other division that meets the needs of the agency. Training and support plans are of particular importance at this time to ensure that all potential users are familiar with pavement management concepts and how they can interact with the pavement management process. Major changes to software, data collection, or data storage should be planned to allow the implementation to continue at the same time that required improvements are under way.

Phase 4: Implementation for Entire Network

After pilot implementation, the pavement management process must be implemented for the remainder of the network. At this same time, needed modifications must be completed. The agency may need to collect new data or collect the same data in a different way for the pilot network. The steps in this phase should include revision of the system, software, and data collection processes, full implementation, and training.

Completion of Required Revisions

The revisions to the software, data collection processes, and data storage procedures need to be made. The revisions may be relatively simple, or they may be major. They can be completed concurrently with the following step.

Completion of Revised Implementation

Completion of revised implementation includes the most intensive data collection and training activities. Several tasks may run concurrently. The implementation can still be staged.

Data Collection

The data collection and inclusion of various elements of the network are often staged even after pilot implementation. The freeways, primary arterials, or primary runways might be included in the first stage. The next most important set of pavements may be included in the next stage. This would continue until the entire network is included in the implementation. Haas (*15*) gives guidance on data collection. A method to ensure the quality of the data collected must be established and in place at this time.

Staff Training

Training should be included as an essential element of each activity. As the scope of pavement management increases and the implementation steps are completed, all of the users and operators involved in pavement management must be trained in pavement management concepts and system use. Included are those who will see new or more complete reports and those who will use the information from the reports to make decisions. A series of meetings may be held with the funding authority to educate the staff about the new information or form of data they will receive. The general public should also be included in the training so that they understand how their facilities are being managed.

Phase 5: Effective Pavement Management Operations

Once the initial data have been collected for the entire network and the first set of reports has been completed, many consider the system implemented. However, a true pavement management process is not a one-time condition survey followed by a report. Pavement management is a structured method for making decisions about pavements, it requires a long-term commitment to improve management practices. A commitment will be needed to repeat the data collection and analysis activities periodically. If pavement management is to be effective, it must become a part of the routine management process and must affect the decisions being made. The purpose of Phase 5 is to institutionalize the pavement management process within the managing organization.

Matching of Output to Management Styles and Needs

Considerable effort is often required to educate upper-level managers about the benefits of using pavement management and the reports generated by the pavement management decision support software. No matter how good the earlier investigations are, some of the reports generated by the software will not meet the needs of the upper-level managers. Pilot implementation will identify some changes, but many needed changes in reports and formats will be found only when the system starts working. The pilot implementation should have identified data problems and needs that should have been corrected subsequently. The changes identified at this point are primarily related to report structure, report format, and presentation style. Such changes are needed at this point in part because the users will not know exactly what they want until they see some of the reports from the system. As they learn to use the information, they will see other ways of using it. As new senior personnel use the system, additional requirements will be identified. It is essential that these requirements be met to maintain the credibility of the system. Some senior managers will be reluctant to use the results of the pavement management process if they do not fully understand them and believe in the accuracy of the information. Considerable training on an informal basis is often needed with some senior managers.

Placement in Organization

To ensure continuity of PMS development, provision must be made to formalize pavement management into the organizational structure. Although a single champion may have led the development and implementation of pavement management in the organization, pavement management responsibilities must be formally designated to survive inevitable management and personnel changes.

The formal responsibility may become a part-time requirement for a single person in small agencies, or it may be a formal assignment of duties to several people in several areas for larger, more complex agencies. The formal organizational arrangement should facilitate development and distribution of information to support the organization's decision making processes at upper-, middle-, and lower-management levels.

Of special importance is the assignment of responsibility for data collection, data entry, and maintenance of integrity of the data base. Only one assigned person should be responsible for adding and modifying data for which the group is responsible. Access for retrieving, reporting, analysis, and other uses of the data should be made as easy as possible to all interested parties.

Training on Continuing Basis

Changes and improvements—especially in the reporting system, the data collection processes, and the analysis techniques—continue indefinitely, although at a much-reduced rate. Training is needed when changes are made to the systems; however, cyclic training is needed even when changes do not occur.

Training must continue on a repeating cycle. Many pavement management personnel work with software and report generation for only a few weeks each year, and condition data are normally collected for a short period each year. These individuals need refresher training each year. The responsible staff will experience turnover, and new members need training on a continuing basis.

Adjustment and Improvement To Meet Changing Capabilities and Needs

Pavement management procedures and data collection procedures continue to evolve as technologies advance. Computer capabilities continue to increase, allowing more complex analysis and storage of larger data sets. Decision support processes that are more easily understandable are being developed, and these can replace complex, difficult-to-understand procedures.

The software system should be modular in form and flexible enough to allow improvements and modifications over time. However, changes made too frequently will frustrate users who think that once they learn the system, it is changed. Training is essential to help users understand the changes.

Assistance

Many agencies use consultants and others outside agency personnel to assist in pavement management implementation. This assistance can be helpful at almost any stage. The amount of assistance needed and its timing depend on the level of pavement management knowledge within the agency. The first phase is generally completed in-house. In some cases, it may be helpful to have outside assistance during the agency persuasion stage. However, when assistance is included at this stage, those who are providing that assistance should be selected to ensure that they are not biased toward one set of software. Such bias can create problems, because many consulting firms have their own software and data collection procedures. Selecting those consultants often means selecting their software and data collection procedures. The agency should complete an investigation of its needs and select the software system and data collection processes that best fits its needs before selecting a consultant with proprietary software to assist in implementation. However, some agencies need assistance in determining their needs and selecting the best system.

Some consulting firms will assist in defining needs and selecting a system. Some firms have a range of software that can fit almost any agency's needs. However, the consulting request for proposal and contract must be properly prepared to include three stages. The first stage should generally be an analysis of needs and identification of the software and data collection needs of the agency. The second stage should be for trial implementation and training. The third stage should be for modifications, training, and completion of implementation.

Some agencies lack adequate personnel to collect the data needed for initial and continuing surveys. Several firms can assist in this process. The request for proposal and contract should be carefully prepared to ask for the data to be collected using the required distress survey procedure, roughness measures, and so forth, without unnecessarily restricting the work. If distress is to be collected, the distress survey manual that is used, the accuracy required, and the format for entry into an automated data base should be identified. A demonstration that the consultant can provide the required information should be required, and the agency should have a quality-assurance plan in place to check the work while it is in progress. The marketplace costs should be allowed to determine if the data will be collected manually or by automated equipment.

SUMMARY

The overall goal here is to make pavement management the standard operating procedure in agencies for pavement decisions. This occurs when agency personnel look to pavement management for information and support when pavement questions occur, funding is planned, and sections are programmed for maintenance and rehabilitation.

A series of phases and steps have been prepared to guide potential adopters of pavement management and those who are trying to make better use of existing PMSs. Each agency is different, and no single set of steps can be followed blindly. The pavement management champion is primarily responsible for working through these guidelines and preparing implementation plans for the agency. Some steps may need to be dropped, and the order of some steps may need to be changed. After initial efforts, some steps may need to be repeated. However, most of these steps are necessary for successful implementation and use of PMS.

Developing an implementation plan can take considerable effort and time, but this planning is essential if the system is to be fully implemented. Failure to involve all users in the process has had dire consequences in several agencies. Smith (*16*) describes some of the problems that have been encountered. This implementation guide was developed to help avoid some of those pitfalls and overcome others. An FHWA course book (*5*) contains a series of checklists that may also be helpful in the implementation process.

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OPTIMIZATION

Application of Markov Process to Pavement Management Systems at Network Level

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The rate of pavement deterioration is uncertain, and a pavement management system (PMS) should portray this rate of deterioration as uncertain. A wide variety of PMSs are used, but unfortunately either these systems do not use a formalized procedure to determine the pavement condition rating, or they use deterministic pavement performance prediction models, or they assign the pavement state transition probabilities on the basis of experience. The objective of the research was to develop a probabilistic network-level PMS on the basis of pavement performance prediction with use of the Markov process. Pavements with similar characteristics are grouped together to define the pavement families, and the prediction models are developed at a family level. The pavement condition index (PCI), ranging from 0 to 100, is divided into 10 equal states. The results from the Markov model are fed into the dynamic programming model and the output from the dynamic programming is a list of optimal maintenance and repair (M&R) recommendations for each pavement family-state combination. If there are no constraints on the available budget, the M&R recommendations from the dynamic programming will give a true, optimal budget. However, because the budgets available are usually less than the needs, two prioritization programs have been developed to allocate the constrained budgets in an optimal way. The first prioritization program is based on simple ranking of the weighted optimal benefit/cost ratios, and the second is based on the incremental benefit/cost ratio. The output from the two programs is a list of sections to be repaired, type of M&R alternatives selected, cost of M&R alternatives, and section and network benefits. The results from the two prioritization methodologies are compared through an actual implementation on an existing airfield pavement network. The prioritization using the incremental benefit/cost ratio program uses the available constrained budget to the best of the full limit. To maintain a specified network PCI, the optimal benefit/cost ratio program will spend less money than the incremental benefit/cost ratio program. The developed optimization programs are very dynamic and robust for network-level PMSs.

The major objectives of a network-level pavement management system (PMS) are to develop short- and long-term budget requirements and to produce a list of potential projects based on a limited budget. The optimum approach to achieve these objectives relies heavily on the prediction of pavement performance and life-cycle cost analysis of all feasible maintenance and rehabilitation (M&R) strategies. To find the optimal solution for the allocation of available funds, operations research techniques are used that may be either deterministic or probabilistic.

Because the rate of pavement deterioration is uncertain, the budget requirement developed at the network level should treat this rate of deterioration as uncertain. Modeling uncertainty requires the use of probabilistic operation research techniques. Most of existing PMSs use neither a formalized procedure to determine the pavement condition rating nor a deterministic approach to model the pavement rate of deterioration. PMSs that use probabilistic prediction models such as Markov models mostly assign the state transition probabilities on the basis of the field staff's experience, which can affect the accuracy of pavement performance prediction. An approach based on the Markov process has been developed for network-level optimization. Homogeneous and nonhomogeneous Markov chains have been used in the development of pavement performance prediction models. The use of Markov chains in prediction models captures the uncertain behavior of pavement deterioration. Integration of the Markov chains–based prediction models with the dynamic programming and the prioritization programs produces a list of optimal M&R treatments and a budget that satisfies the given performance standards. Conversely, a list of potential projects can be generated so that a limited available budget is spent in an optimal way.

Research Approach

The overall flow chart for the research study is shown in Figure 1. The major portion of research was a part of an ongoing effort to improve the MicroPAVER system developed at U.S. Army Corps of Engineers Research Laboratory in Champaign, Illinois. The development of the Markov prediction model (*1*), the dynamic programming (*2*), and the prioritization based on optimal benefit/cost ratio (*3*) of the overall flow chart have been published earlier. This paper describes in detail the following research elements:

- Development of a prioritization program based on the incremental benefit/cost ratio technique,
- Integration of the Markov prediction process with the dynamic programming and the prioritization programs, and
- Example application of the network optimization system to an existing airport pavement network.

Development of Markov Prediction Model

A pavement begins its life in a near-perfect condition and is then subjected to a sequence of duty cycles that cause the pavement condition to deteriorate. In this study the state of a pavement is defined in terms of a pavement condition index (PCI) rating. The PCI, which ranges from 0 to 100, has been divided into 10 equal states, each of which is a PCI interval of 10 points. A duty cycle for a pavement is defined as 1 year's duration of weather and traffic. A state vector indicates the probability of a pavement section being in each of the 10 states in any given year. Figure 2 is the schematic representation of state, state vector, and duty cycle.

After filtering and outlier analysis, all the surveyed pavement sections of a family are categorized into 1 of the 10 states at a particular age. A pavement section is defined as a part of the pavement network that has same type, structure, construction history, condition, use, and rank. A pavement family is defined as a group of pavement sections of similar characteristics. It is assumed that all the pavement sections are in State 1 (PCI of 90 to 100) at an age of 0 years. Thus, the state vector in Duty Cycle 0 (age = 0) is given by (1, 0, 0, 0, 0, 0, 0, 0, 0, 0), because it is known (with probability of 1.0) that all the pavement sections must lie in State 1 at an age of 0 years.

To model the way in which the pavement deteriorates with time, it is necessary to establish a Markov probability transition matrix. In this research, the assumption is made that the pavement condition will not drop by more than one state (10 PCI points) in a single year. Thus, the pavement will either stay in its current state or transit to the next lower state in 1 year. Consequently, the probability transition matrix has the form

$$P = \begin{matrix} p(1) & q(1) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p(2) & q(2) & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & p(3) & q(3) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & p(4) & q(4) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p(5) & q(5) & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & p(6) & q(6) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & p(7) & q(7) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & p(8) & q(8) & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p(9) & q(9) \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{matrix}$$

where $p(j)$ is the probability of a pavement staying in State j during one duty cycle, and $q(j) = 1 - p(j)$ is the probability of a pavement's transiting down to next state $(j + 1)$ during one duty cycle. The entry of 1 in the last row of the transition matrix corresponding to State 10 (PCI of 0 to 10) indicates an "absorbing" state. The pavement condition cannot transit from this state unless repair action is performed.

The state vector for any duty cycle t is obtained by multiplying the initial state vector $\tilde{p}(0)$ by the transition matrix P raised to the power of t. Thus,

$$\tilde{p}(1) = \tilde{p}(0) * P$$

$$\tilde{p}(2) = \tilde{p}(1) * P = \tilde{p}(0) * P^2$$

$$\dots$$

$$\tilde{p}(t) = \tilde{p}(t-1) * P = \tilde{p}(0) * P^t$$

With this procedure, if the transition matrix probabilities can be estimated, the future state of the pavement at any duty cycle, t, can be predicted.

Development of Pavement Families

Input: PCI Vs. Age raw data and common characteristics to classify pavement sections into families (Surface type, Traffic, Primary cause of distress Maximum deflection Do, etc.).

Output: Classification of pavement families with PCI Vs. Age data.

Development of Markov Prediction Models

Input: Pavement families with PCI Vs. Age data

Output: Markov transition probabilities for each pavement family.

Dynamic Programming Program

Input: Markov transition probabilities, M & R options, M & R cost by state and family for each M & R alternative, planning horizon, interest and inflation rates, performance standard by family, benefits by state.

Output: Optimal M & R action (on basis of minimized cost) for family/state combination with associated benefit/cost ratio and benefits & costs of all feasible M & R alternatives.

Prioritization Based on Optimal Benefit/Cost Ratio

Input: Optimal M & R recommendations and the benefit/cost ratio for each section, available budget, weighting factors, etc.

Output: M & R action for each section including do nothing.

Prioritization Based On Incremental Benefit/Cost Ratio

Input: All feasible M & R options and the associated benefits and costs for each section, available budget, weighting factors, etc.

Output: M & R action for each section including do nothing.

Implementation to An Existing Airport Pavement Network

FIGURE 1 Research approach flow chart.

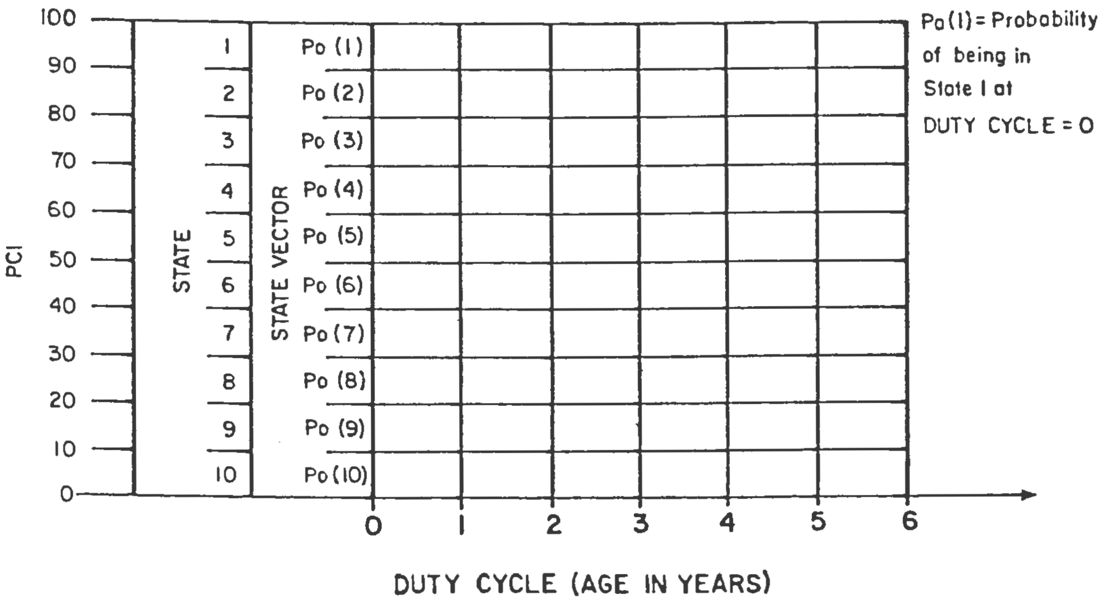

FIGURE 2 Schematic representation of state, state vector, and duty cycle.

To estimate the transition matrix probabilities, a nonlinear programming approach is used. The objective of the search is to determine values of the nine parameters, $p(1)$ through $p(9)$, that would minimize the absolute distance between the actual PCI-versus-age data points and the expected (predicted) pavement condition for the corresponding age generated by the Markov chain using these nine parameters.

The objective function has the following form:

Minimize

$$\sum_{t=1}^{N} \sum_{j=1}^{M(t)} |Y(t,j) - E[X(t,p)]|$$

where

N = total number of duty cycles (age) for which PCI-versus-age data are available within each family,

$M(t)$ = total number of data points recorded at a duty cycle (age) t,

$Y(t,j)$ = PCI rating for each sample taken at a duty cycle (age) t, and

$E[X(t,p)]$ = expected value in PCI at a duty cycle (age) t, as predicted by current Markov values.

To allow for changes in traffic loads and maintenance policies over the pavement life, different duty cycles have been introduced to create a nonhomogeneous Markov model. A scheme has been developed in which the life of the pavement is divided into zones. It is assumed that each zone has a constant rate of deterioration and, hence, that a constant duty cycle has been assumed within each zone. The rate of deterioration is assumed to vary from one zone to another; therefore, different duty cycles have been assigned to different zones.

Because the duty cycle within a zone is assumed to be constant, a homogeneous Markov chain has been used for each zone and a separate transition matrix has been developed for each zone. The duty cycle varies from one zone to another. Therefore, a nonhomogeneous Markov chain has been used for transition from one zone to another. Figure 3 shows an example pavement condition prediction curve that uses a nonhomogeneous Markov model.

Dynamic Programming Model for Network-Level Optimization

The probabilistic dynamic programming model for network-level optimization developed as a part of an

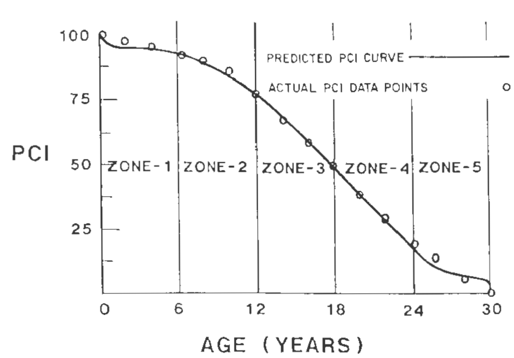

FIGURE 3 Pavement condition prediction curve using Markov model.

earlier research has been described by Feighan et al. (*2*). The Markov transition probabilities generated from the Markov prediction model are used in the probabilistic dynamic programming model. The objective function of dynamic programming is based on minimization of the M&R cost for the network. The dynamic programming model has been further modified to produce benefits and costs of all feasible M&R alternatives for every family-state combination for every year of the analysis period. The output from the dynamic programming consists of the following:

1. Optimal M&R alternatives for every year (stage) for every family-state combination.
2. Present worth costs that correspond to the optimal M&R alternatives for every year (stage) for every family-state combination.
3. The optimal benefit/cost ratios that result from following the optimal decisions, calculated for every family-state combination. The benefit is defined as the area under the PCI-versus-age curve over 1 year. The midpoint of each state is used to represent the benefit obtained in 1 year.
4. Benefits and present worth costs for all feasible alternatives for every family-state combination for every budget year.
5. Optimal M&R recommendations and the corresponding present worth costs, benefits, and benefit/cost ratios for Years 1, 2, 3, 4, 5, 10, 15, and 20, for every pavement family and for every state above or equal to the minimum allowable state.

The application of the optimal M&R recommendation from the dynamic programming will produce a true optimal M&R budget for the given constraints. However, it is possible that the available budget is less than the true optimal budget. Therefore, prioritization programs have been developed to spend the limited available budget in an optimal way. These programs are described in the following section.

Prioritization Methodologies

To achieve the maximum benefit from the limited available budget, two prioritization methodologies have been developed. The prioritization methodology based on optimal benefit/cost ratio was developed as a part of earlier research (*3*), and the prioritization methodology based on incremental benefit/cost ratio has been developed as a part of this research program.

Prioritization Using Optimal Benefit/Cost Ratio

A detailed description of this methodology is given by Feighan et al. (*3*). The prioritization method based on the optimal benefit/cost ratio uses the optimal M&R recommendations and the corresponding benefit/cost ratios for each family-state combination produced from the dynamic programming. On the basis of the user-defined weighting factors for each pavement section, all of the pavement sections in the given network are ranked with the use of weighted optimal benefit/cost ratios. The higher the weighted optimal benefit/cost ratio of a section is, the higher the priority of that section will be for repair. The available budget is allocated to the pavement sections by selection of one section at a time from the ranked section list. The search for the section selection is stopped when the available budget is completely exhausted. The do-nothing or routine maintenance is done for the sections that do not receive major rehabilitation.

Prioritization Using Incremental Benefit/Cost Ratio

The incremental benefit/cost ratio technique is a heuristic method for budget optimization. This technique is used to maximize benefits from limited M&R funds for one pavement section at a time (project-level optimization) or for a group of pavement sections to maximize the overall benefits (network-level optimization) (*4*).

The output from this program is a list of sections to be repaired, type of M&R alternative selected, cost of M&R alternative, section benefit, and total network benefits. The program also lists the section PCI before and after the M&R application and network PCI weighted and unweighted by section area.

The overall flowchart for the prioritization algorithm with the use of the incremental benefit/cost ratio technique is shown in Figure 4. The prioritization process is composed of five main modules:

1. Benefit computation,
2. Cost computation,
3. Routine maintenance,
4. Budget optimization, and
5. PCI adjustment.

Figure 4 also shows the input data required for this prioritization algorithm. A detailed description of each of the five prioritization modules is given next.

Benefit Computation Module

The flow chart for the benefit computation module is shown in Figure 5. Each section in the network is first identified on the basis of section characteristics and assigned pavement family. The section state is determined from the PCI value of the section. On the basis of the section's family-state assignment, the benefits of all feasible

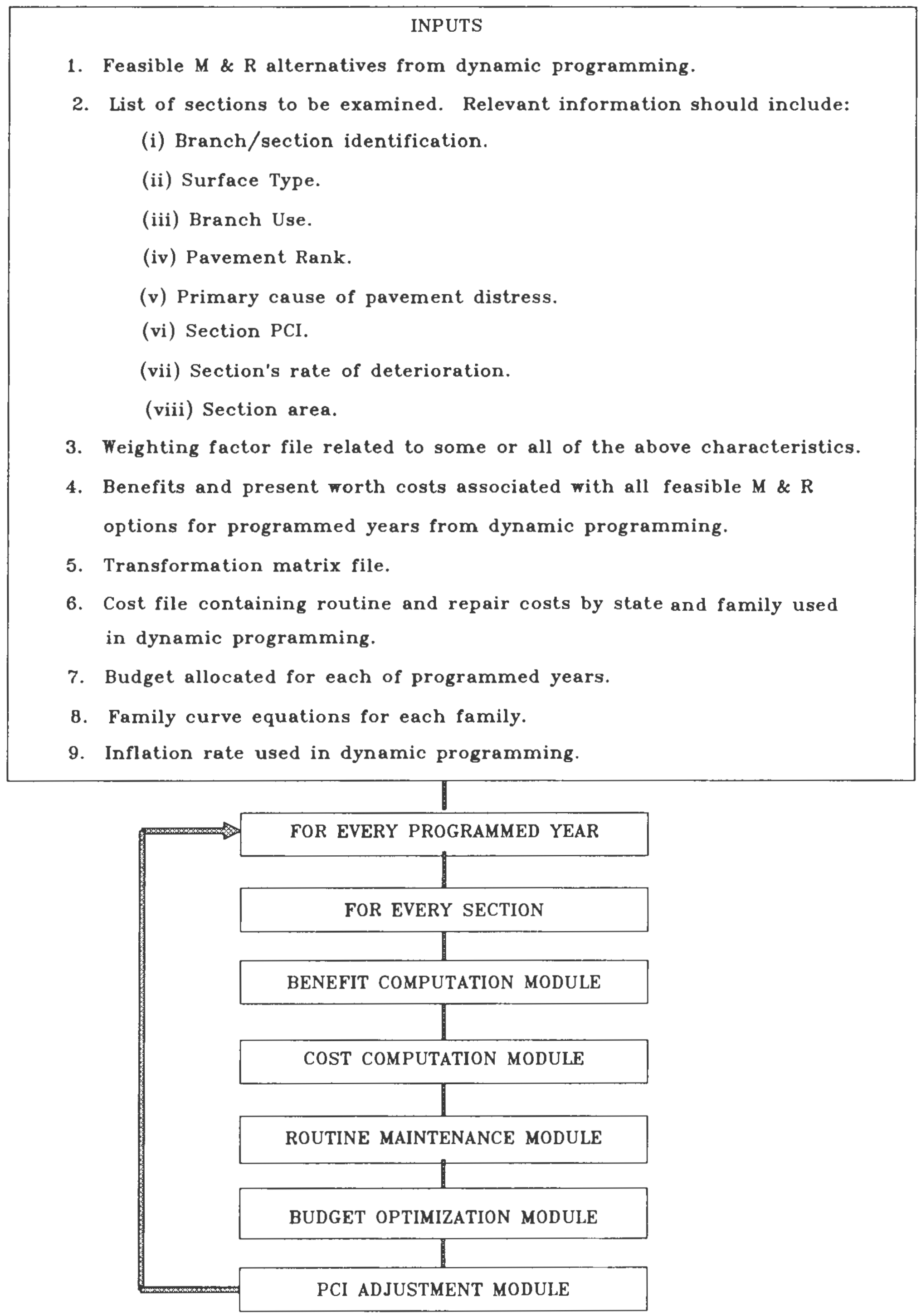

FIGURE 4 Prioritization using incremental benefit/cost ratio.

M&R alternatives are obtained that correspond to this family-state combination. They are multiplied by the user-defined weighting factors to obtain the weighted benefits for all feasible M&R alternatives of the section. Similarly, the weighted-section benefits for all the sections are calculated and stored for use in the budget optimization module.

Cost Computation Module

The flow chart for the cost computation module is shown in Figure 6. On the basis of each section's family-state assignment, the present-worth costs and initial costs of all feasible M&R alternatives that correspond to the family-state combination are obtained. The initial costs of all fea-

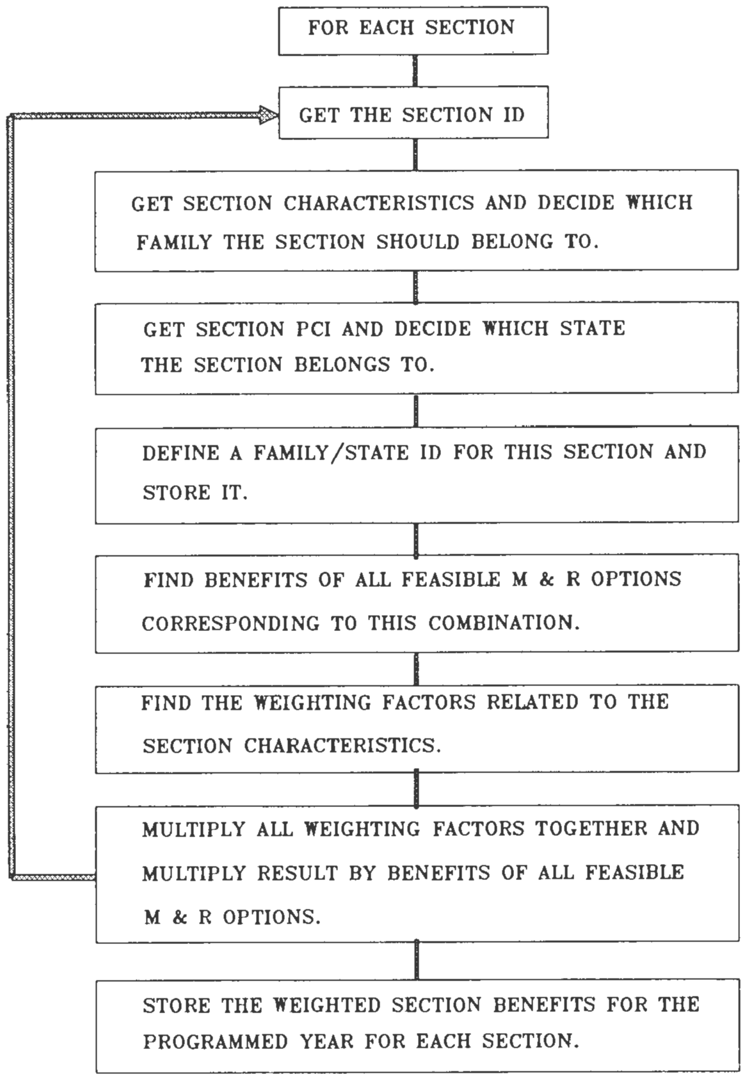

FIGURE 5 **Benefit computation module.**

sible M&R alternatives of a section are multiplied by the section area and inflation rate, and the inflated initial costs of each pavement section are stored for use in the budget optimization module.

Routine Maintenance Module

The routine maintenance module shown in Figure 7 is the same as the one used for the prioritization program that uses optimal benefit/cost ratio. The output from the routine maintenance module is directly used in the budget optimization module.

Budget Optimization Module

The flow chart for the budget optimization module is shown in Figure 8. In the budget optimization module, all feasible M&R alternatives of a section are identified, and the corresponding inflated initial costs, present-worth costs, and weighted benefits are obtained from the benefit computation module and the cost computation module. The available budget is obtained from the routine maintenance module. This information is used in the incremental benefit/cost ratio program to produce optimal M&R recommendation for each pavement section, including initial cost and type of treatment. The budget optimization module also gives the total network-weighted benefits corresponding to optimal M&R recommendations.

PCI Adjustment Module

The PCI adjustment module is shown in Figure 9. This module recomputes the PCI values for each section when the recommended M&R alternative is performed on the section. The pavement family curves developed from Markov output data are used for predicting the PCI val-

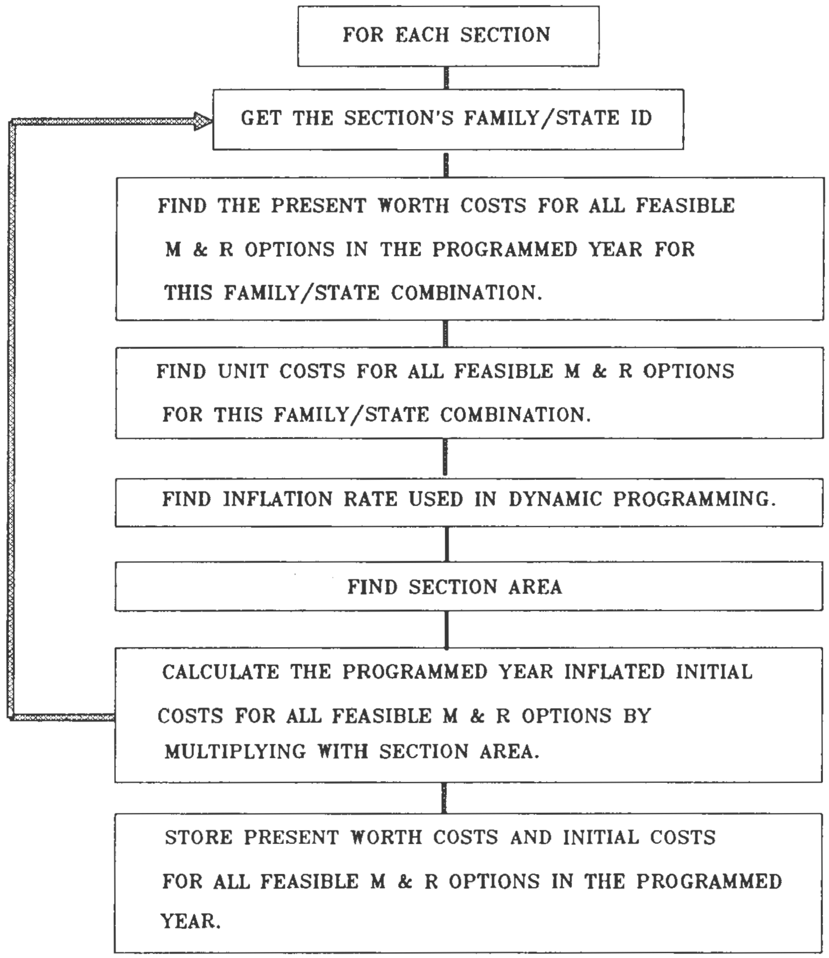

FIGURE 6 Cost computation module.

ues, because the comparison of the Markov prediction model results with constrained least-squares model showed similar trends.

Implementation

The purpose of this section is to demonstrate the applicability of the developed pavement management tools through implementation on an actual pavement network. The pavement performance prediction models that use the Markov process have been developed from data collected from 22 airports. Dynamic programming and prioritization schemes were applied at one airport to develop an optimal M&R plan. The following sections describe in detail the various steps of implementation.

Development of Pavement Performance Prediction Models

The Markov model defined earlier was used to develop the probabilistic pavement performance prediction models. The program was run on each of the pavement families from 22 airports. Table 1 presents the Markov transition probabilities for each pavement family.

Application of Dynamic Programming

One of the outputs from the dynamic programming is the optimal M&R recommendation for every family/state combination in every year of the analysis period. Dynamic programming does not produce the M&R recommendation directly at the section level. The following paragraphs describe the input data used in the dynamic programming and the output from dynamic programming.

Input Data for Dynamic Programming

1. Number of families: 13.
2. Interest rate: 9 percent.
3. Inflation rate: 6 percent.
4. Life-cycle cost analysis period: 20 years.
5. Number of maintenance options: three, which are (*a*) routine maintenance, (*b*) surface treatment, and (*c*) structural overlay.

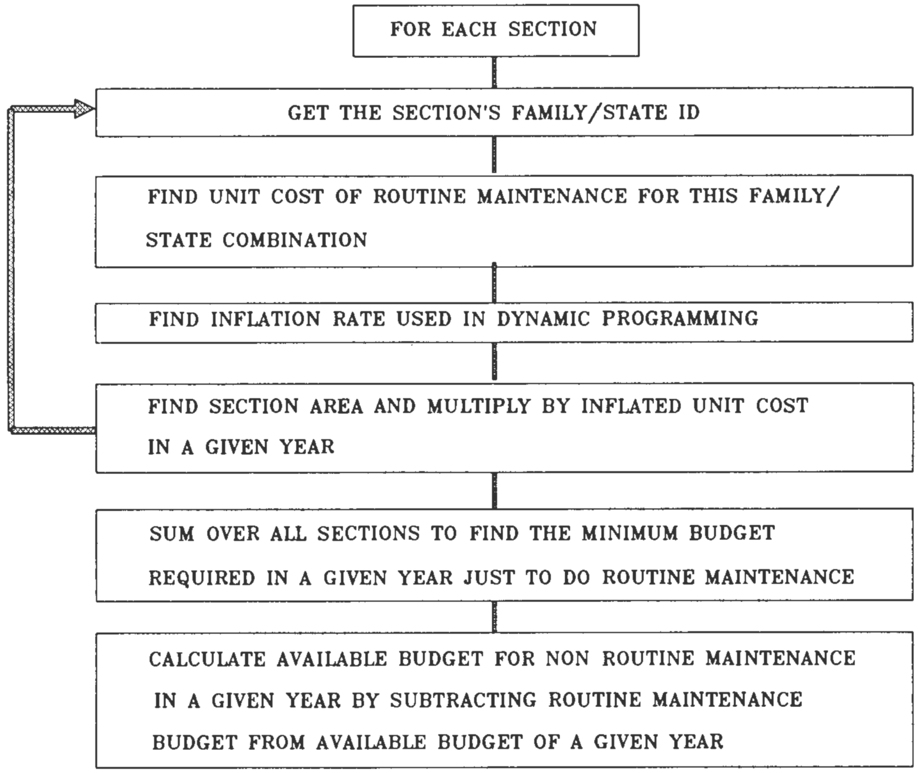

FIGURE 7 Routine maintenance module.

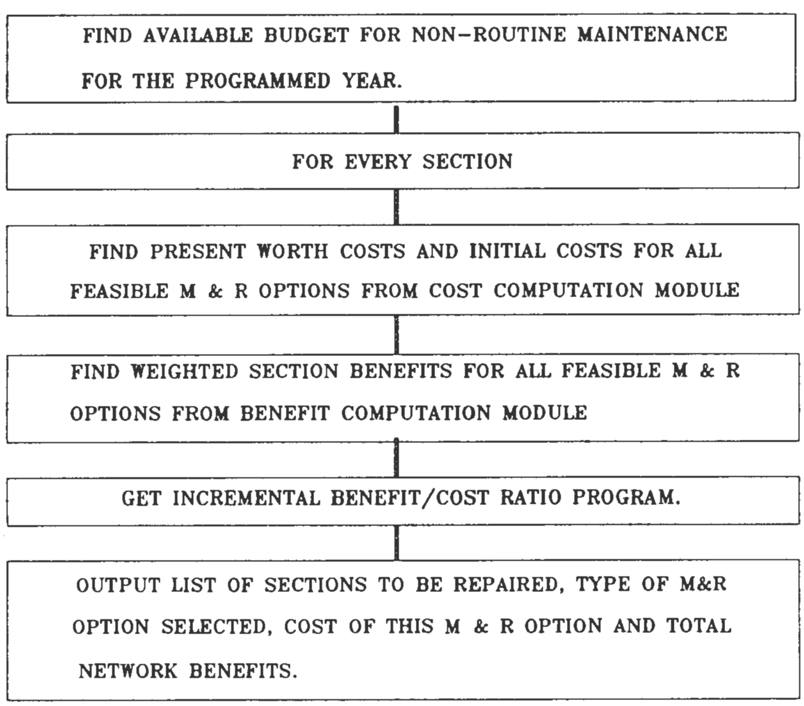

FIGURE 8 Budget optimization module.

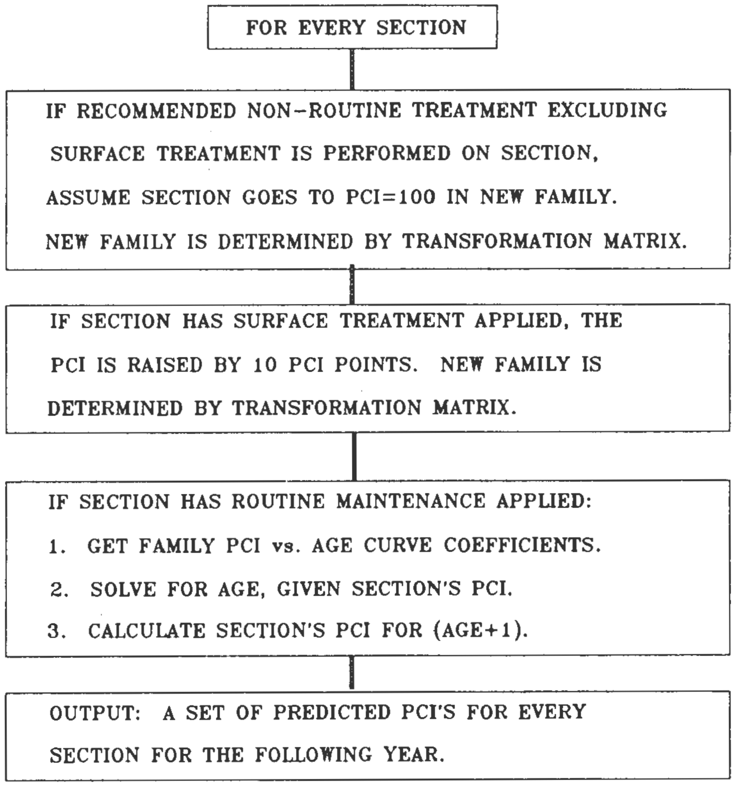

FIGURE 9 PCI adjustment module.

TABLE 1 Markov Transition Probabilities

Family Name	Zone	Age (Years)	State 1	State 2	State 3	State 4	State 5	State 6	State 7	State 8	State 9	State 10
RUNA	1	5	0.7000	0.9891	0.7661	0.7606	0.8750	0.4931	0.5006	0.3002	0.6454	1.0000
	2	18	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	1.0000
RUNB1	1	14	0.2111	0.5998	0.5839	0.6184	0.6344	0.2071	0.2639	0.3123	0.3534	1.0000
RUNB2	1	8	0.3184	0.1203	0.9485	0.7875	0.9898	0.3939	0.0950	0.9637	0.9046	1.0000
RUNB3	1	18	0.9900	0.6222	0.6205	0.6238	0.0012	0.5760	0.4346	0.2838	0.2147	1.0000
RUNB4	1	9	0.6000	0.6000	0.9900	0.9900	0.5059	0.5003	0.6896	0.2866	0.1905	1.0000
	2	14	0.9900	0.9900	0.9900	0.9900	0.0944	0.9681	0.9669	0.9669	0.9669	1.0000
RUNC	1	5	0.7000	0.7000	0.9900	0.9424	0.7441	0.6255	0.5620	0.5376	0.5322	1.0000
	2	18	0.0010	0.6999	0.4620	0.9900	0.8547	0.8351	0.7478	0.6269	0.8862	1.0000
RUNEND	1	11	0.8647	0.8992	0.8975	0.8964	0.4898	0.4857	0.5577	0.4752	0.2344	1.0000
	2	18	0.6000	0.6000	0.8742	0.7390	0.6395	0.5977	0.5809	0.5739	0.5709	1.0000
PTW1	1	9	0.3000	0.3568	0.8544	0.4733	0.0010	0.0325	0.0489	0.2845	0.3251	1.0000
PTW2	1	14	0.6993	0.8201	0.7765	0.7531	0.0016	0.0005	0.0010	0.0102	0.0447	1.0000
PTW3	1	18	0.9209	0.9349	0.9780	0.9821	0.9820	0.8822	0.8795	0.8794	0.8794	1.0000
CTW	1	4	0.4995	0.8005	0.0489	0.0013	0.4772	0.5003	0.5003	0.4607	0.9471	1.0000
	2	12	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	1.0000
	3	18	0.9000	0.9000	0.9900	0.9900	0.9900	0.9127	0.8966	0.8931	0.8925	1.0000
APRAC	1	6	0.6000	0.6000	0.7739	0.4853	0.5343	0.5498	0.5025	0.5002	0.9620	1.0000
	2	16	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9900	0.9613	0.7733	1.0000
APRPCC	1	14	0.6635	0.9628	0.9013	0.9011	0.2129	0.6280	0.6435	0.6502	0.6527	1.0000
	2	25	0.5000	0.5000	0.8270	0.7102	0.6418	0.6154	0.5837	0.5452	0.5160	1.0000

6. Minimum allowable state for each family: five for Families 1 through 13.

7. State benefits: the benefit is defined as the area under the PCI-versus-age curve over 1 year. The midpoint of each state was used to represent the benefit over 1 year. State benefits used in this analysis are given in Table 2.

8. Markov transition probabilities for each family: Markov transition probabilities given in Table 1 were used in the analysis.

9. Transformation matrix: transformation matrix defines the new pavement family to move to if a certain M&R action is taken.

10. M&R Cost: PCI-versus-M&R cost relationships were used to calculate M&R cost of application of each of three maintenance options to each pavement family-state combination.

Dynamic Programming Output

The output from dynamic programming for every family-state combination consists of

1. Optimal M&R recommendations in every year,
2. Present-worth cost of optimal M&R recommendations,
3. Benefit/cost ratio of optimal M&R recommendations,

TABLE 2 State Benefits Used in Dynamic Programming

State	PCI Range	Benefit
1	90-100	95
2	80-90	85
3	70-80	75
4	61-70	65
5	50-60	55
6	40-50	45
7	30-40	35
8	20-30	25
9	10-20	15
10	0-10	5

4. Benefits and costs of all feasible M&R alternatives, and
5. Optimal M&R recommendations and the corresponding present-worth costs, benefits, and benefit/cost ratio in Years 1, 2, 3, 4, 5, 10, 15, and 20 for pavement states equal to or less than 5.

The data in Elements 1 through 4 listed previously are directly used in the prioritization programs.

Prioritization

Two computer programs have been written for prioritization;

1. Prioritization using optimal benefit/cost ratio, and
2. Prioritization using incremental benefit/cost ratio.

Both programs were used to develop a 5-year M&R plan for the airport.

Prioritization Using Optimal Benefit/Cost Ratio

Five budget scenarios were considered for the 5-year analysis period; the scenarios are given in Table 3. Budget Scenario 1 had available budgets of $5 million, $4 million, $3 million, $2 million, and $1 million, respectively for the programmed Years 1 through 5. The reason that a very high budget was selected for the first year of the analysis period was that most of the sections at the airport require major rehabilitation during the first year of the analysis period. Another reason that higher available budgets were selected for the remaining years of the analysis period was to determine the budget required if no budgetary constraints are applied. Budget Scenarios 2, 3, and 4 had uniform available budgets of $1.5 million, $1.0 million, and $500,000, respectively, for every year of the analysis period. Budget Scenario 5 had $4.5 million available for the first year so that all major M&R requirements are satisfied and then a uniform budget of $100,000 for the remaining years of the analysis period. The effect of different budget scenarios on network PCI is shown graphically in Figure 10.

The curves of Budget Scenarios 1 and 5 are almost identical because both scenarios have enough money allocated during the first year that all optimal M&R requirements identified by the dynamic programming are satisfied. Budget Scenarios 2, 3, and 4 have uniform budgets allocated over the 5 years of the analysis period. Budget Scenario 4 shows a decrease in network PCI with time.

TABLE 3 Prioritization Using Optimal Benefit/Cost Ratio

Budget Scenario	Year	Budget Available	Budget Used	PCI Before	PCI After	Network Benefit
1	1	5,000,000	2,706,638	60	88	8,065
	2	4,000,000	60,823	88	86	5,393
	3	3,000,000	40,260	86	84	5,093
	4	2,000,000	108,502	84	83	4,869
	5	1,000,000	160,390	83	82	4,555
2	1	1,500,000	1,355,013	60	72	7,998
	2	1,500,000	1,207,587	72	82	5,759
	3	1,500,000	575,695	82	85	5,277
	4	1,500,000	108,502	85	84	4,869
	5	1,500,000	160,390	84	83	4,555
3	1	1,000,000	927,987	60	67	7,690
	2	1,000,000	904,262	67	73	5,931
	3	1,000,000	163,949	73	72	5,161
	4	1,000,000	233,174	72	70	4,971
	5	1,000,000	292,543	70	69	4,646
4	1	500,000	465,113	60	61	7,546
	2	500,000	412,670	61	60	6,357
	3	500,000	302,562	60	58	5,678
	4	500,000	380,103	58	56	5,437
	5	500,000	423,289	56	54	5,024
5	1	4,500,000	2,706,638	60	88	8,065
	2	100,000	60,823	88	86	5,393
	3	100,000	40,260	86	84	5,093
	4	100,000	45,510	84	82	4,865
	5	100,000	79,489	82	81	4,557

Prioritization Using Incremental Benefit/Cost Ratio

The same five budget scenarios were used in this program. A summary of the output results from this program is given in Table 4. Figure 11 represents the effect of different budget scenarios on network PCI. Budget Scenarios 1 and 5 show almost identical trends, and Budget Scenarios 2, 3, and 4 show that with the gradual increase in the available budget, the network PCI improves. This improvement in network PCI is more significant in the later years of the analysis period.

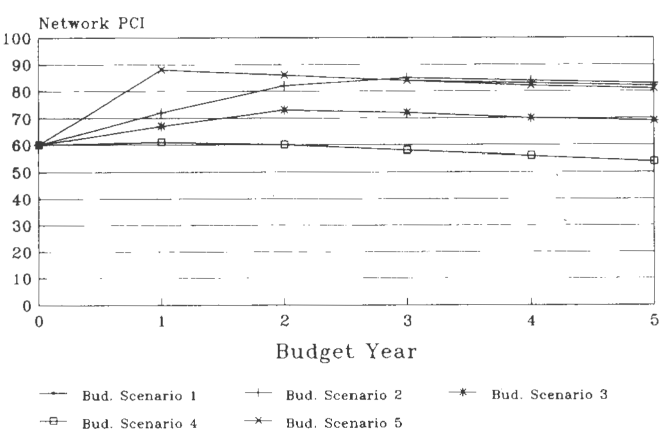

FIGURE 10 Effect of different budget scenarios on network PCI using optimal benefit/cost ratio.

Comparison of Two Prioritization Methodologies

The comparative network PCI–versus–budget profiles obtained from the two prioritization programs showed that prioritization using incremental benefit/cost ratio method results in higher network PCI values than prioritization using the optimal benefit/cost ratio. The other trend noticed from prioritization results indicated in Tables 3 and 4 is that the optimal benefit/cost ratio program consistently results in a lower amount of the budget being utilized compared with the incremental benefit/cost ratio program.

The yearly budget used from each budget scenario was converted into present-worth cost and then summed up as the total budget used over 5 years. The plot of total budget used from each budget scenario versus final-year network PCI is shown in Figure 12. It is observed in this figure that for a given network PCI, the incremental benefit/cost ratio program will require that more money be spent to maintain that level of PCI. The advantage of the incremental benefit/cost ratio program is that the available budgets are best used to their full limit.

CONCLUSIONS

The developed optimization scheme uses a formalized pavement condition survey procedure and is dynamic and robust for network-level PMS. The pavement performance prediction model based on nonhomogeneous

TABLE 4 Prioritization Using Incremental Benefit/Cost Ratio

Budget Scenario	Year	Budget Available	Budget Used	PCI Before	PCI After	Network Benefit
1	1	5,000,000	4,161,751	60	99	9,720
	2	4,000,000	91,820	99	96	6,021
	3	3,000,000	87,613	96	93	5,825
	4	2,000,000	286,295	93	93	5,721
	5	1,000,000	288,774	93	93	5,503
2	1	1,500,000	1,499,414	60	73	5,872
	2	1,500,000	1,498,240	73	85	6,538
	3	1,500,000	1,490,785	85	95	6,423
	4	1,500,000	250,591	95	94	5,688
	5	1,500,000	166,248	94	93	5,388
3	1	1,000,000	999,567	60	67	8,351
	2	1,000,000	997,522	67	73	6,882
	3	1,000,000	996,461	73	78	6,250
	4	1,000,000	970,779	78	82	6,068
	5	1,000,000	350,127	82	80	5,526
4	1	500,000	498,460	60	61	8,162
	2	500,000	499,637	61	62	6,991
	3	500,000	495,490	62	61	6,234
	4	500,000	478,642	61	60	5,980
	5	500,000	488,286	60	58	5,515
5	1	4,500,000	4,161,751	60	99	9,720
	2	100,000	91,821	99	96	6,021
	3	100,000	87,613	96	93	5,825
	4	100,000	99,086	93	92	5,624
	5	100,000	93,177	92	90	5,197

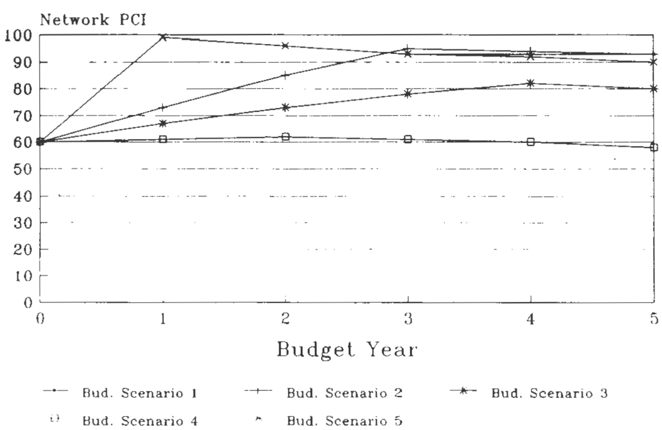

FIGURE 11 Effect of different budget scenarios on network PCI using incremental benefit/cost ratio.

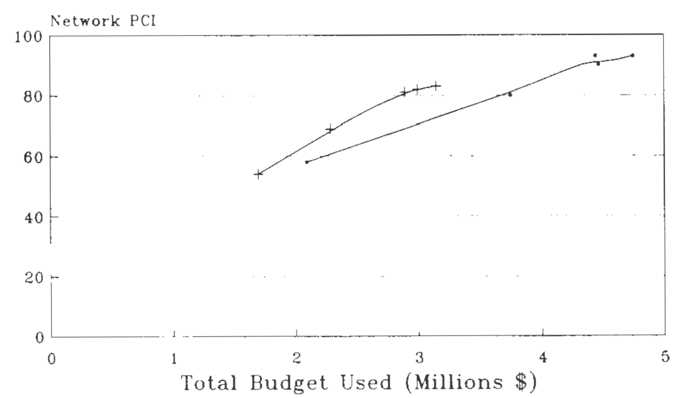

FIGURE 12 Network PCI versus total budget used.

Markov chains successfully captures the probabilistic pavement deterioration process. The Markov process in conjunction with the dynamic programming produces the optimal budget requirements for the given analysis period. The prioritization schemes have been developed to allocate the constrained budget. The prioritization method using incremental benefit/cost ratio provides the best use of available limited funds, when the funds must be completely exhausted during the assigned year. However, if the available funds can be carried over the next years, then the optimal benefit/cost ratio program provides the best use of available limited funds. The findings of this research effort will be incorporated in the MicroPAVER Version 5.

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Design of Project Selection Procedure Based on Expert Systems and Network Optimization

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Rehabilitation project selection and pavement network optimization are integral parts of the Highway Preservation Program of the Arizona Department of Transportation (ADOT). In order to assist the decision makers in the selection process, techniques in expert systems were used to simulate the process of initial project selection. In addition, the results from the network optimization system (NOS) are used in preparing budget proposals for the 5-year Highway Preservation Program. The project selection is an interactive process with a constantly monitored budget proposal based on NOS. The initial list of rehabilitation projects was determined through the use of a knowledge development environment, TIRS, from IBM. The design of this knowledge-based expert system (KBES) was illustrated by the use of actual screen shots of the development environment. A basic knowledge base was established that contained the rules and conditions necessary to generate project recommendations through an interactive input process. In order to be able to process batch data for the entire pavement network, a delineation method was used to divide the highways into homogeneous logic sections. The integration of designed KBES with newly improved NOS is being implemented in ADOT in an advanced desktop platform.

Network optimization system (NOS), deployed in the Arizona Department of Transportation (ADOT) for the last 13 years, has been used actively as a budget-planning tool for developing resource requirements rather than for scheduling rehabilitation projects for specific pavement sections. The manual process of determining pavement rehabilitation projects is an integral part of the current ADOT Highway Preservation Program. Project selection is a complex, less defined process than mathematical modeling. Furthermore, the selection process requires the application of knowledge, judgment, and experience of pavement engineering specialists. The project assignments are site specific and may not be based on exact engineering criteria. Many factors influence the selection process, some of which cannot be defined explicitly through equations. Therefore, other means are necessary to automate the process of generating a list of candidates for pavement rehabilitation projects. It was determined that, coupled with the optimized financial information from NOS runs, techniques of knowledge-based expert systems (KBES) can be used to assist ADOT decision makers to select the appropriate statewide rehabilitation projects over the 5-year planning horizon. This paper presents the design of such a procedure.

Techniques and Applications

KBES is an intelligent computer program that uses knowledge and inference procedures of human experts to solve difficult problems. Expert systems provide ways to simulate the real decision-making process to an extent that is impossible for traditional mathematical modeling, such as linear programming. In many cases, when a decision problem cannot be solved satisfactorily with traditional mathematical models, expert systems can be used. However, this requires identifying human knowledge used in the decision process and placing this information in a data base.

Structure of KBES

Typically, KBES is made up of three primary components (*1*):

- A *knowledge base* containing the domain specific facts and heuristics associated with a particular field. It contains the facts and rules representing the experts' knowledge. Knowledge can be represented in the knowledge base in several ways; the most widely used method is through rules. Other methods include frames, objects, and semantic networks (*2*).
- A *rule interpreter,* or inference engine, that can use the knowledge base to solve a domain-specific problem. It is the component of an expert system that manipulates the knowledge in the knowledge base to solve the problem at hand. It performs two principle tasks: first, it examines existing facts and rules, and second, it determines in what order the inferences are made. One commonly used method is forward chaining (data driven). The inference engine normally has the capability to report to the user how the rules are applied and how conclusions are reached. Examination of the chain of rules can help the user understand the logic of the application of the knowledge. This capability can be used for debugging the system and training new engineers.
- A *context,* or a global data base or work space that maintains the problem status, the input data, the relevant history of the actions taken by the system on the current problem, and the user interface. It is a data base containing information of the problem under study, including the problem data (user input data, and data derived through the application of rules), the solution status, and the action history. The user interface usually contains two standard components: an explanation module and a knowledge acquisition module. The explanation module reveals the chain of rules used to obtain the results in response to the inquiry made. The knowledge acquisition module lets the user enter knowledge or rules into the knowledge base. This module then translates the rules into representation that the inference engine can manipulate.

Existing KBES Applications in Pavement Engineering

Ross et al. (*3*) state that although the manual process of determining rehabilitation schemes has been effective, computerized KBES would allow a more detailed preliminary estimation of rehabilitation needs such that costs could be better ascertained. In addition, good KBES can be used as an experienced training engineer in its domain so that trainees can have access to knowledge without the limitations imposed by a human environment. Expert systems technology has been applied to transportation engineering as shown in the literature of Alshawi and Cabrera (*4*), Aougab et al. (*5*), Greenstein and Berger (*6*), Haas and Shen (*7*), Hajek et al. (*8*), Hall et al. (*9*), Hendrickson and Janson (*10*), Richie (*11*), Rolston (*12*), Ross (*13*), and many others.

During the past decade, highway agencies have been using KBES in pavement engineering in a number of applications. The pavement rehabilitation analysis and design mentor (PARADIGM) is a well-known expert system application on pavement rehabilitation for the Washington State Department of Transportation (WSDOT) (*1*). It consists of three components: the surface condition expert for pavement rehabilitation (SCEPTRE), the overlay design heuristic advisor (OVERDRIVE), and network optimization. PARADIGM Version 1.0 is a forward-chaining KBES employing if-then-else production rules in its knowledge base with links to conventionally coded external programs. The system was developed with the use of the EXSYS KBES development environment and other programming tools. The knowledge base contains more than 470 rules. A brief description of the knowledge system used in PARADIGM is given in the next two paragraphs (*1*)

SCEPTRE evaluates project-level pavement surface distress and other user inputs and recommends feasible rehabilitation strategies for subsequent detailed analysis, design, and network optimization. Surface condition survey is based on three performance indicators: ride quality, safety, and surface distress. SCEPTRE queries the user for inputs that are used by the system to make inferences based on a collection of facts and heuristics in the knowledge base. Seven basic factors from the user inputs are type of surface course, type of surface distress, amount of surface distress, severity of surface distress, existing pavement performance (rate of deterioration), traffic levels, and climate.

The knowledge base has been constructed with the use of the combined expertise of two pavement specialists. SCEPTRE considers a list of 23 rehabilitation options. From user inputs, SCEPTRE refines the list to form an appropriate subset. Another component in PARADIGM is OVERDRIVE, which is a KBES for assessing existing pavement structural adequacy and the design of flexible asphalt concrete overlays on existing flexible pavement. The structure of the OVERDRIVE knowledge base is similar to that of SCEPTRE. An actual project was demonstrated in which SCEPTRE recommended that the 1.2-mi, two-lane highway be preleveled or milled and then rehabilitated with a medium asphalt concrete (AC) overlay. This section of pavement was expected to complete its service life in 7 years. SCEPTRE's recommendation proved to model accurately the decisions made by WS-DOT engineers for this section of highway.

Project Selection, Network Optimization

Attempts were made in the early application of NOS to use optimization results to select rehabilitation projects. However, the network optimization used in ADOT is aggregation-based and probabilistic in nature. The Markovian prediction models defined in NOS are based on each of the 15 road categories without direct consideration of engineering factors of specific pavement sections. The current role that NOS plays in the ADOT Highway Preservation Program is providing 5-year budget recommendation (1993–1997) for the state highway network. Table 1 gives the budget recommendation for the 15 road categories of the network. This recommendation breaks down the 5-year budget needs for six categories of Interstates and nine U.S. primary and state highway categories.

Experience shows that human examination of specific pavement sections, coupled with the existing engineering data such as roughness and distress, results in much better decision making than sole reliance on computer printouts. As a result, a manual process has been used to determine the rehabilitation projects for the Highway Preservation Program. In essence, NOS helps ADOT decision makers at the macrolevel for financial planning, and human engineering knowledge plays a central role at the microlevel of project selection.

TABLE 1 NOS Budgetary Recommendation (millions $)

Road Category	Area Size (Million SY)	Year					Total
		1993	1994	1995	1996	1997	
Medium[g]/D[c], I[a]	12.338	5.072	3.485	4.389	3.561	3.611	20.118
Medium/T[d], I	1.239	0.168	0.384	0.479	0.363	0.347	1.741
Medium/M[e], I	N/A	N/A	N/A	N/A	N/A	N/A	N/A
High[h]/D, I	20.082	12.050	11.882	23.923	22.585	22.996	93.436
High/T, I	17.605	11.404	8.590	20.875	16.567	16.149	73.585
High/M, I	3.691	1.185	2.124	4.932	4.947	4.985	18.173
Sub-Total	54.955	30.879	28.465	57.598	52.023	53.088	207.053
Low[f]/D, N[b]	12.191	4.233	1.773	3.783	3.064	3.036	15.889
Low/T, N	26.472	8.998	8.028	9.359	7.902	7.900	42.187
Low/M, N	8.967	0.986	2.804	3.102	2.735	2.693	12.320
Medium/D, N	19.560	4.490	2.667	6.423	4.971	5.083	23.634
Medium/T, N	17.979	4.587	6.051	6.627	5.405	5.485	28.155
Medium/M, N	10.119	1.963	5.074	5.325	4.470	4.226	21.058
High/D, N	4.359	2.429	2.255	2.321	2.005	2.070	11.080
High/T, N	1.965	0.381	0.902	0.969	0.847	0.861	3.960
High/M, N	2.00	1.084	1.150	1.194	1.048	1.067	5.543
Sub-Total	103.612	29.151	30.704	39.103	32.447	32.421	163.826

[a, b] Interstate Highway and Non-Interstate Highway respectively.

[c, d, e] Desert area, Transition area and Mountain area respectively.

[f, g, h] Low traffic level, Medium traffic level and High traffic level respectively.

Road Category of Interstate with Medium Traffic, Mountain Area does not exist.

Rehabilitation project selection in the ADOT Highway Preservation Program is a process of interactive decision making by application of pavement engineering knowledge, the use of results from NOS, and the extensive communication between the pavement management engineer and other highway officials, including district engineers. The existing decision process of selecting rehabilitation projects is illustrated in Figure 1.

First, NOS runs are conducted to derive the 5-year budget needs for the preservation program for the state highway system. The state pavement management engineer analyzes the pavement management system (PMS) data base and determines a set of initial candidate projects. This set of projects is broad-based and normally consists of a large number of projects that would cost much more than the approved budget. These candidate projects are considered for other engineering issues that may concern only the district engineers and are not in the knowledge domain of the pavement management engineer. The funding for the 5-year program proposed to ADOT management and the legislature is based on the analysis of NOS runs. The approved funding level acts as input data and plays an important role in every stage of the entire process of project selection, because the proposed total spending for the rehabilitation projects must be at the approved level.

After the initial candidate projects are generated, the pavement management engineer conducts field reviews with each district engineer and other engineering staff for each candidate project. During the field trips the engineers arrive at consensus on the severity of roughness and distress and on issues related to traffic, environment, and

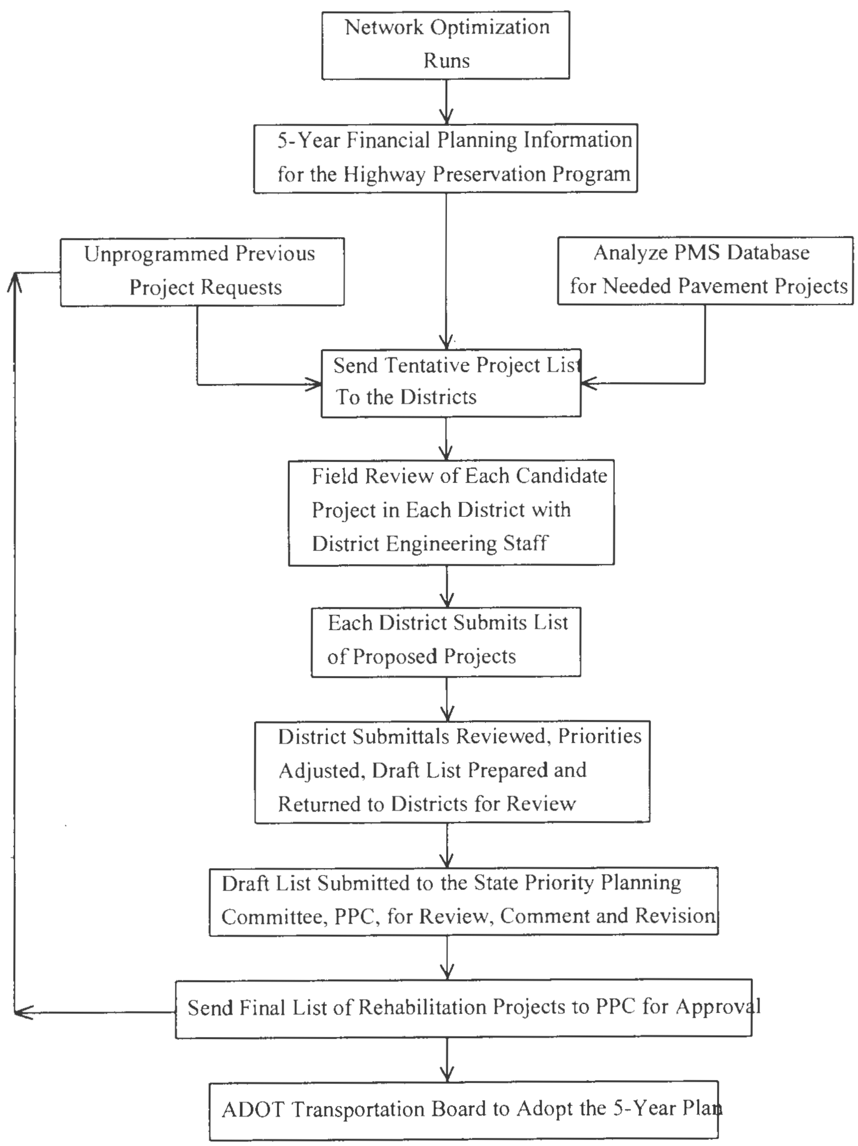

FIGURE 1 Existing decision process of ADOT pavement rehabilitation project selection.

community needs. After the field reviews, each district submits a short list of candidate projects for further evaluation.

The next stage involves extensive discussions among ADOT management, the pavement management engineer, the pavement services engineer, and district engineering staff about the proposals submitted by districts. Priorities of different projects are adjusted and from those discussions, and a draft list of candidate projects is returned to the districts for further review. Upon completion of this review, the draft list is submitted to the state Priority Planning Committee (PPC) for final review, comment, and revision. After PPC's revision, a final list of rehabilitation projects is generated for approval. Subsequently, ADOT Transportation Board reviews the list and approves its adoption. Candidate projects deemed necessary but deleted from the approved list because of inadequate funding automatically become the members of the next year's initial candidate list.

The generation of the initial candidate list is a knowledge application process that requires highly skillful engineering judgment and experience. Furthermore, the discussions and communications among ADOT management and engineering staff involve logic reasoning and presentation of knowledge that probably only a few engineering staff have. Therefore, the computerization of the generation of the initial candidate list of rehabilitation projects and the presentation of the reasoning steps behind each selection can reduce the work load of the engineering staff and provide insight into the engineering knowledge actually used to derive certain conclusions.

Development Platform for ADOT Project Selection Procedure

An improved version of NOS in C language was developed in ADOT recently (*13*) in the 32-bit OS/2 2.x operating environment on a microcomputer. OS/2 2.x is an ideal platform for conducting heavy-duty engineering work, because it provides the power and functionality of a mainframe computer and at the same time has the flexibility and ease of use of a desktop system. It also has excellent compatibility with current ADOT DOS and Windows applications. In addition, the financial information from OS/2-based NOS runs is used as an important constraint in the entire process of project selection. Therefore, it was determined the KBES-based project selection process should be integrated into a comprehensive package with the new NOS in the same operating environment.

The Integrated Reasoning Shell

The Integrated Reasoning Shell (TIRS) is a cross-platform KBES development environment from IBM for OS/2-, RS/6000-, and VMS-based mainframes. The 32-bit OS/2 version of TIRS is a graphical application development and delivery tool that lets developers create, build, and run knowledge applications. A TIRS application has three components: (*a*) reasoning component, (*b*) external routines, and (*c*) environment interface routines.

The central component of a TIRS application is the reasoning component, which contains the knowledge base and the interface engine provided by TIRS. During the building process, the knowledge base is integrated with the reasoning function in the inference engine. External routines are programs written specifically for an application. For example, in the case of the ADOT PMS, the external routines can be the PMS data bases, pavement design routines, and, more importantly, the new OS/2-based NOS, and other related routines as shown in Figure 2.

TIRS also provides extensive C-language support through routine calling procedures. In addition, TIRS input and output data bases can be built to automate the knowledge application process for the statewide network. The development of the project selection KBES into an integrated pavement design and management package can be eased by applying these technologies.

Inference and Knowledge

One recommendation or a set of recommendations can result from the reasoning process, on the basis of the knowledge base, existing pavement engineering data, and other needed contexts. Therefore, project selection is a data-driven, forward-chaining process. This means that when the knowledge application begins running, TIRS initializes data items and obtains values for forward-

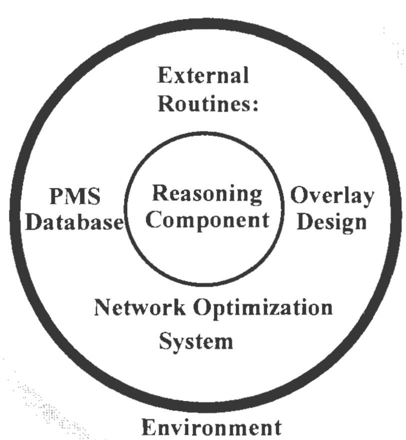

FIGURE 2 Components of integrated PMS based on TIRS.

chaining data items if possible. It reaches conclusions from the data by processing the rules in the recognize-act cycle.

The collection of the knowledge base and the use of the inference engine are the two most important factors when any application of an expert system is set up. The knowledge base of the project selection process can be determined through a variety of approaches. In the case of SCEPTRE in PARADIGM, the knowledge has been constructed with use of the combined expertise of two pavement specialists with extensive experience in pavement rehabilitation. It was determined that a consultation procedure can be used in ADOT's system by conduction of informal interviews with experienced pavement engineers. In addition, NOS results should also be used in the knowledge base to represent the available budget for each year.

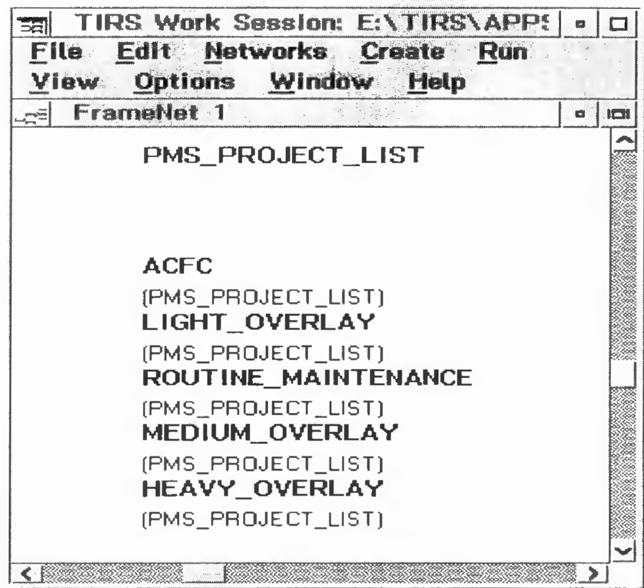

FIGURE 3 Five rehabilitation actions used for project selection KBES.

KNOWLEDGE BASE DEVELOPMENT

Knowledge collection was conducted from experienced engineers. Five types of rehabilitation action, shown in Figure 3, are used in this KBES. Routine maintenance applies to any pavement sections under any circumstances. This allows the deferral of a needed action because of budget constraints. Five engineering factors or attributes were input parameters shown in Figure 4. Each factor is divided into three levels: 1, 2, and 3.

Through interviews with engineers in pavement design and management, a specific action was assigned to pavement sections based on condition levels for the five factors. Figure 5 shows that AC friction course is applicable for pavements with medium to high severity of skidding safety problem. A number corresponding to the level of the factors shown in Figure 5 means the rehabilitation action is applicable; that is, this level is true for the pavement section. A 0 assigned to a factor means the specific action is not applicable. For example, in Figure 5 AC friction course is applicable regardless of traffic level (ADT1:1, ADT2:2, and ADT3:3) and roughness level (ROUGHNESS1:1, ROUGHNESS2:2, and ROUGHNESS3:3). However, it is not applicable when rutting exists (RUTTING1:0, RUTTING2:0, and RUTTING3:0). The rule logic listed next is used to determined the rehabilitation actions by examination of the combinations of different levels of the five factors:

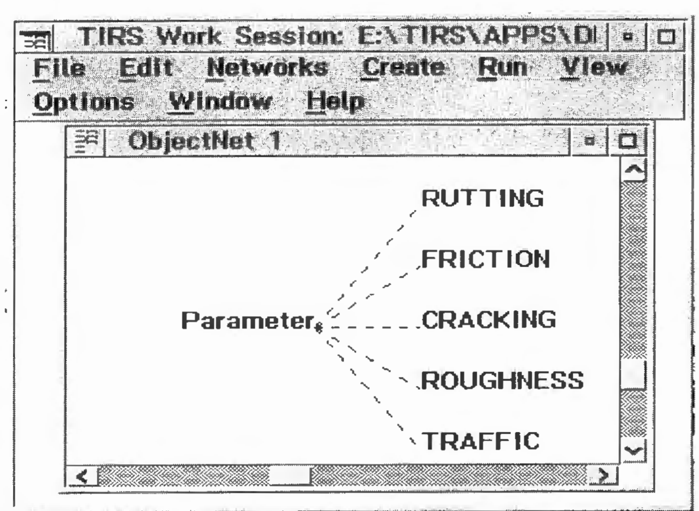

FIGURE 4 Five parameters to identify pavement sections.

result1: PMS_PROJECT_LIST

IF

((result1.ADT1 = TRAFFIC) OR
(result1.ADT2 = TRAFFIC) OR
(result1.ADT3 = TRAFFIC)) AND
((result1.ROUGHNESS1 = ROUGHNESS) OR
(result1.ROUGHNESS2 = ROUGHNESS) OR
(result1.ROUGHNESS3 = ROUGHNESS)) AND
((result1.CRACKING1 = CRACKING) OR
(result1.CRACKING2 = CRACKING) OR
(result1.CRACKING3 = CRACKING)) AND
((result1.RUTTING1 = RUTTING) OR
(result1.RUTTING2 = RUTTING) OR
(result1.RUTTING3 = RUTTING)) AND
((result1.FRICTION1 = FRICTION) OR
(result1.FRICTION2 = FRICTION) OR
(result1.FRICTION3 = FRICTION))

THEN

SHOW 'The Recommended Rehabilitation is: *result1. Rehabilitation*' *result1* is an instance variable representing the frame type.

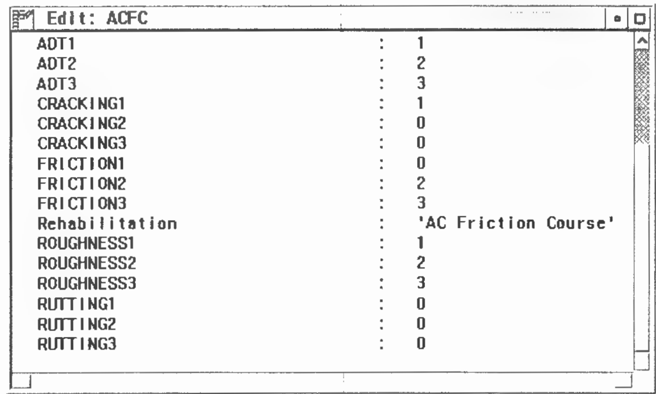

FIGURE 5 Factor levels for rehabilitation action AC friction course.

PMS_PROJECT_LIST. TRAFFIC, ROUGHNESS, CRACKING, RUTTING, and FRICTION are the input context from the user identifying the pavement section in question. The variable *result1.Rehabilitation* is the recommended rehabilitation action for the conditions.

Figures 6 and 7 demonstrate the input and resulting recommendations generated by the knowledge base. A

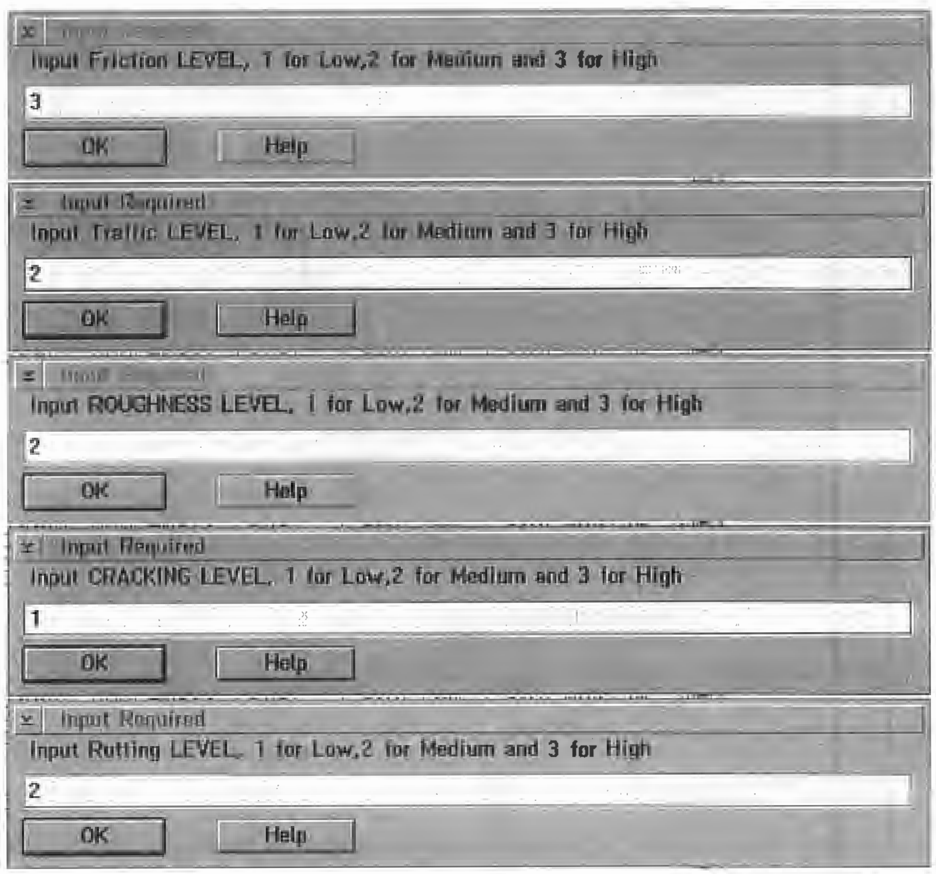

FIGURE 6 TIRS input screens for sample problem.

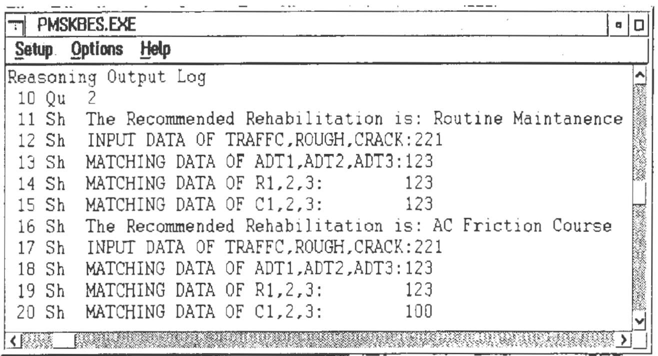

FIGURE 7 TIRS output screen for sample problem in Figure 6.

pavement section with high level of skidding safety problem, medium levels of traffic, and roughness and rutting, and low level of cracking is used as input. The recommended rehabilitation actions are routine maintenance or AC friction course.

The graphical development environment in TIRS allows the developers and users to visualize and examine the relationships among objects. Figure 8 visually displays the rule object "Recommendations" and the context source. Three approaches can be used as input sources to the KBES: the interactive question method; the procedure method, which allows large data bases to be used as inputs and outputs; and the Entry_KB, which interfaces with external knowledge bases.

Development of Context for Project Selection KBES

The interactive input mode demonstrates the feasibility and operation of the knowledge base. However, the ADOT pavement management data base consists of more than 7,200 mi of pavement sections. Therefore, a batch mode of operation was required for processing the data and generating the initial candidate list.

The entire pavement network needs to be broken down into "logic sections," each of which has homogeneous properties based on selected response measurements. Engineering information on each logic section can be used as an input data set for the project selection KBES. The unit delineation method by cumulative differences provided by the AASHTO *Guide for Design of Pavement Structures* (*14*) applies to the determination of the logic or homogeneous sections. The structure of ADOT pavement performance data base is shown in Figure 9. In this data base, pavement engineering data were measured or determined at the constant interval of 0.62 km (0.39 mi). The five factors used in developing the project selection KBES were used as the response measurements to define the logic sections.

The determination of the cumulative differences of one response measurements is shown as follows:

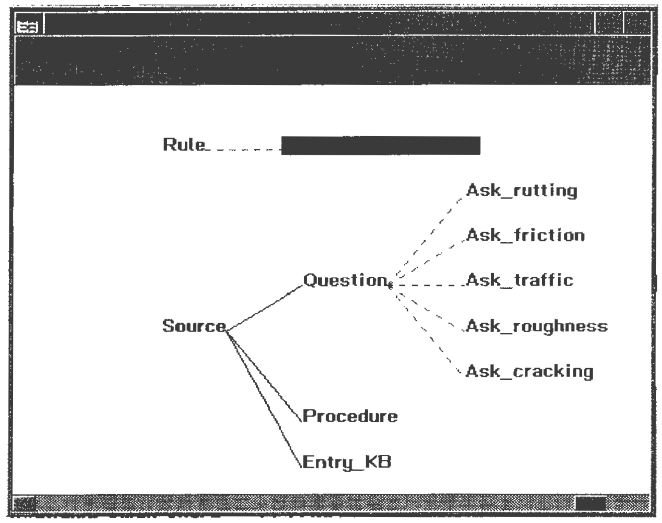

FIGURE 8 Visual display of relationships among objects in TIRS.

$$Z_x = \sum_{i=1}^{n} a_i - \frac{n}{n_t} \sum_{i=1}^{n_t} a_i \tag{1}$$

$$a_i = \frac{r_{i-1} + r_i}{2} \tag{2}$$

where

- Z_x = cumulative difference at milepost x,
- n = number of measurements conducted from beginning of highway under study to milepost x,
- n_t = total number of measurements conducted for highway under study,
- a_i = average of response values between mileposts $i - 1$ and i, and
- r_i = response measurement at milepost i.

Table 2 presents the logic sections for Interstate 10 in Arizona. It should be noted that there are long sections, the lengths of which can be up to more than 100 mi as shown in Table 2. The existence of long homogeneous sections can be the result of large investments made in the past few years in the rehabilitation and maintenance activities for the Interstate highways. A more detailed analysis is necessary where judged to be so.

Results of NOS runs are used for the budget constraints of ADOT Highway Preservation Program. These constraints should be used as monitoring parameters in the project selection KBES, such that comparisons of available budget and the total costs for the proposed initial candidates projects can be conducted, and adjustments to the list can be made.

Question About Optimality

Budget planning based on optimization is optimal only relative to the model structure and input data. NOS is

FIELD NAMES	A	RTNO	D	MP	L	REG	ADT	ADL	GF	->
DATA RECORDS	I	8	E	1	2	0.4	11915	1247	4.3	->
	I	8	E	2	2	0.4	11915	1247	4.3	->
	...	...	...	...	...	...	...	...	...	->
	U	666Y	E	89	2	1.9	167	16	1	->
	U	666Y	E	90	2	1.9	167	16	1	->

C79	...	C91	R72	..	R91	M72	..	M91	RUT86	...	RUT91	->
0	...	4	x	.:	45	x	.:	x	0.12	...	0.25	->
0	...	9	x	.:	60	x	.:	x	0.29	...	0.3	->
...	...	...	...	.:	...	...	.:	...	...	...	...	->
5	...	10	x	.:	87	x	.:	x	x	...	0.2	->
3	...	0	x	.:	71	x	.:	x	x	...	0.1	->

P79	...	P91	F79	..	F91	MC_79	...	MC_91	SN
0	...	0	5	.:	4.5	4	...	61	3
0	...	0	4.5	.:	3.5	1412	...	2991	3
...	...	...	...	.:	...	...	...	...	...
0	...	0	5	.:	4.5	0	...	0	2.96
0	...	0	5	.:	4.5	0	...	0	2.96

Notes:

-> : Continue;

"x" indicates the value in the particular cell is not available.

Field Name Designations:

- Functional Classification, I=Interstate, S=State Highway, U=US Highway;
- RTNO, D, MP, L: Route Number, Direction, Milepost and Number of Lanes respectively;
- ADT, ADL, GF: Average Daily Traffic, Average Daily Load and Traffic Growth Factor respectively;
- Ci, Ri, Mi, RUTi, Pi, Fi, M_Ci: Cracking, Roughness, Mu Meter Number, Rutting, Patching, Flushing, Maintenance Cost in year i respectively;
- SN: AASHTO Structural Number;

FIGURE 9 Data format of ADOT pavement management data base.

aggregate-based and specific to the road category. As a result of NOS model structure, it is not capable of conducting realistic project selection by itself. Arizona's experience shows that the effectiveness of the models and tools are not determined by finding the "true optimal," because sometimes the true optimal may not be the best possible alternative at all. The improvement of the decision-making process is a more important issue. NOS has been an important instrument in producing pavement rehabilitation budget requirements for the state of Arizona. The efforts to improve the project selection procedure by using KBES in conjunction with NOS are another endeavor to incorporate new technologies continuously in the decision process. Traditional optimization techniques are still being widely used as one of the important decision support tools for pavement management. It should be noted that the application of true optimization techniques in pavement management in the last 10 years demonstrates that the comprehension and support of new technologies by the management is crucial for a successful implementation.

CONCLUSION

KBESs have been playing ever increasing roles in assisting highway officials in identifying problems and making appropriate decisions. More engineers realized the conveniences and cost-effectiveness of a good KBES application. This study designed a KBES application in order to reduce the work load of pavement engineers and to improve the objectivity and accuracy in identification of initial candidate rehabilitation projects for the state highway network of Arizona. This development can also provide some guidance in the efforts to improve pavement overlay design procedures by computerization of design knowl-

TABLE 2 Logic Sections for I-10 Derived from Five Factors Based on Delineation Method of Cumulative Differences

MILE	INTERVAL	ADT	CRACKING	ROUGHNESS	MU METER	RUTTING
1	0	*	*	*	*	*
2	1					*
10	8					*
28	18			*		
63	35				*	
79	16				*	
90	11				*	
94	4				*	
107	13				*	
113	6				*	
115	2				*	
123	8					*
139	16					*
153	14	*				
279	126		*			
324	45		*			
334	10		*			
359	25			*		
378	19				*	
387	9				*	
390	3					*
391	1	*	*	*	*	*

*: delineation cut point based on the corresponding factor.

edge into a knowledge base. More important, in conjunction with ADOT NOS, an integrated software application is being considered in ADOT Pavement Services in an advanced 32-bit operating environment that combines network optimization for budget planning, knowledge system for project selection, and improved design procedure for overlay design. ADOT realized the importance of decision-making tools in assistance to the resource allocation process. As a result, additional development efforts are on the way to further enhance and integrate the PMS along with other management systems required by the Intermodal Surface Transportation Efficiency Act of 1991.

ACKNOWLEDGMENTS

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Making Optimization Practical in Pavement Management Systems: Lessons from Leading-Edge Projects

Paul D. Thompson, *Cambridge Systematics, Inc.*

Much has been written in the past 10 years about the development of new optimization techniques for pavement management systems. However, few public agencies are using optimization in their routine budgeting and programming activities. The reasons for this and the keys to making optimization more practical lie in taking a new look at its role in decision making and at the means by which optimization techniques are implemented. Several recent projects to create new pavement management systems or revamp old ones have demonstrated that the techniques do not have to be excessively complex or data-intensive and that they can be very effectively implemented on personal computers connected to shared data bases. The effective use of optimization signals the beginning of a new generation of pavement management systems.

The term "optimization" is a generic word that describes any systematic attempt to measure and adjust the performance of a mechanism or policy to produce better performance. In pavement management the thing to be optimized is a policy, program, or budget allocation for pavement maintenance, rehabilitation, and reconstruction. To perform optimization, it is necessary to identify and measure the objectives that a policy is meant to accomplish, such as pavement preservation, reducing user discomfort, or reducing citizen complaints. The optimization procedure can be a completely subjective, trial-and-error process, it can be fully automated, or it can be a combination of subjective and automated elements.

Historically, there has been a very distinct disciplinary separation between those who pursued subjective optimization approaches (largely political approaches to achieving a vision of prudent facility management with a long-term perspective) and those who pursued automated mathematical approaches (largely from an operations research background). The former did not consider their activity to be optimization, even though it fit the definition given here, and very few people were fluent in both of the very different languages spoken by the two groups. This led to a widespread misperception that optimization could only be a fully automated mathematical process with no room for engineering or managerial judgment. Uncomfortable with this notion, few agencies could see any realistic role for optimization in their decision-making processes.

What has happened since the mid-1980s to change all this is the emergence of an understanding of optimization as a hybrid combination of mathematical software techniques and judgmental decision making. The impetus for this change originally came from a 1980s political philosophy that government activities must be carefully scrutinized and must be expected to justify themselves in economic terms. Intense competition for government funding in the federal and state arenas has led to the use of economic data as a competitive weapon. Deluged with data, legislators and other high-level decision makers began demanding brevity and focus in the information, along with proof of the validity of the economic analysis. Every transportation agency manager understands the central role of managerial judgment in the development of policy, program, and budget allocation decisions. Now, however, these managers are being forced to back up their decisions with rigorous economic arguments in order to defend transportation's share of the budget against increasingly sophisticated advocates of the many other ways of spending government funds. Because optimization models have the unique capability of reducing a large amount of data to a small amount of useful information about key decision trade-offs, optimization is becoming a powerful ally for top management and an integral part of a new professional standard for decision-making processes.

At the same time that the demand for optimization has increased, its technology has also undergone fundamental changes. In the past, optimization models were synonymous with huge mainframe systems, where even a single model run was a large production involving hours of a person's time and the use of very expensive equipment. The "turn-around time," the time from the posing of a question by a top manager or legislator to the delivery of the answer, could stretch into days. Because of the time and expense involved, such systems were seldom used in the kind of "what-if" style (which could involve dozens of model runs) that is most useful for the support of managerial judgment. The technological factors that have changed all this since the mid-1980s are the increasing speed and capacity of personal computers that permit large mathematical models to be developed and executed in seconds and the widespread acceptance of client-server software architectures, which separate the complexity of data base management and data sharing from the development and use of the economic models. No longer is the use of an optimization model a major production: increasingly such models will be built into personal computer software as subsidiary components of reports and analyses focused on particular questions of management interest.

Together, these factors are now leading to a new definition of the role of optimization in pavement management systems, consisting of two components: (a) a process, which involves one or more decision makers shaping and revising a policy or program by using their judgment to weigh political, engineering, and economic factors and (b) a set of models, including what are traditionally thought of as optimization models, providing quantitative feedback and suggestions on any portions of the problem for which quantitative analysis is feasible, particularly regarding the economic factors.

This perspective is much different from the traditional view of optimization, because the quantitative models are no longer the centerpiece of the system. In fact, the pavement management systems (PMSs) might not have a single central optimization model but might instead have a collection of models that address portions of the overall analysis. Under this paradigm, for instance, a network optimization model does not necessarily find the one best set of policies and budgets; instead it compares the overall performance of two or more different proposed policies, shows how each can be fine-tuned, and shows the trade-offs among various decision criteria.

A central difference between the two perspectives is the control of the decision-making process: in the traditional view of optimization, the massive mainframe model dictates the decision-making schedule, limits the number and type of alternatives that can be considered, and forces management to justify any deviations from the "optimal" plan; in the new view, management controls the schedule and the agenda, uses the optimization models as a toolbox for expediently considering and discarding a wide range of alternatives, and exploits the models to help policies quickly adapt to new, unpredictable constraints or considerations that may arise.

For optimization models to function effectively in support of a management-controlled decision process, they need to have several attributes that are now possible with today's technology.

- Modularity. Rather than being a single monolithic computer program, an optimization model is easier to understand and more flexible if it can be divided into parts that can be manipulated separately.
- Consistent methodology. The separate modules should be consistent and compatible with each other. There should be a simple central organizing framework that ties the parts together and permits the addition of new models as needed.
- Speed and ease of use. Management confidence in an optimization system is gained primarily by experimentation and "what-if" analysis. Rapid turnaround is therefore essential.
- Flexibility. Because no model system can fully describe the range of policies and conditions that might be covered by a pavement management system, the model system must be modifiable and adaptable to new situations.
- Correct methodology. Correctness is, of course, essential to the credibility of an optimization model, but correctness is not an absolute: it is a continuum of levels of detail. Because policy formation is a complex process, making an optimization model exactly fit reality in all its details leads to excessive complexity of the model, which detracts from its usefulness. A practical optimization model is an approximation of reality, having an appropriate balance between correct details and simplicity. The ar-

eas of greatest policy sensitivity should have the greatest emphasis on correctness.

Successful implementation of optimization models in pavement management systems requires that they be unintimidating to their users: they need to be small, flexible, easily manipulated, and easily tested. Even though optimization can have a substantial impact on the economic performance of a policy or program, users of the models should perceive them as a fine-tuning and feedback mechanism, not as a recipe for policy.

Historical Evolution

Optimization in its broad sense in pavement management has its roots in the 1960s, when the AASHO Road Test (*1*) first systematically quantified pavement performance over time, and when Winfrey (*2*) published data relating pavement quality to its effect on road users. Analysts began using this information to estimate the life-cycle costs of various pavement designs and to quantify the agency and user benefits of maintenance and rehabilitation actions. In the 1970s numerous researchers turned these new tools to the problem of finding optimal pavement policies under various conditions (*3–7*). Beginning in the 1970s and continuing into the 1980s, state departments of transportation and other agencies began implementing pavement management system software having some level of optimization capabilities (*8–14*).

The earliest pavement management system optimization procedures were project-level tools, which were primarily intended to prescribe the optimal long-term strategy and short-term action for a single given pavement. These were firmly grounded in engineering principles, and some became quite sophisticated in their analysis of the details of a pavement's behavior. A natural extension of these models was to apply them to all of the pavements in a data base, then through summation calculate the agency wide cost of an optimal policy. Early versions of the World Bank's Highway Design and Maintenance Standards Study, in particular, thoroughly exploited this style of analysis.

Project-level tools developed in the 1970s were very popular because of their relevance to engineering concerns and their consistency with engineering judgment. They had a significant drawback, however, in that the cost totals generated by the summation process did not yield realistic budget levels. Upper management and elected officials found the models difficult to understand and impossible to use, because the models were not sensitive to important policy variables such as geographic distribution of funds and overall funding levels. In addition, because most of these systems lacked any quantitative indication of road user benefits, they did not describe the performance of the pavement inventory in a manner that had any political relevance.

To overcome these concerns, pavement management systems began to incorporate explicit budget constraints and user cost models. Because there were no models to relate pavement condition or user cost standards directly to budget requirements, these systems applied iterative adjustment processes to modify condition standards until the total cost, generated by summation, agreed with the budget limit. The incremental benefit-cost method and variations of it were popular mechanisms for this. All of these methods were based on project-level models, so they were often quite limited and time-consuming in their network-level facilities. To perform even one budget analysis for 1 year, a project-level model for each of tens of thousands of road segments for a dozen or more sets of condition standards would have to be evaluated. Multiyear programming required that this whole process be repeated several times for a complete result. This required a large, expensively gathered data base and a mainframe computer, and yet it was orders of magnitude too slow to perform "what-if" analysis or provide the degrees of policy sensitivity wanted by elected officials and upper management. Frequently, application of these systems was limited to a small subset of roads, such as the Interstate highway system, and therefore provided little, if any, assistance in policy formation or budgeting for the majority of the highway network.

Largely in response to the combinatorial problem of having a project-level basis for network-level analysis, agencies began experimenting with mathematical programming techniques that could efficiently eliminate project alternatives without fully evaluating them, thus shortcutting the process of finding a set of projects that best accomplish agency objectives within a limited budget. These techniques, often referred to as "formal optimization," take advantage of the mathematical structure of a set of models, using specialized computer algorithms. The earliest examples of these systems, such as those in works by Lytton (*5*) and Ullidtz (*12*), were still based on project-level models, but they used the technique of integer programming to find projects that could most clearly be eliminated from the program to bring the overall cost in line with budget limits. This technique avoided the need to reconsider the eliminated projects on further iterations of the analysis, and so it saved computer time. The time savings of these methods were substantial, but the overall problem of statewide multiyear programming with "what-if" analysis remained too large even for these methods.

A real breakthrough in this problem occurred in the early 1980s in the development of a pavement management system in Arizona (*14*). Charged with the delivery of a multiyear optimization representing the entire state, the developers understood that any project-level approach would be impossible, in terms of both computational and data collection requirements. Their innovation was to divide the road network into classes and then to summarize the condition of each class as a whole by dividing it into 135 discrete condition levels, or states, and modeling the deterioration of and potential actions for each of these states. Based on the number of miles of pavement in each state at any given time, the total cost of needed actions could be calculated. Collapsing thousands of miles of pavement into just 135 states greatly reduced the size of the optimization problem and permitted statistical methods to be used, in place of exhaustive surveys, to develop predictions of pavement deterioration. The developers chose a Markovian decision process as the basic organizing framework of the models, borrowing a technique that had been used in fleet management, financial planning, and other applications (*15*), but never in infrastructure management. Linear programming was the computational method used to quickly weed out economically unattractive policies to arrive at the best-performing alternatives.

In addition to its unique capability to conduct a comprehensive statewide multiyear analysis, the Arizona PMS incorporated features for policy sensitivity to budget levels and condition standards, which were available without the necessity of repeatedly running a large set of computer programs. Even though the models could not provide on-the-spot answers to "what-if" queries, they did provide slates of alternative policies at various budget levels, thus permitting management flexibility and discretion in the use of the results. This made the first truly network-level PMS attractive to other agencies: modifications of the original Arizona software are now in use in the departments of transportation in Alaska, Kansas, and Connecticut, as well as Arizona.

Although the Arizona models were a significant step forward in the application of optimization techniques, the software still had significant drawbacks that prevented more widespread adoption of this highly promising methodology. In terms of the requirements listed, the pavement management systems incorporating this technique still lacked modularity, speed, ease of use, and flexibility. Innovation in the past 10 years has concentrated on these attributes.

Modularity, Convenience, and Flexibility

Arizona's optimization models are often referred to as an example of large-scale optimization, and this certainly is an apt characterization: they comprehensively cover a large number of pavements and a large number of management considerations, and the models are themselves very large. The size and comprehensiveness of the models are a distinct disadvantage, however: they make the system very intimidating to users, they make turnaround times long, and they make it very difficult for managers to get quick answers to ad hoc "what-if" questions.

In 1985 the National Road Administration of Finland began the development of a pavement management system (*13*), hoping to gain the benefits of optimization without the problems recognized in the Arizona system. The developers reviewed the literature of the time and concluded, as the Arizona developers had, that Markovian models would be the only framework that could meet the agency's requirements. The Finland developers, however, approached the overall project in a different way, applying three new principles.

- Instead of viewing the Markovian decision process as the organizing framework of the PMS, a judgmental "what-if" decision-making style supplemented by a simple benefit-cost model framework provided the basic structure of the system. Markovian optimization models similar to the Arizona models were an important part of the system, but they acted as separate modules providing intermediate results to the overall analysis. This perspective, reinforced by close top management involvement in defining the product, led to a much different definition of the software requirements and a much different package in the end.
- Recognizing that the mainframe computer was a significant bottleneck and an intimidating barrier to users, the developers decided to exploit newly available microcomputer technology. Although the mainframe, in principle, could execute optimization models much faster, no agency then or now would be willing to dedicate such an expensive machine to the system. In competition with numerous other users on a production system, mainframe optimization models had very long turnaround times. Inexpensive microcomputers, fully dedicated to a single task, would be able to present their results faster.
- User cost models were an explicit part of the measured policy objectives. In Arizona, pavement performance requirements were provided as a constraint, in a form that was difficult to relate to agency effectiveness and complicated to manipulate. In Finland the user cost models converted pavement performance into a single economic indicator that was relevant to top management, had a clear and meaningful definition, and was easy to use.

The microcomputer platform of the Finland system was a particularly important aspect of the package. Although the agency's main Road Data Bank remained on a mainframe computer, all of the analytical capabilities of the system operated on a personal computer. The overall PMS was therefore a hybrid system. Today, with the advent of client-server system architectures, hybrid platforms remain the most common and appropriate choice for implementing optimization in a management system. Recently, for instance, Arizona completed a major revision of its optimization models, which now operate on personal computers (*16*).

The success of the Arizona and Finland systems led to increased interest in optimization for other management system applications. In 1989, for instance, FHWA Demonstration Project 71 decided to use optimization models for its new Bridge Management System, called Pontis (*17*). With very close participation of senior bridge managers from six state departments of transportation, the Pontis developers (which included members of the earlier Finland and Arizona PMS teams) continued the trend established in the Finland system of making the optimization models small and manageable and subjugating them to a simpler overall benefit-cost model framework. The Pontis system again used Markovian models for parts of the system (those concerned with maintenance, repairs, and rehabilitation), but it also used decision trees and regression models for other parts of the system in which such models would be easier to implement and use. Because of the simple benefit-cost basis of the system, and the data base–centered structure of the software, it is highly flexible, permitting user overrides of all intermediate model results and providing many opportunities for future enhancement and expansion of the system. The increased power of personal computers, combined with innovations in the user interface and algorithms, made the system very quick and easy to use. Every effort was made in the design to encourage users to test the system and perform "what-if" analysis with it. The system has become exceedingly popular. Thirty-eight states are now committed to their participation in AASHTO's continued support of it.

Relating Models to Nonmathematician Users

Many of the techniques used in optimization can be quite specialized and complex. They are, after all, advanced technologies in many respects. A significant barrier to implementation of optimization methods is that users of pavement management systems usually are not experts in, or usually conversant in, these methods. This problem is compounded by the fact that pavement management systems are used by a variety of people with different backgrounds. Successful implementation efforts include a multifaceted development and training approach.

- The development team should contain representatives of each involved discipline: engineering; programming, planning, and budgeting; operations research and economics; statistics; computer software; and others as appropriate. Each representative must be an effective communicator with his or her own constituency.
- Engineers should review the engineering validity of the models and describe and defend them to their peers in engineering terms. This was part of the attractiveness of early PMS models, but it was missing from the later attempts to introduce formal optimization.
- Similarly, planning and budgeting staff must understand and accept optimization models in the language of management and legislative strategy.
- Quantitative economists and statisticians should review the mathematical validity of the models and describe them in mathematical terms. This type of communication is for peer review only. It does not take precedence over engineering and management-oriented validity and understanding of the models.

When the application of optimization models to PMS was new and the models were very large and time-consuming, it was very difficult to explain them to managers or to gain managers' confidence. Implementation success required that managers be trained sufficiently in the mathematical concepts of the models, that they could understand them mechanistically. Only in a very few cases were managers sufficiently prepared or willing to explore the technical details of the models. With current technology, however, there is an alternative to mechanistic understanding: it is holistic understanding, the same type of knowledge that any operator of complex equipment gains by experimentation, testing, and "pushing the envelope"—a level of confidence gained from experience without having to study the internal workings of the equipment. The modularity and speed of optimization models today make this type of learning relatively quick and simple, compared with models of only 5 years ago.

Data Needs and Management

Another important barrier to optimization is the availability of data. Like any data processing procedure, an optimization model is only as good as the data provided to it. Data collection is an expensive ongoing concern in a management system; developers must weight it carefully. Network-level optimization models have generally been less data-intensive than project-level models in terms of the number of items of data required. Although such models can operate effectively on statistical random samples of the pavement inventory, in practice agencies have almost always developed the models from complete inventories. As state highway agencies begin the implementation of the seven management systems mandated by the Intermodal Surface Transportation Efficiency Act of 1991, they are increasingly exploiting new data base technologies and new organizational mechanisms to share expensive data and provide reliable quality control.

In addition to data on pavement segments, PMS optimization models require data on deterioration rates, agency costs, and user costs. A few systems, such as Washington State's PMS (*18*) and the Pontis bridge management system, incorporate statistical models capable of updating their own deterioration models from new raw condition data. The technical methods for this are well established, and Pontis has shown that personal computer implementation of such procedures is feasible. Updating of cost models can be performed in a similar manner, if adequate work accomplishment data are available.

Even with the tremendous improvement in automated data collection equipment in the past decade, certain types of data used in a PMS remain highly subjective. Examples of such data include initial deterioration and cost data (when historical data are not available or are not suitable), policy variables (such as the considerations that define pavement surface quality standards), and potential funding levels. Because judgments on these issues are most reliable if they are elicited from a group of knowledgeable people, there is potential for computer support of judgmental data gathering through software designed to support group processes. The generic term for this kind of software is *groupware,* which software publishers have defined as a merger of electronic mail and data base technology. As transportation agencies increasingly implement internal and external electronic mail systems, the potential for groupware features in a PMS will become apparent.

CONCLUSIONS

Along with advances in data collection technology, a revitalized role for network-level optimization will define the next generation of pavement management systems. By providing a tool to link pavement policies to funding strategy, optimization will be instrumental in efforts to ensure stable funding, consistent policy, and agency programmatic credibility.

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Enhancements to the Network Optimization System

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The network optimization system (NOS) used by the Kansas and Alaska departments of transportation addressed the question, What are the minimum budget requirements necessary to maintain prescribed performance standards? Each road category, with its unique performance models, was solved individually with its own preselected performance standards. The reverse question, What maximum performance standards can be maintained for a fixed budget? had to be solved by an iterative approach. In a constrained funding environment, the more important reverse question required considerable time and computer resources. The resulting solution may not be optimal, because several combinations of performance standards can meet the fixed budget. The methodology of NOS was enhanced to perform as a linked model. Once an initial feasible solution is obtained for the network using the original version of the NOS, an initial percentage budget is specified for each category as a starting point. A linked model, long-term solution is obtained before running the linked-model, short-term model. Both solutions work by creating a master matrix that is revised for each iteration of the linked model until an optimal solution is found. The solution includes optimal performance standards for each road category at a specified total budget. Initial runs of the model result in improved pavement condition when optimized statewide at the budget level recommended by the optimization of individual road categories.

The network optimization system (NOS) used by Kansas Department of Transportation (KDOT) and the Alaska Department of Transportation and Public Facilities (ADOT&PF) addresses the question, What are the minimum budget requirements necessary to maintain prescribed performance standards? Each road category, with its own performance models, was solved individually with the use of preselected performance standards. All the category budgets were totaled to obtain the system budget. The reverse question, What maximum performance standards can be maintained for a fixed budget? had to be solved by an iterative approach. In a constrained funding environment, the more important reverse question requires considerable time and computer resources. The resulting solution may not be optimal, because several combinations of performance standards can be chosen to meet the fixed budget.

This paper discusses the original NOS and an enhancement to the methodology called a linked model. The linked model allows the departments to maximize the benefits of individual roadway categories subject to one statewide pavement rehabilitation and maintenance budget. Both KDOT and ADOT&PF present experience gained from initial runs of the linked model.

Original NOS Model

KDOT and ADOT&PF implemented a NOS that maximizes benefits from the expenditure of rehabilitation funds. Each state defined a set of mutually exclusive road categories based on two or more factors, such as region, traffic, functional classification, pavement type, and sensitivity to frost damage. Each 1-mi road segment in the state was evaluated for each factor and placed in one of the road categories. The condition of each 1-mi road segment is surveyed annually for pavement distresses appropriate for its pavement type. These distresses include measures of roughness and various types of cracking, rutting, and joint distress. The full range of each pavement distress is divided into two to four subranges, which are referred to as levels of distress. The condition of each road segment can then be expressed in terms of the level for each of its pavement distresses. This is referred to as the distress state of the road segment.

The benefit to a department of a road segment being in one distress state versus another is expressed by a benefit scale. The best condition is assigned a value of one and the worst, zero. The remaining distress states are assigned a benefit value between zero and one that expresses their benefit relative to the best distress state. The benefit scale is also used to measure the average performance of a road category and even of the entire network as discussed later.

Only routine maintenance and rehabilitation actions that are appropriate to a road category are considered for analysis. The average cost per square yard of application of an action to a road segment is used by NOS to determine budgets. The cost of application of routine maintenance actions is sensitive to the distress state of the road segment, whereas the rehabilitation actions are not. The deterioration rate of a road segment regarding one or more of its pavement distresses depends mainly on which rehabilitation action has been most recently applied to it. Typically, the rehabilitation actions are divided into four or five groups where each action in a group is assigned the same index-to-first distress (IFD). The change in distress is the amount of deterioration that has occurred over the previous year to one or more of the pavement distresses. The change in distress combines with IFD to provide considerable flexibility in the modeling of pavement deterioration.

Each possible combination of distress state, previous change in distress, and IFD is identified with a unique number. This number, referred to as the condition state, ranges from one to the total number of combinations. The condition state is computed for each 1-mi segment after every survey. This fully describes the condition of the road segment to NOS and, therefore, is referred to as the current condition state. The distribution of the total area of a road category among the condition states can be computed from the current condition states and areas of the road segments that are included in the road category. This distribution is expressed as the proportion of the road category that is currently in each condition state and thereby describes the current condition of the road category as a whole. An overall measure of road category performance is the sum of its condition state proportions weighted by the corresponding benefit values. Besides measuring current performance, NOS also uses this value to set performance goals and estimate expected performance for each year in the planning period.

One of the key capabilities of NOS is its ability to estimate the proportion of the road category in each of the condition states for each of the years in the planning period. This is accomplished by use of the Markovian properties of the transition probability matrices. A transition probability matrix exists for routine maintenance action and each rehabilitation action for each road category. A 1-year condition state probability distribution is the probability of a segment being in each of the possible condition states 1 year after the action was applied. A transition probability matrix contains a 1-year condition state distribution for each condition state. These probabilities can be estimated from pavement inventory data or can be computed from information obtained from an expert panel.

NOS can be used either to minimize cost given a set of one or more performance standards or to maximize benefit given fixed budgets. NOS generates these models as a linear program (LP) and uses an LP package to obtain the optimal solution. Both cost minimization and benefit maximization begin with a long-term model that provides the cost of various levels of performance. The model requires a run for each road category. The long-term solution gives the optimal distribution of the road category area among the condition states and actions that apply to the road segments in each of the condition states.

After a satisfactory long-term solution has been found for all road categories, the next step is to proceed to the short-term model. The cost-minimization short-term model finds the least expensive solution for getting a road category from its current condition to the long-term optimal distribution within a specified planning period. Performance standards are specified from the second year to the second-to-last year of the planning period and are usually phased in gradually. The benefit mode short-term model finds the solution with the highest benefit for moving a road category from its current condition to the long-term optimal distribution within a specified planning period. Budget constraints need to be specified for each year of the planning period.

When both the long- and short-term models have been solved for all the road categories, NOS generates reports, summarizes performance and budgets, and provides a work plan for each year of the planning period. The work plan reports the recommended action with its associated cost and most probable condition state of each 1-mi segment for the entire planning period. Recommendations can be overridden for individual segments or groups of consecutive segments. For a further discussion of NOS, see Kulkarni (*1*).

Enhancements to Model

The cost-minimization model described earlier directly addresses the question, What are the minimum budget requirements necessary to maintain prescribed performance goals? The reverse question, What maximum performance goals can be maintained from a fixed budget? can only be answered through an iterative approach. The performance goals are lowered for many road categories until the overall budget limits are met. The benefit maximization model requires the overall budget to be divided among all road categories. Budgets are shifted from road category to road category until the performance goals are met for all the road categories. In a constrained funding environment, the reverse question must always be answered requiring solutions of multiple linear programming problems. This approach places heavy demands on computer resources. Also, the resulting solution is questionable, because several combinations of performance goals can allow the optimal rehabilitation strategy to meet a fixed budget.

Because of a need to address directly the fixed budget solution, NOS has been enhanced with a new model. The enhancement provides optimal allocation of the total network budget among individual road categories. The new model maximizes the total benefit across all road categories and meets specified annual budgets. The entire set of road categories can be viewed as part of a very large, linear programming problem, which comprises the entire set of road categories, constrained by an overall budget constraint for each year of the planning period, with the objective of maximization of the total benefit. Computing resources needed to solve such a problem within a reasonable time would considerably exceed practical hardware and software limitations. The new model in NOS implements a technique that iteratively solves the entire set of road categories under the direction of a master linear program. This technique is formally known as Dantzig-Wolfe decomposition. In NOS, the new model is called the linked model, because linear programs for each road category are linked to the master LP.

Dantzig-Wolfe decomposition is used to obtain the optimal allocation. It does this by simulation of a decentralized two-level, decision-making process. A "master problem" plays the role of a top-level manager who allocates budgets to independent "subproblems" that represent maintenance activities for different road categories. Each subproblem (category) makes specific maintenance proposals to the coordinating master problem. Each proposal is represented by the benefit level achieved over time and by the maintenance expenditure in each time period. The master is empowered to construct an overall system allocation over time by construction of weighted combinations of the proposals submitted from each category. At the end of the process, each category is allocated the budget computed from this weighted combination of proposals.

The solution process is iterative. At each iteration the master coordinator solves an LP that maximizes system benefit over time, subject to limited statewide budgets available for each time period. The decision variables in this problem correspond directly to proposals offered by the different road categories. The solution of this problem provides an estimate of the systemwide marginal benefit per dollar of budget in each time period. Given such an estimate, the master solicits maintenance proposals from each category in accordance with the following artificial concept: each category is allowed to expend as much as it likes of the total state budget in each period, provided that the marginal benefit per dollar spent does not fall below the announced system average. When a new set of proposals is obtained, the master resolves its allocation problem to obtain new estimates of marginal benefit. This iterative process continues until the marginal benefit estimates stabilize, at which point the categories would start repeating the same proposals. Rigorous theoretical results establish that the process terminates (with the optimal allocation) in a finite number of iterations.

In practice, the finite number of iterations to "pure" optimality could be quite large. Fortunately, the implementation of the Dantzig-Wolfe method provides rigorous estimates of lower and upper bounds for the systemwide total benefit. The user can stop the process when the bounds are close enough together. These bounds are obtained as follows: because the master's decision problem is composed of viable proposals from all road categories, the proposal-averaging solution from the master at any point provides a feasible and implementable budget allocation that is optimal over the set of proposals obtained so far. Because the collected proposals may not yet span the entire beneficial range of activity from each category, it follows that this master solution is a lower bound for the obtainable maximum benefit. Because at each iteration the master's opportunity set is expanded by the addition of new and improved proposals, this achievable lower bound for system benefit is increasing at each iteration. An upper bound is obtained from the subproblem perspective. For any announced marginal benefit level, the proposal from each category represents the maximum benefit obtainable at no more than that marginal value. There is no guarantee, however, that the sum of the expenditures from all such proposals lie within the actual statewide budget limit. Hence, the sum of the benefits from all proposals represents a nonobtainable upper limit on the total benefit. These estimated upper limits are not monotonically decreasing at each iteration, but it is mathematically valid to track the lowest upper bound obtained over the course of the iterations. If the growing lower bound ever reaches this lowest obtained upper bound, the process has converged to a pure optimum. In practice, it is typical to stop the process when the gap between upper and lower bound becomes sufficiently small.

The long-term linked model finds the maximum networkwide benefit that can be maintained yearly for the same total fixed budget. Upper and lower budget limits can be specified for individual road categories when needed to maintain minimum performance goals. The original NOS long-term solution would be difficult to find by solving individual road categories and iterative shifting of the budgets. The linked model is also much easier to solve, because allocation of the overall budget into individual road categories is not required.

The short-term linked model finds the maximum networkwide benefit that can be achieved during the planning period while satisfying the long-term solution and the total fixed budget for each year of the planning period. Both upper and lower annual budget limits can be specified for individual road categories when needed to maintain minimum performance goals. The original NOS solution would be much more difficult to find, solving individual road categories and iteratively shifting the budgets from one year to another and from one road category to another. Only the length of the planning period and annual overall budgets are needed to solve the linked model. For a more detailed discussion, see Alviti et al. (2).

Kansas Experience

Background

Kansas began active use of its NOS in 1986 as a tool to estimate funding requirements, allocate resources, and develop the substantial maintenance program. Substantial maintenance projects are those intended to protect the investment in Kansas' highway system by preserving the "as-built" condition as long as possible, thus minimizing the need for major improvements.

Kansas' original NOS software ran in an IBM:MVS operating system environment from 1986 through 1991. Along with the development of an annual substantial maintenance program, NOS solution outputs were used to support the 1989 passage of a major multiyear comprehensive highway program funding package by the Kansas legislature. NOS solution outputs have provided impact analyses of the price of oil on the substantial maintenance projects and other funding constraint "what if" scenarios. NOS solution outputs are already being requested to substantiate the next generation of funding, because the current legislation terminates in 1997. The magnitude of preservation actions at different levels of funding will be a subject of considerable analysis and debate; the NOS process provides credible alternatives for this decision process.

A new use for NOS solution outputs involves support for goal programming, which is a new concept being implemented in Kansas to optimize allocation of funds to all highway programs based on minimization of deviations from agency goals. When fully implemented, goal programming will help establish funding levels for the two major programs that address pavement surfaces: substantial maintenance and major modification. Major modification projects go beyond preservation and focus on extending service life and enhancing safety.

Use of Linked Model

In 1992, Kansas implemented the NOS linked model software in an IBM:VM operating system environment, so experience with the model has been somewhat limited. One of the primary enhanced operational capabilities with the linked model is the ability to make trade-offs between road categories. Kansas' road categories are 1-mi highway segments categorized by Interstate/non-Interstate, pavement type pavement width group, and load range group.

Kansas had expectations of providing linked model with a fixed budget and generating an optimal solution with minimal user interaction. This capability exists but is not as straightforward as originally conceptualized.

Four long-term runs were produced in support of the substantial maintenance program development effort. Five additional long-term runs were produced to provide pavement management system (PMS) data input to goal programming. Eight of the long-term runs were cost minimization runs where the performance standards were specified for each road category. One long-term benefit maximization run was made to determine the impact of optimization between road categories.

Kansas' performance levels are composed of pavement condition states with the following categories: level one is in "good" condition, level two is in "deteriorating" condition, and level three is in "deteriorated" condition. During benefit maximization optimization, 5 of 23 road categories fell somewhat below acceptable performance to as low as 57 percent in level one performance. However, overall statewide performance increased for both Interstate and non-Interstate pavements for identical budgets. Interstate realized 74.3 percent level one and 2.6 percent level three as compared with 73.5 percent level one and 3.7 percent level three. Non-Interstate realized 78.3 percent level one and 2.3 percent level three as compared with 73.8 percent level one and 2.7 percent level three.

Four short-term runs were produced in support of the substantial maintenance program development effort. The first three runs were "cost minimization" runs. The fourth run was a "benefit maximization" run that used the third run as a basis.

Major shifts of funds from non-Interstate to Interstate were made after the third short-term run. This precluded any direct comparisons between achieved performance levels. However, based on the experience with the 1992 long-term runs, Kansas is confident that an optimal solution was achieved rather than just any solution.

Alaska Experience

The state of Alaska DOT&PF implemented the original NOS in 1991, using it to select pavement rehabilitation projects for a 6-year capital improvement plan. The department does not have a dedicated rehabilitation budget; the rehabilitation projects are funded out of the total highway construction budget. Of the projects recommended by NOS, approximately 90 percent was funded. In 1993, the department implemented the routine maintenance (crack-sealing) recommendations from NOS.

The NOS software ran on a IBM:VM mainframe operating system environment. During the summer of 1993, the software was converted to run on a IBM:UNIX minicomputer environment.

To test the linked model, the Alaska DOT&PF input the same statewide, long-term budget (rehabilitation and maintenance) recommended by the original NOS for each category that uses the benefit maximization model. Each category was optimized separately using this method, which optimized the cost given the benefit or pavement condition target. The selected benefit for each of 69 categories had been based on the historic average pavement condition, except for a few categories that were obviously substandard. The sum of the individual rehabilitation and maintenance budgets totaled \$40.0 million. This resulted in a statewide average benefit (pavement condition) of 0.82 on a scale from 0.0 to 1.0.

The linked model was then run statewide across all 69 categories with the \$40.0 million budget in the cost mode. This determined the optimum benefit for the given budget. By optimization between categories, the resulting benefit was increased from 0.82 to 0.86. Figure 1 shows a cost versus relative benefit curve that uses the benefit mode and sums the budgets of each category. Figure 1 also shows that to achieve a benefit of 0.86 through use of the benefit mode would require a total budget of \$48.2 million. If one looks at it alternatively, to keep the pavement in the same condition, increased optimization across all categories saves \$8.2 million.

If one looks at the changes in individual categories, the linked model recommended reduction of benefits for urban categories and increase of benefits for rural categories. For example, the high-traffic urban interstate historic average benefit was 0.91; the linked model recommends 0.85. For high-traffic rural interstate, the historic average benefit was 0.88; the linked model recommends 0.91. The cost versus benefit curves for the urban categories are much steeper than those for the rural categories, because of larger traffic volumes and more rutting. The linked model determined that it is more cost-effective to put money into the roads with better relative performance. By functional class, the linked model recommended a higher benefit for higher functional classes.

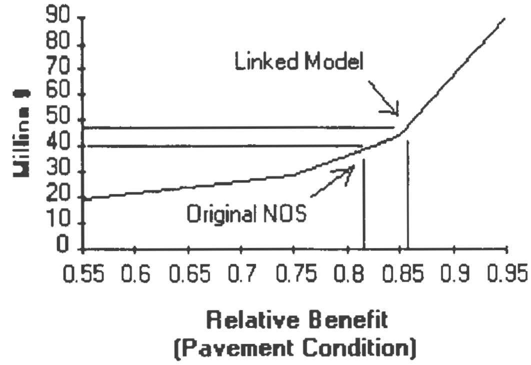

FIGURE 1 Linked model versus original NOS.

At the writing of this paper, no statewide short-term runs have been made. The department has revised its long-term pavement condition targets (benefits) based on the results of the linked-model runs. Future short-term runs will be made using the linked model.

Conclusion

In summary, the NOS linked model helps allocate its funds to achieve the maximum benefit across the entire road network. It assists in setting long-term performance goals and finding the best way to achieve them. The linked model extends the solid mathematical foundation established by the original NOS for optimally allocating road category resources to networkwide resources. Both Alaska and Kansas reported an increase in predicted statewide pavement performance over the original NOS using the linked model with the identical budget. Alaska reported effective annual savings of \$8.2 million on a total budget of \$40.0 million that used the linked model at identical performance target. The linked model is a valuable tool for making the best use of limited pavement and rehabilitation funds.

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Network Pavement Management System Using Dynamic Programming: Application to Iowa State Interstate Network

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Use of a deterministic, dynamic program for network-level pavement management optimization is applied. Dynamic programming, a mathematical programming technique, provides a systematic procedure for determining the decision or combination of decisions that increases the overall effectiveness of resources allocated to the pavement network. Deterministic dynamic programming is applied to the optimization of network-level pavement management, and Iowa segments of Interstate 80 are used as a case study. The network model is based on data provided by the Iowa Department of Transportation (Iowa DOT) and uses the Iowa DOT's pavement performance curves for predicting pavement condition. The model decision variables are the selection of a pavement section's treatment or rehabilitation strategy and the point in time when the treatment is to be applied to the section. Although the model is flexible and may consider several objectives and constraints, it is applied with a cost minimization objective while pavements are constrained to minimum performance levels. I-80 pavement data were provided by the Iowa DOT. In addition, a complete construction project listing for I-80 between 1987 and 1992 was used for comparing the treatment strategies selected by the model with those actually scheduled by Iowa DOT engineers. Although strategies selected by the model and the Iowa DOT engineers are likely to be different, a correlation between the two would tend to validate the results of the model. However, the model should make better decisions than the decisions made with engineering judgment. The dynamic program that performs the network optimization is written in FORTRAN 77. When the results of the computer model were compared with the actual construction project data, in almost 35 percent of the pavement sections, the treatment or rehabilitation strategy and implementation time selected by the optimization model match the Iowa DOT strategy and time. For 40 percent of the pavement sections, the treatment strategy selected by the optimization matched the one selected by Iowa DOT engineers, but the timing was different. The remaining sections showed some inconsistency in the data and the decision-making process. The network optimization model, if implemented, adds to the Iowa DOT's flexibility, consistency, speed in decision making, and ability to forecast the implications of specific decisions, changes in cost structure, changes in assumptions, or changes in resource limitations.

Pavement management systems (PMSs) have become an integral part of the management process for state highway agencies. Because maintenance and rehabilitation funds are limited, cost-effective decisions must be made about the allocation of resources among competing pavement projects during a certain planning period. In March 1989 FHWA issued a policy that requires each state highway agency to have a PMS (*1*). The different PMSs developed should be based on concepts described in the AASHTO publication *Guidelines for Pavement Management Systems* (*2*). FHWA policy also requires that state highway agencies should have PMS operational by January 13, 1993, and that it should be acceptable to FHWA.

There are different definitions for PMSs. A simple definition is as follows: "PMS is an integrated set of systematic procedures designed to help highway engineers or managers in making cost effective, and reasonable decisions related to pavement maintenance and rehabilitation" (3). The AASHTO guide on pavement management provides the following definition: "a PMS is a systematic approach to providing highway administrators and engineers with the types of information needed to effectively and efficiently manage their highway pavements" (2).

Adoption of PMS may result in large savings through more efficient allocation of resources. In Arizona, for example, a savings of $40 million occurred between 1980 and 1985 after the development and implementation of the state's network optimization PMS (4).

PMS have been developed for several states, and most have been tailored for the needs of a particular state to enhance information availability and increase the pavement network's overall quality through better decisions on allocating funds for maintenance and restoration. The sophistication of resource allocation methodology incorporated in PMS depends on the needs of each highway agency. PMS resource allocation methodologies employed ranged from simple decision trees to large-scale deterministic or stochastic mathematical programs.

This paper presents the application of deterministic dynamic programming to network-level pavement management resource allocation. Segments of Iowa's Interstate 80 are used as a case study application for the model. The case study is based on data provided by the Iowa Department of Transportation (Iowa DOT).

Dynamic programming is a member of the family of mathematical programs. It provides a systematic procedure for determining the decision or combination of decisions that increases the overall effectiveness of the system considered (5). There is no general algorithm for dynamic programming models, and the equations used in the model must be developed to fit the individual situation being considered.

Dynamic programming applications are divided into stages and states. In PMS terms, stages define the years in the planning horizon and states define pavement condition. The solution procedure for dynamic programming begins with the last stage and ends with the first. When dynamic programming is used to solve a multidecision process, as for network-level pavement management, it significantly reduces the problem size and still guarantees an optimal or best solution.

More commonly, the optimal allocation of pavement resources to a particular year and to the application of a particular treatment to a particular section is solved in an integer programming context. In an integer programming context, applying or not applying a treatment strategy is represented by a 0-1 integer switch variable. A decision variable assigned the value 1 means that a treatment strategy is applied; 0 means that no treatment is assigned. However, applications of general-purpose integer programming solution packages to large-scale network problems become computationally intensive and the computation times, unreasonably long. The application of dynamic programming to the allocation of pavement maintenance and rehabilitation resources is a special-purpose integer programming algorithm. Dynamic programming more efficiently reaches the same optimal solution found by a general-purpose integer programming package. However, dynamic programming is able to find the solution with the use of a more robust solution-seeking approach and thus reaches the optimal solution in reasonable-length computer runs.

Most pavement management resource allocation systems include two submodels: the first model estimates the future performance of the pavement, and the second allocates resources to maintenance and restoration activities in the future based on estimated levels of future performance. This paper focuses on the second part of the system and is discussed throughout the remainder of the paper. Additional research is need to improve performance prediction techniques. However, improvement of the fidelity of pavement prediction models is left to future investigations.

Pavement performance is defined as the "ability of a pavement to fulfill its purpose over time" (2). A prediction method is a "mathematical description of the expected values that a pavement attribute will take during a specified analysis period" (2). Prediction models can be deterministic or stochastic. In this paper, the Iowa DOT pavement condition rating (PCR) equations are used to develop a performance curve (deterministic model) to predict pavement condition. Performance curves normally define a relationship between the expected serviceability and age or future traffic (6). In this case, the pavement performance curve describes the relationship between PCR and age expressed in years.

Methodology

Deterministic dynamic programming is used to develop a network-level pavement management resource allocation model for the Iowa DOT Interstate highway network. The deterministic approach means that the state (pavement condition) at the next stage (year) is completely defined or determined by the state and decision at the current stage. The following is a list of definitions to provide the resource allocation model a dynamic programming framework:

- Each *stage* in the dynamic programming model will represent 1 year in the planning horizon. The planning horizon can be 5, 10, or 20 years.

• *States* are 10-point ranges of the PCR value, which are between 0 and 100.

State	*PCR Value*
1	100–90
2	89–80
3	79–70
4	69–60
5	59–50
6	49–40
7	39–30
8	29–20
9	19–10
10	9–0

Each pavement section is in one of the previous states depending on its PCR value.

• *Decision variables* represent different types of maintenance treatments or policies to apply to each pavement section.

• The *objective function* minimizes the total cost of maintenance and rehabilitation.

To understand further how dynamic programming works, consider the following example, which is designed to illustrate the features of dynamic programming when used in PMSs. The example considers five pavement sections. The condition of the pavement is determined by calculating the PCR value from a performance curve. The performance curve, in terms of PCR, is assumed to be a function of only the total number of 18K equivalent single-axle loads (ESALs) that the pavement has experienced. The traffic volume information covers 10 years, and the PCR values for each section during the 10-year period are given in Table 1. The performance curve in the example has the following form:

$$PCR = 100 - a\,(\text{total 18K ESALs})$$

where a is a constant depending on surface type.

Pavement condition is divided into seven states. The first six states have a PCR range between 40 and 100, and the seventh state has a PCR value of less than 40. The additional information needed is related to the available treatment strategies and the cost of applying each alternative. The following table contains a list of the available treatment strategies and their associated costs (all costs are assumed values and are based on two 12-ft lane-mi).

Treatment Strategy	*Cost ($/mi)*
Routine maintenance	5,000
Surface treatment	20,000
Overlay ≤ 4 in.	70,000
Overlay > 4 in.	80,000
Pavement replacement	125,000

After the pavement sections are divided into different states on the basis of their PCR values, the feasible treatment strategies for each state should be identified. Table 2 defines the feasible strategy for each state.

The objective to be achieved in this example is to minimize the total cost over a 10-year period. There will be no consideration for interest or inflation rates. To make the example as simple as possible, only one constraint is considered. The constraint deals with the minimum allowable state that any pavement section can reach before replacing the pavement. The constraint is that the minimum allowable state is a PCR value of 40.

The solution obtained for the example shown that uses dynamic programming is summarized in the following:

For rigid pavements and for the data given in the example, the following treatment strategies were selected:

- State 1: Routine maintenance,
- State 2: Routine maintenance,
- State 3: Surface treatment,
- State 4: Surface treatment,
- State 5: Surface treatment,

TABLE 1 Estimated PCR Values for Sections More Than 10 Years Old

Section Number	Section Length	PCR*									
		1	2	3	4	5	6	7	8	9	10
1	2.50	90	88	85	82	79	75	70	65	59	54
2	2.35	91	89	84	80	77	72	69	64	60	57
3	3.50	49	40	32	25	18	15	14	12	10	09
4	1.50	70	67	63	60	57	53	50	46	43	39
5	2.70	67	63	59	56	52	48	44	41	38	35

* PCR values are based on: PCR = 100 - (a x (Total 18K ESAL))

TABLE 2 Feasible Treatment Strategies

Pavement State	Feasible Treatment Strategies				
State # 1	1	2	3	4	5
State # 2	1	2	3	4	5
State # 3	2	3	4	5	
State # 4	3	4	5		
State # 5	3	4	5		
State # 6	4	5			
State # 7	5				

1. Routine Maintenance 2. Surface Treatment 3. Overlay ≤ 4" 4. Overlay > 4" 5. Pavement Replacement

- State 6: Overlay ≤ 4 in.,
- State 7: Pavement replacement,
- State 8: Pavement replacement,
- State 9: Pavement replacement, and
- State 10: Pavement replacement.

To determine the solution for each section, the following procedure is used:

1. Determine the condition (PCR value) for the section from the data given or the performance curve.
2. Determine the state of the pavement section depending on the PCR value.
3. When the state is defined, select the appropriate treatment strategy from the previous list.
4. Increase the PCR value depending on the type of treatment strategy selected for the pavement section.
5. Determine the cost for each year and find the total cost for the planning horizon.

Usually the cost of applying each treatment strategy depends on the state of the pavement section, but to simplify the example treatment costs are assumed to be constant regardless (see previous in-text table).

The following is an interpretation of the results for Pavement Section 1: From the data given in Table 1, the decreases in PCR values for section 1 are 2, 3, 3, 3, 4, 5, 5, 6, and 5 points for Years 2 through 10, respectively. The resulting maintenance strategies according to the dynamic programming solution are surface treatment for years 5 and 9 and routine maintenance for all other years.

Pavement Section 1 is 2.5 mi in length and its total cost is $200,000. For the remaining sections, the same procedure is followed, and the following is a summary of the total cost for each section:

Section	*Cost ($)*
2	223,000
3	665,000
4	187,500
5	378,000

Figure 1 shows the network used to solve the dynamic program used to model the pavement management system.

Application

Deterministic dynamic programming is used to develop the mathematical tool used in building the pavement management resource allocation model. After the objective function was selected (i.e., minimization of maintenance and rehabilitation costs) and the pavement management model was defined in terms of dynamic programming characteristics, a computer program was written using Microsoft FORTRAN (7). The software uses FORTRAN 77. Only data from Iowa's I-80 are used; the data included the following elements:

1. Section identification information:
   –Section identification number,
   –County,
   –Direction of travel, and
   –Pavement type.
2. Section characteristics:
   –Section length (miles),
   –18 K ESALs (yearly and total), and
   –PCR values.
3. Treatment strategies:
   –Feasible treatment strategies for each pavement type at different states,

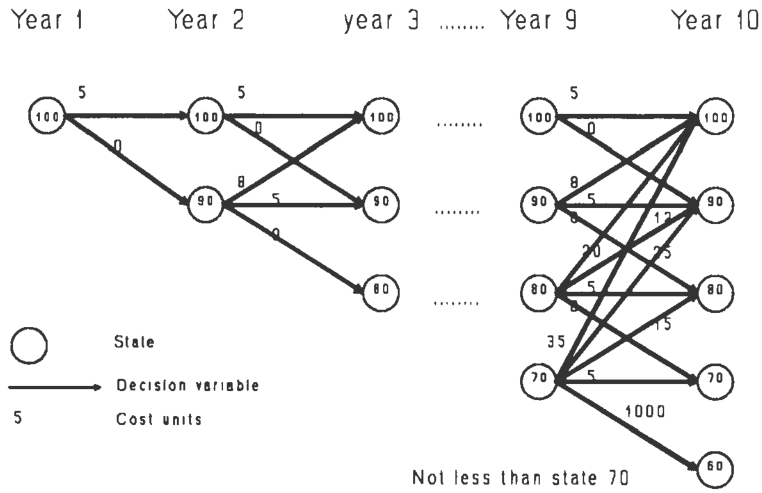

FIGURE 1 Dynamic programming network, State 1 pavement section.

–Cost of applying different treatment strategies, and

–Increase in PCR value after a certain treatment strategy was applied to a pavement section at a certain state.

Tables 3 through 8 show the information needed for the dynamic programming model. The following information is included in each of the tables:

- Available treatment strategies for flexible and rigid pavements and their application costs are given in Tables 3 and 4.
- Feasible treatment strategies for each state for flexible and rigid pavements are included in Tables 5 and 6.
- The increases in PCR value after application of a certain treatment strategy for both flexible and rigid pavements are included in Tables 7 and 8.

After all the data were loaded into the computer program, the model was on a Z-386/25 Zenith personal computer with 4M of random access memory (RAM) and a 80387 math coprocessor. The running time to solve the dynamic program for 121 sections on I-80 was about 2 min. The planning horizon for the application was 5 years. The results were obtained in the following format:

1. Section identification information and length;
2. Yearly program that includes
   –Year,
   –Type of treatment strategy recommended, and
   –Cost of applying the treatment strategy; and
3. Total cost for the entire pavement network for the planning horizon.

Furthermore, the data can be analyzed to arrive at such information as

1. Number of miles in each state for every year;
2. Average PCR value for each pavement type;
3. Average PCR value for the entire pavement network;

TABLE 3 Available Treatment Strategies, Flexible Pavements

Type of Treatment	Code	Cost
Routine Maintenance	00	$3,000
Crack Sealing	02	$5,000
Patching	20	$125,000
Resurfacing - 3"	43	$150,000
Resurfacing - 4.5"	44	$215,000
Resurfacing - 6"	45	$270,000
Pavement Replacement	70	$1,000,000

TABLE 4 Available Treatment Strategies, Rigid Pavements

Type of Treatment	Code	Cost
Routine Maintenance	00	$5,000
Joint / Crack Sealing	03	$10,000
Full Depth Patching	10	$200,000
Partial ACC Patching	20	$125,00
Resurfacing - 4"	72	$275,000
Resurfacing - 6"	75	$470,000
Pavement Replacement	70	$1,000,000

TABLE 5 Feasible Treatment Strategies, Flexible Pavements

State #	PCR Range	Feasible Treatments
1	100 - 90	00, 02
2	89 - 80	00, 02, 20, 43
3	79 - 70	00, 02, 20, 43, 44
4	69 - 60	00, 02, 20, 43, 44, 45
5	59 - 50	00, 20, 44, 45, 70
6	49 - 40	00, 44, 45, 70
7,8,9,10	Less Than 40	70

TABLE 6 Feasible Treatment Strategies, Rigid Pavements

State #	PCR Range	Feasible Treatments
1	100 - 90	00, 03
2	89 - 80	00, 03, 20
3	79 - 70	00, 03, 20, 72
4	69 - 60	00, 03, 10, 72, 75
5	59 - 50	00, 10, 72, 75, 70
6	49 - 40	00, 10, 72, 75, 70
7,8,9,10	Less Than 40	70

4. PCR value for a certain section for every year in the planning horizon; and
5. Maintenance and rehabilitation costs for each pavement type (by year or total).

To better understand how the PMS model functions, the following small-scale example from I-80 is considered. Consider a pavement section with the following set of information:

- Section number: 872500,
- County: Pottawattamie,
- Direction: East,
- Pavement type: continuous reinforced concrete (CRC).
- Section length: 4.60 km (7.41 mi),
- Age since last rehabilitation action: 18 years,
- Planning horizon: 5 years,
- Actual PCR value: 34, and
- Predicted PCR value: 31.

TABLE 7 Resulting PCR Values After Application of Different Treatment Strategies, Flexible Pavements

Initial State	Feasible Codes	PCR Increase
1	00	Same
	02	5
2	00	Same
	02	5
	20	10
	43	15
3	00	Same
	02	5
	20	10
	43	15
	44	20
4	00	Same
	02	5
	20	10
	43	15
	44	20
	45	30
5	00	Same
	20	10
	44	20
	45	30
	70	90
6	00	Same
	44	20
	45	30
	70	90
7,8,9,10	70	90

The solution procedure for the PMS model consists of several steps. The following is a brief description of each:

- Determine the state of the pavement section that depends on the PCR value. The PCR value is between 31 and 40, and, therefore, the state is 7.
- Check to determine if pavement replacement is the only feasible alternative. Because the state of the pavement section is less than 6, pavement replacement is the only feasible alternative.
- Update the PCR value to reflect the treatment strategy applied. Pavement replacement increases the PCR value to 97.
- Use the performance curve to predict the future PCR values for the remaining years in the planning horizon:
  –Year 2: 96,

TABLE 8 Resulting PCR Values After Application of Different Treatment Strategies, Rigid Pavements

Initial State	Feasible Codes	PCR Increase
1	00	Same
	03	5
2	00	Same
	03	5
	20	10
3	00	Same
	03	5
	20	10
	72	25
4	00	Same
	03	5
	10	10
	72	25
	75	35
5	00	Same
	10	10
	72	25
	75	35
	70	90
6	00	Same
	72	25
	75	35
	70	90
7,8,9,10	70	90

–Year 3: 94,
–Year 4: 93, and
–Year 5: 91.

- Determine the state of the pavement section for each year that depends on the predicted PCR value:
  –Year 2: 1,
  –Year 3: 1,
  –Year 4: 1, and
  –Year 5: 1.
- The dynamic program will determine the best feasible treatment strategies for each year.
  –Year 1: Pavement replacement ($1,000,000),
  –Year 2: Routine maintenance ($3,000),
  –Year 3: Routine maintenance ($3,000),
  –Year 4: Routine maintenance ($3,000), and
  –Year 5: Routine maintenance ($3,000).
- The total cost for the pavement section is $1,012,000.
- The average PCR value is 94.

Conclusions

To provide a degree of validation to the computer model, the results from the dynamic programming model were compared with the I-80 construction data for the years

1987 through 1992. The decisions of the Iowa DOT pavement managers did not correspond exactly with the decisions of the computer model. The Iowa DOT pavement managers did not necessarily use the same object when they made resource allocation decisions, and they had the entire Iowa pavement network to consider, budget limitations to weigh, and political and other subjective issues to consider. Therefore, the solution of the mathematical program should not necessarily be the same as the solution reached by Iowa DOT pavement mangers. However, the solution developed by the mathematical program should not vary widely for the actual decisions. I-80 consists of 121 sections with a total length of 379.78 two-lane-km (611.2 two-lane-mi) (about 305 mi). When the results were compared with the historical data, the following conclusions were drawn:

1. Twenty-eight sections were found to match exactly with the historical construction data (i.e., type of treatment strategy selected and the implementation time).
2. Fifty-four sections matched the treatment strategy selected, but there were 1 or 2 years' difference in implementation times.
3. The rest of the 39 sections did not match with the historical construction data. There were incidents when the same treatment strategy was applied, but the timing was different.
4. In an examination of the results from the PMS dynamic program model, it was noticed that some of the pavement sections had undergone a major maintenance activity and were scheduled to be replaced or reconstructed in the next year or two.
5. No cost numbers were compared directly in the results because of the nature of the objective function selected. A comparison of the total cost from the dynamic program ($299,607,000) with the cost of the I-80 construction history ($211,412,000) indicates that the results from the dynamic program are close to those from the Iowa DOT, if one keeps in mind the difference in formulating each program. The dynamic program was formulated to minimize agency costs based on a performance standard (PCR $\geq$ 70 for the given example). The Iowa DOT results are not based on the same performance standard.
6. To determine the difference in PCR values between the Iowa DOT program and the dynamic program, 20 random sections were selected and compared. The comparison showed that the PCR values that resulted from the dynamic program at the end of the 5-year planning horizon were slightly higher than those from the Iowa DOT data.

These conclusions indicate that similarities exist between the new model and Iowa DOT practices and, therefore, that the model is making decisions that reflect actual conditions. However, if the Iowa DOT decided to adopt such an approach for its PMS, more work should be done to fit its needs. Areas that need more investigation are the following:

1. Pavement performance prediction (performance curves);
2. Treatment strategies in terms of
   –Costs of applying different treatment strategies at different states,
   –Resulting PCR value after application of certain treatment strategies, and
   –Determination of the feasible treatment strategies for each state;
3. Validation and calibration of the model;
4. The structure of the computer program:
   –The computer program should be developed in a user-friendly modeling system, and
   –An operational manual should be developed for the computer program.

In conclusion, the suggested approach (deterministic dynamic programming) used in development of the mathematical model for the PMS is beneficial and achieves the required goals of the system. Dynamic program has been shown to be an efficient means of solving the integer pavement management optimization problem. The results from the developed model are promising, but more work should be conducted to make the procedure directly implemented by a state department of transportation.

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MUNICIPAL/LOCAL DEVELOPMENTS AND ISSUES IN PMS IMPLEMENTATION

Arizona Airport Pavement Management System

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The Aeronautics Division of the Arizona Department of Transportation (ADOT) is responsible for the funding of assistance for pavement projects at 56 primary airports throughout the state. In 1991 the department began the development of a network-level pavement management system. The development of the system, its functional parts, and the implementation of the system within the department are described. The development of the system included the marriage of existing Macintosh computer software for land use capability and noise studies for the airports with new software dealing with pavement deterioration and repair. The unique side of the development process was the need to formulate a system that could be used by all members of the Aeronautics Division during yearly 5010 safety inspections and produce meaningful prediction of pavement service life, rehabilitation requirements, and prioritization of pavement projects across the state. The Arizona Pavement Rating system uses a new pavement distress rating procedure to evaluate pavement condition. The system is based on experienced gained from pavement evaluations that use pavement condition index procedures, but the system is not as labor-intensive and does not produce as much quantitative information. The development of this process is described, and its relationships to pavement condition index procedures are shown. The system calculates remaining service life and generates a prioritized project listing for each airport. The resultant project costs are combined into a statewide fiscal plan for funding requests. Software development and structure are described as are the links to the existing land use noise and 5010 data base software. The computer system and data base were installed in November 1992. Field training of ADOT users was completed during June and July 1992.

The Aeronautics Division of the Arizona Department of Transportation (ADOT) is responsible for managing and allocating funding for 56 public-access airports. The division also provides an interface between the individual airport management and FAA. Pavement preservation is one of the major funding functions of the division. The Arizona Transportation Board selects projects for funding on the basis of recommendations from the division. The engineers and administrators of the division decided to pursue the development of a pavement management system (PMS) with the objective of assisting the division in formulating and presenting recommendations to the transportation board.

Although the ADOT Aeronautics Division has responsibility for project selection, funding, and quality assurance, it does not have direct responsibility for the management and operation of the individual airports (other than the Grand Canyon Airport, which is owned and operated by the state). The lack of centralized operation and management for the airports increases the complexity of making budgeting decisions, because each airport competes for funding from the divisions to achieve its individual objectives. To resolve this problem, the department needed a way to define systematically the needs and priorities of each of the individual airports.

An initial attempt to develop a PMS was unsuccessful for several reasons. However, it did provide several valuable lessons that were incorporated into the terms of reference for the development of a new system. This allowed the division to define clearly the roles and responsibility of the consulting firm selected for the development and initial implementation of the system. First, the "network" boundaries with which the division was concerned included all of the primary airports in the state. PMS had to be able to determine the preservation needs of each of the individual airports and to assess the relative priorities of the projects between the airports. This definition of the network boundaries generates several unique requirements on the development of the system.

Because the management of the airports is decentralized, the consultant needed to work extensively with the individual airport managers for the development of the data base. Second, the Aeronautics Division was to be responsible for the annual updating of the pavement condition data base. Manpower availability of the department dictated that the pavement condition data collection be performed on the same day as the annual 5010 safety inspection required by FAA. This required development of a new condition survey procedure, because the existing methods were too labor-intensive to meet the staffing constraints of the department.

The ADOT Aeronautics Division uses Macintosh computers. Because PMS software was not available for Macintosh, the consultant had to develop new software. The programs had to take full advantage of the user interface capability of the Macintosh to simplify operation of the PMS program. Upon completion of the project, the division required that all software developed by the consultant for the system be placed in the public domain.

In addition to pavement management, the Aeronautics Division has computerized the land use mapping, noise contours, and 5010 data sheets. PMS interfaces with the other data bases, providing an integrated airport management capability.

Construction History Data Base

The construction history data base includes the location and dimensions of all aircraft pavement construction projects at each airport, information on the year of last construction or overlay, and descriptions of materials and layer thicknesses as well as maintenance activities. A technician reviewed airport records and microfiche files at ADOT, recording available data on project construction and maintenance history. In Arizona individual airports design and oversee construction and maintenance projects. Thus, local authorities have more pavement history documentation than state officials.

Where information was not available from ADOT records, the technician telephoned local airport officials and their engineering consultants to obtain needed data. When required information could not be transmitted over the telephone or by mail, and in cases where the exact scope of information was not known, the technician visited the airport, reviewed records, interviewed airport personnel, and observed pavement geometry on site. Historical information was then reviewed and entered into the construction history data base. Elements of the data base were subsequently used to develop and refine the airport layout sketches.

For each airport in the survey, a layout sketch of the aircraft pavement was developed from airport layout plans, drawings of construction projects, and aerial photographs and then subdivided by material type, composition, and function. Sketches were developed on AutoCad and translated to the Macintosh operating system with the use of MapGrafix.

Referencing System

A pavement referencing system was developed to subdivide the pavement into functional areas, pavement sections, and samples. A functional area has a specific operational purpose and a defined identity at the airport; such areas are runways, taxiways, and aprons. Sections are subdivisions of functional areas, which represent construction management units, with consistent surface type, time of construction, design thickness, and composition. Each section was subdivided into samples 30 m (98 ft) long. On runways and taxiways, the sample width equals the section width. Apron samples were 30 m (98 ft) wide.

Section Layout

Runways wider than 30 m (98 ft) were divided into one keel section 15 m (49 ft) wide and centered on the runway and two wing sections of equal width to account for concentration of traffic. Section boundaries were recorded in a pavement sketch. Dimensions from points of reference on the ground were noted to facilitate location of section boundaries in the field.

Referencing Identifiers

Functional areas were identified by a two-field alphanumeric code. The first field identifies the type of functional area as R, T, or A for a runway, taxiway, or apron, respectively. The second field defines the direction of runway, the sign designation of a taxiway, or the functional use of an apron. Sections are identified by the functional code and a two-digit numeric code, and samples are numbered sequentially within the functional area. Figure 1 is a typical layout sketch.

Pavement Condition Evaluation

The pavement condition index (PCI) rating procedure FAA AC 150/5380-6 (*1*) was used in the initial attempt to develop a PMS for the Aeronautics Division. However, the data collection process required greater resources than the division could justify for network-level decisions. Thus, an initial task of the project was to develop a simplified data collection procedure that would yield sufficient information for network planning.

Development

Historical pavement condition information was evaluated to determine which distress types occur on Arizona airport pavements. An initial condition survey procedure was developed with the use of the six predominant distress types. The procedure was evaluated at five Arizona airports with varying traffic, age, and climate. During the evaluation, both the proposed and PCI procedures were performed to assess the accuracy, repeatability and reliability of the new procedure. This evaluation found that the basic method was acceptable if approximately 10 percent of the samples in a section are surveyed. However, because of the wide use of surface treatments and their unique characteristics, a surface treatment quality rating was added to the survey procedure.

Table 1 identifies the distresses included in the ADOT aeronautics procedure. A categorical procedure is used to rate the extent and severity of each distress type. On the basis of limits established during the project, distress severity and extent are each categorized as low, medium, or high. A comparison with the PCI data demonstrated that little information was lost in the reduction of the number of distress types from 16 to 7.

From this information, a data collection manual was prepared. ADOT engineers and the consultants went through several evaluations and refinements of the procedures, definitions, and field manual. This review process resulted a pavement condition evaluation method that met the needs of ADOT, that is,

- Acceptable accuracy and repeatability;
- Minimum amount of training, effort, and equipment required; and
- Ability to be performed concurrently with 5010 safety inspections.

The pavement condition data are used to rate the overall condition of the pavements and for the selection of pavement repair alternatives. A deduct system is used to determine the overall airport pavement rating (APR). The APR is on a 0-to-10 scale, 10 being a "perfect pavement." Deduct values given in Table 2. The APR is computed as

$$\mathrm{APR} = 10 - \text{minimum } (d_i/i,\ 10)$$

where d_i is the ith value of the individual deduct values ordered from maximum to minimum.

For example, if the following distresses are observed, the APR of a sample is computed as

- A/E cracks = LM;
- Load cracks = ML;
- Surface erosion = LM.

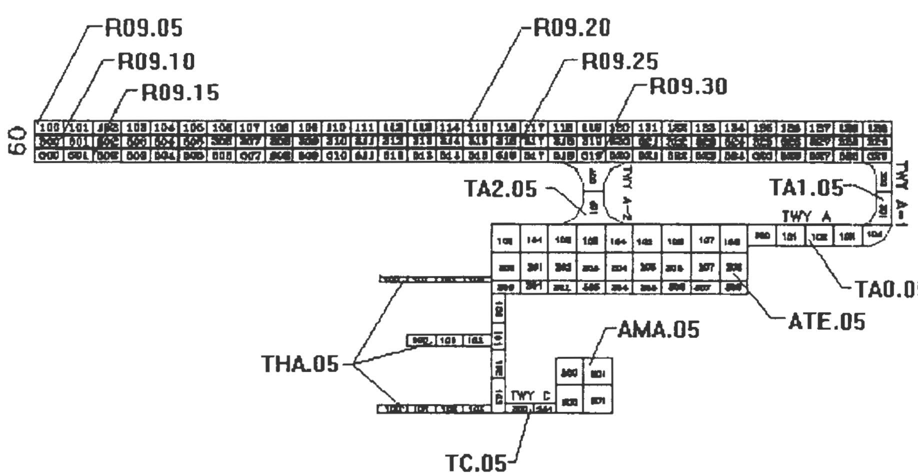

FIGURE 1 Typical layout sketch.

TABLE 1 Distress Types (*3*)

Distress	Causes	Description - Comparable PCI Distress Numbers
1. Age Cracks	AGE • Sun/wind/rain • Thermal stress • Loss of resilience • Base movement	• Single non load related cracks • poor paving lane cracks • Poor paving lane joints • Block pattern in advanced stages • Incudes block, longitudinal and transverse, joint reflection, slippage, #3, 7, 8, 15 (1)
2. Load Cracks	• Wheel load, single or repeated	• Appearance of alligator skin • Usually in heavy traffic areas channelized in wheel paths • Includes alligator cracking, #1 (1)
3. Surface Deformations	• Wheel loads • Subgrade consolidation • Poor construction • Thermal change above 4,000 ft. MSL	• Ruts, depressions, swells, shoving, corrugation • affect rideability (ride quality) • Includes # 4,5,13,14,16 (1)
4. Patches	• Pavement/base failure • Utility trenches	• A replacement of material using same or different material, #10 (1)
5. Flushing	• Excess asphalt	• Pooling of asphalt on surface, #2 (1)
6. Surface erosion	• Effects of sun/wind/rain • Freeze-thaw • Traffic abrasion • Age	• Loss of fines/aggregate particles, #6, 9, 11, 12 (1)
7. Surface treatment distress	• Environmental • Age • Traffic	• Chip/fog/slurry seals • Loss of bond • Loss of material

TABLE 2 Distress Deducts for Flexible Pavements

DISTRESS	DENSITY	SEVERITY		
		LOW	MEDIUM	HIGH
AGE CRACKS	L	0.5	1.5	3.0
	M	1.0	2.5	4.0
	H	1.5	3.5	5.0
LOAD CRACKS	L	1.0	2.5	4.0
	M	1.5	3.5	5.0
	H	2.0	4.5	6.0
DEFORMATION	L	1.0	2.5	4.0
	M	1.5	3.5	5.0
	H	2.0	4.5	6.0
PATCHES	L	0.5	1.5	2.5
	M	1.5	2.5	4.5
	H	3.0	4.0	6.0
FLUSHING				
Runway	L	0.5	1.0	1.5
	M	1.0	2.0	3.0
	H	1.5	4.0	5.0
Other	L	0.0	0.5	1.0
	M	0.5	1.0	1.5
	H	1.0	2.0	3.0
SURFACE EROSION				
	L	0.2	0.5	1.0
	M	0.5	1.0	1.5
	H	1.0	2.0	3.0
SURFACE TREATMENT		EXCELLENT	GOOD	POOR
		0	0.5	2.0

NOTE: L = low, M = medium, H = high

Deduct values are

- A/E = 1.0;
- Load = 2.5;
- Surface erosion = 0.5.

Calculated deduct is

$$2.5 + 1.0/2 + 0.5/3 = 3.2$$

$$\text{APR} = 10 - 3.2 = 6.8$$

A section rating is calculated with the use of the average of the deduct values for each distress type as shown in Table 3. (If sample sizes vary, the average value is weighted by sample area.) In Table 3, the calculated deduct is

$$2.3 + 1.7/2 + 1.0/3 + 0.5/4 + 0.3/5 = 3.7$$

and

$$\text{APR} = 10 - 3.7 = 6.3$$

Productivity

Field testing indicated a typical primary airport (one runway, parallel taxiway, and terminal apron) can be inspected in approximately 4 hr. Table 4 shows some actual field productivity statistics for the APR survey method. The PCI procedure requires approximately twice the inspection time. Typically, the PCI procedure averages four to six samples per hour.

The productivity figures in Table 4 were obtained by trained pavement condition survey crews who used vehicles to carry the equipment and travel between sections. Because the aeronautics staff flies to some airports for the 5010 inspection, a survey vehicle will not always be available for the PMS data collection. In these cases the 5010 and PMS data will be collected on separate visits to the airport. It is anticipated the PMS data will be collected for a half of the airports each year.

TABLE 3 Average of Deduct Values for Each Distress Type and Action Taken

	Sample				
Distress	100	106	112	Average	Action
A/E crack	2.5	1.0	1.5	1.7	Seal/patch
Load crack	2.5	2.0	2.5	2.3	Seal/patch
Deformation	0	1.0	0	0.3	None
Patches	0	0	1.5	0.5	None
Flushing	0	0	0	0	None
Surface erosion	0.5	1.0	1.5	1.0	None
Surface treatment	None	None	None		None
Sample APR	6.1	6.9	5.9		

Repair Strategies

The strategies considered in this network-level PMS are the following: quantifiable alternatives are surface treatment, overlay, and reconstruction, and other strategies include crack sealing and patching.

TABLE 4 Productivity

AIRPORT	TOTAL SAMPLES	TOTAL TIME (HRS)
Page	47	4
Grand Canyon	80	4
Kingman	60	4
Bullhead Laughlin	26	3
Flagstaff	96	6.5
Sedona	41	3.5
Cottonwood	20	2
Prescott	83	6
Winslow	82	4.5
Holbrook	32	2
Taylor	23	1.5
Show Low	40	3
St Johns	32	2
Springerville	21	1.5
Payson	33	2
Bagdad	13	1
Wickenberg	32	2
Glendale	48	4
Phoenix-Goodyear	73	8
Buckeye	27	3
GilaBend	21	1.5
Ajo	6	1
Yuma	92	11.5
Phoenix-Deer Valley	143	15
Scottsdale	129	15
Mesa	118	12
Globe-San Carlos	26	4
Chandler	74	5.5
Coolidge	36	2
Casa Grande	47	3
Eloy	22	1.5
Marana -Pinal	33	3
Tucson Avra Valley	72	5.5
Tucson Ryan	65	6
Safford	39	4.5
Greenlee	8	1.5
Wilcox-Cochise	11	2
Bisbee-Douglas	26	5
Douglas	15	2.5
Cochise College	13	2
Bisbee	27	2
Sierra Vista	17	3
Nogales	26	2
Keyenta	11	1.5
Window Rock	16	1
White River	23	1.5
Parker Avi Suquilla	25	2
Chandler Stellar	52	3.5
TOTALS	2102 SAMPLES	188 HRS

AVG.SAMPLES/AIRPORT=43
AVG. HOURS/AIRPORT= 3.9
AVG. SAMPLES/HOUR=11

Repair strategies are dictated by the dominant distress in the pavement. Some repair alternatives may be performed independently, whereas others are mutually exclusive. Patching, crack sealing, and surface treatments may be recommended concurrently, but reconstruction would eliminate all other options. Table 5 gives APR levels used for strategy selection. The highest level alternative(s) required by the various deducts is the dominant action and is recommended.

For the example in Table 3, the dominant actions are "crack seal and/or patch." Note, however, that if the load cracking deduct value had been three-tenths of a point higher (2.6), an overlay would have been recommended.

Forecasting Future Needs: Remaining Service Life

Future pavement condition depends on the current condition and the deterioration rate, which vary for each distress type in a pavement section. Annual deterioration was calculated for a distress type by dividing the deduct value for that distress by the age of the pavement, in years. Corrective action is selected on the basis of the deduct value of the critical distress, as demonstrated earlier.

To predict when a corrective action will be needed, future deduct values are calculated for each distress each year during the programming period. Then the appropriate corrective action can be programmed for implementation in the year that the deduct value of the critical distress first reaches the level presented in Table 5.

If the pavement described in Table 3 were 10 years old at time of inspection, deduct values would be forecast as presented in Table 6.

A 5-year program for this pavement section, based on the most severe corrective action from Table 5, would be the following:

Year	*Corrective Action*	*Critical Distribution*
Inspection year	Crack seal and/ or patch	A/E and load cracking
First outyear	Surface treatment	Surface erosion
Second outyear	Overlay	Load cracking
Third outyear	No change	
Fourth outyear	No change	
Fifth outyear	No change	

Some judgment is needed before commitments are made. In the previous example, given that an overlay will be

TABLE 5 Alternative Actions

DISTRESS TYPE	NO ACTION	CRACK SEAL	PATCH	SURF TREAT	OVERLAY	RECON
A/E CRACK	0-1.5	1.6-3.5	1.6-3.5	-	3.6+	–
LOAD CRACK	0-1.0	1.1-2.5	1.1-2.5	-	2.6-5.0	5.1+
DEFORMATION	0-1.0	-	1.1-2.0	-	2.1-4.5	4.6+
PATCHES	0-2.5	-	2.6-4.0	-	4.1-4.5	4.6+
FLUSHING	0-1.5	-	-	1.6-2.5	2.6-4.0	4.1+
SURF EROSION	0-1.0	-	-	1.1-2.5	2.5+	-
SURF TREAT.	0-1.0	-	-	1.0+	-	-

TABLE 6 Forecast Deduct Values for Pavement in Table 3

		Deduct Value for Outyear				
Distress	Calculated Deduct	First	Second	Third	Fourth	Fifth
A/E crack	1.7	1.9	2.0	2.2	2.4	2.6
Load crack	2.3	2.5	2.8	3.0	3.2	3.5
Deformation	0.3	0.3	0.4	0.4	0.4	0.5
Patches	0.5	0.6	0.6	0.7	0.7	0.8
Flushing	0	0	0	0	0	0
Surface erosion	1.0	1.1	1.2	1.3	1.4	1.5
Surface treatment	None	None	None			

needed in the second outyear, if the overlay can be programmed for that year, other maintenance actions on the pavement probably should be suspended. However, the pavement manager has the option to carry out all the recommendations. If funds or local support are not expected to be available for an overlay in the second outyear, perhaps the maintenance actions should be scheduled.

Project Priority

Before this project, the Arizona Transportation Board policy on priority ranking aviation projects complied with Arizona Revised Statutes 28-111 but did not have the ability to include pavement distress information. Using a minimum service level and the APR, the department can now grade projects in order of priority on the basis of pavement rehabilitation needs. Within the airport management system, each section has been assigned a minimum service level. The following table shows the default service levels:

Functional Area	*Minimum Service Level*
Runway	7.0
Taxiway	6.0
Apron	5.0

The airport PMS calculates a priority number for each project within the data base. The priority number is the difference between the minimum service level and the APR for the section. With the use of the minimum service level, a pavements repair priority increases with the service-level margin. For example, if the runway section of the airport has an APR of 8.2, and the minimum service level for runways is 7, then the priority number for the section is the difference of $(7 - 8.2)$, or -1.2. If the adjacent section of the runway has an APR of 4.8, then the priority number for the section is $(7 - 4.8)$ or 2.2. The present priority system awards points for a number of criteria. By adding the priority number for a project recommended, based on pavement deterioration, the department will be able to compare projects across the board while it takes into consideration the condition of the pavement.

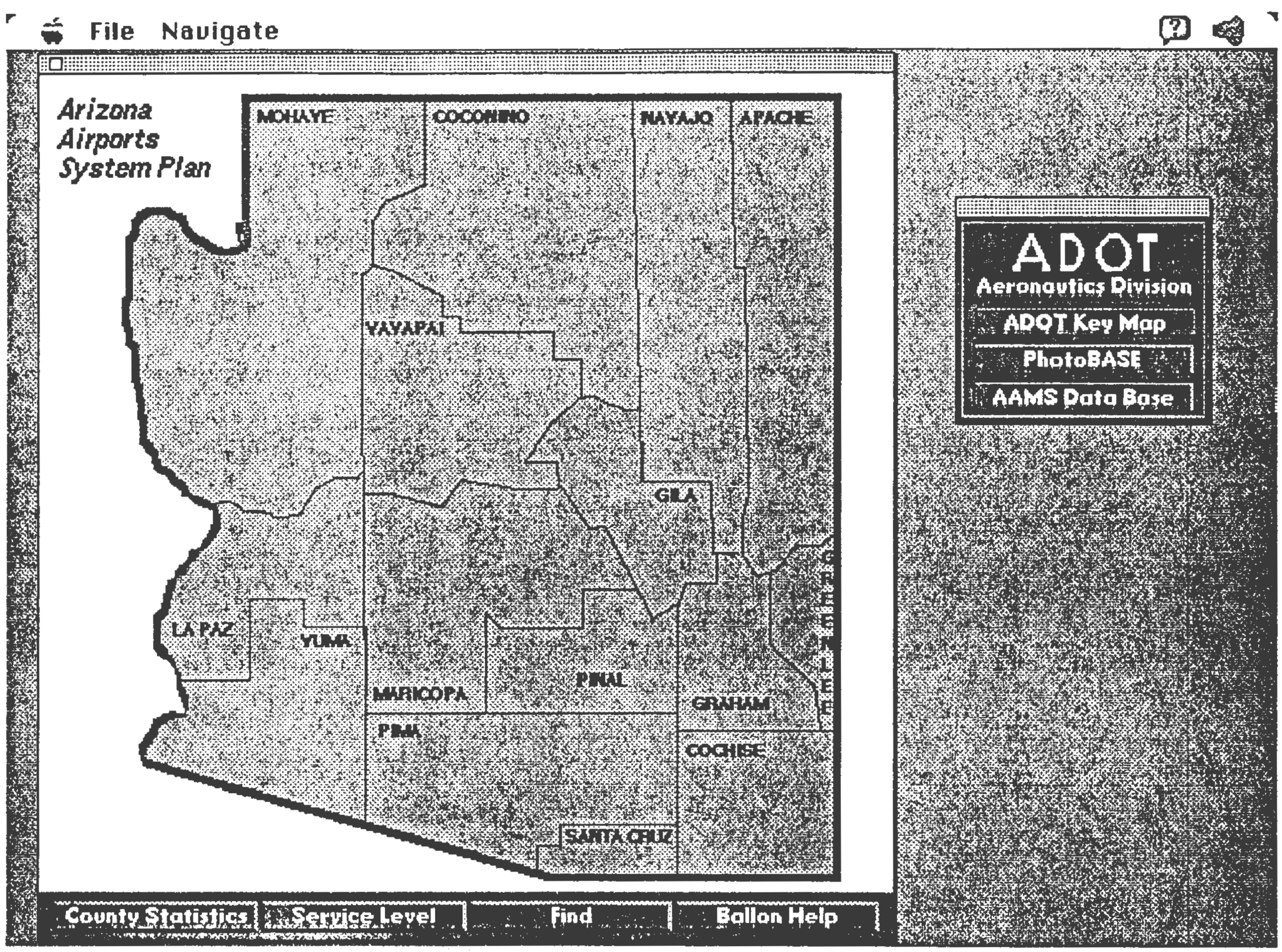

FIGURE 2 Access to software functions.

Because the minimum service level is higher for runways than for other functional areas, the priority number for a given APR is greater for runways than for other pavement types. If a runway and an apron each has an APR of 5, the priority numbers will be 2 and 0, respectively.

Computer Software

The software developed for this project is available through the ADOT Aeronautics Division. Details on the system can be found in the users' manual (*2*). The software allows the user to access the pavement management data base and a number of other management tools including plans, land use maps, noise contours, and 5010 data sheets for each airport. Figure 2 shows the screen for access to each of the these areas.

Figure 3 shows the section summary detailing APR, recommended action, and capacity analysis function. From this area, the operator can review details of the distress found in the survey and access the inventory data base.

Figure 4 shows the typical inventory data base information available for each pavement section. This area can contain all historical information for the section as well as project tracking numbers for repairs and maintenance. Figure 5 shows the capital improvement spreadsheet that contains the actions recommended for each pavement section. The cost totals are stored in a statewide data base to allow statewide overview of expenditures.

System Applications

Evaluation of the health of the pavement network is one of the significant by-products of the PMS. Figure 6 shows the distribution of APR values for the 1,046 pavement sections surveyed. For the survey, 82 percent of the pavement sections have an APR greater than or equal to 6.0.

The primary objective of the Arizona Aeronautics Division PMS was to give the division an objective method for formulating the portion of the 5-year plan dedicated to pavement restoration and preventive maintenance on the primary airports. The system can generate a needs-

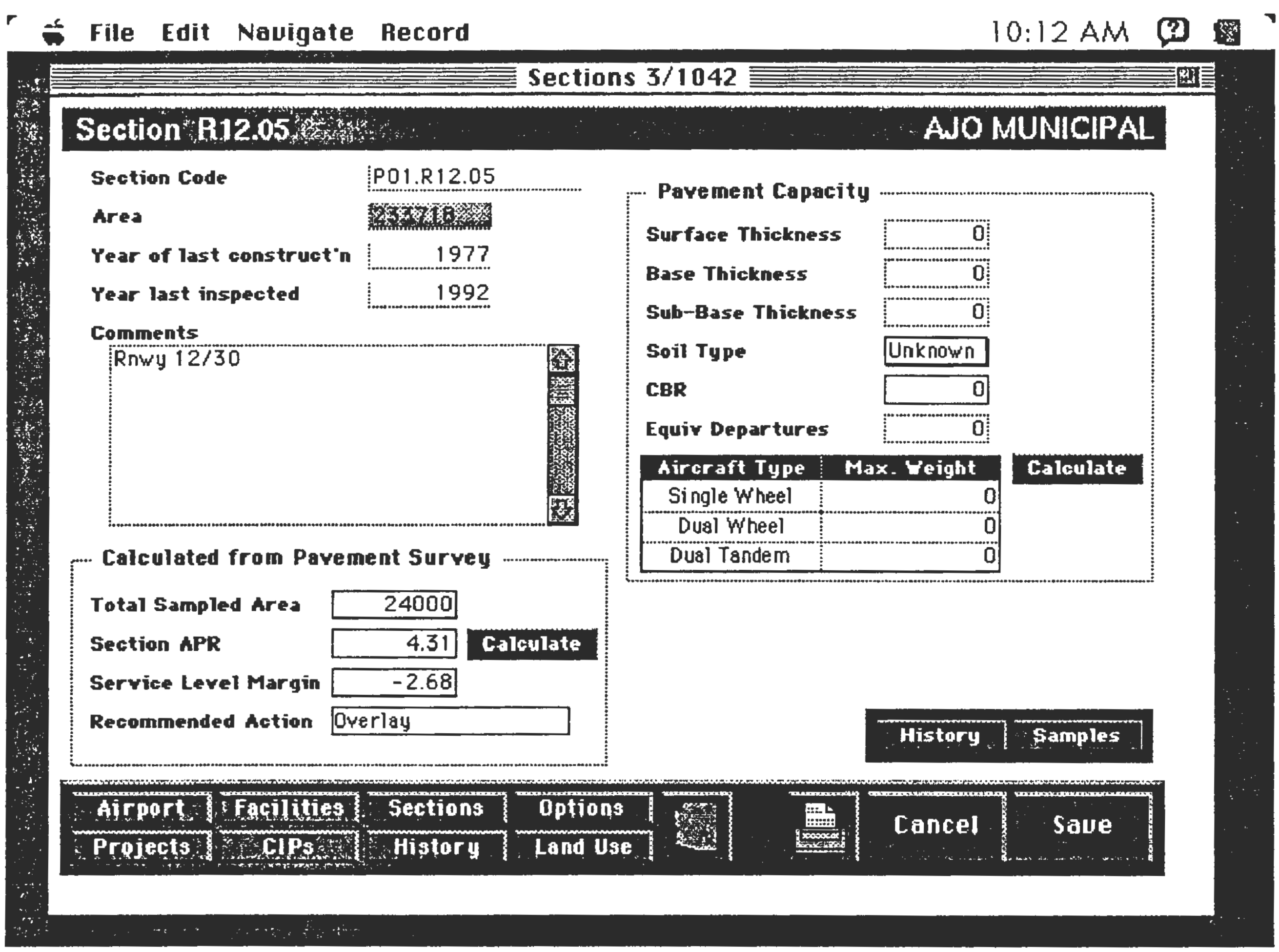

FIGURE 3 Section details.

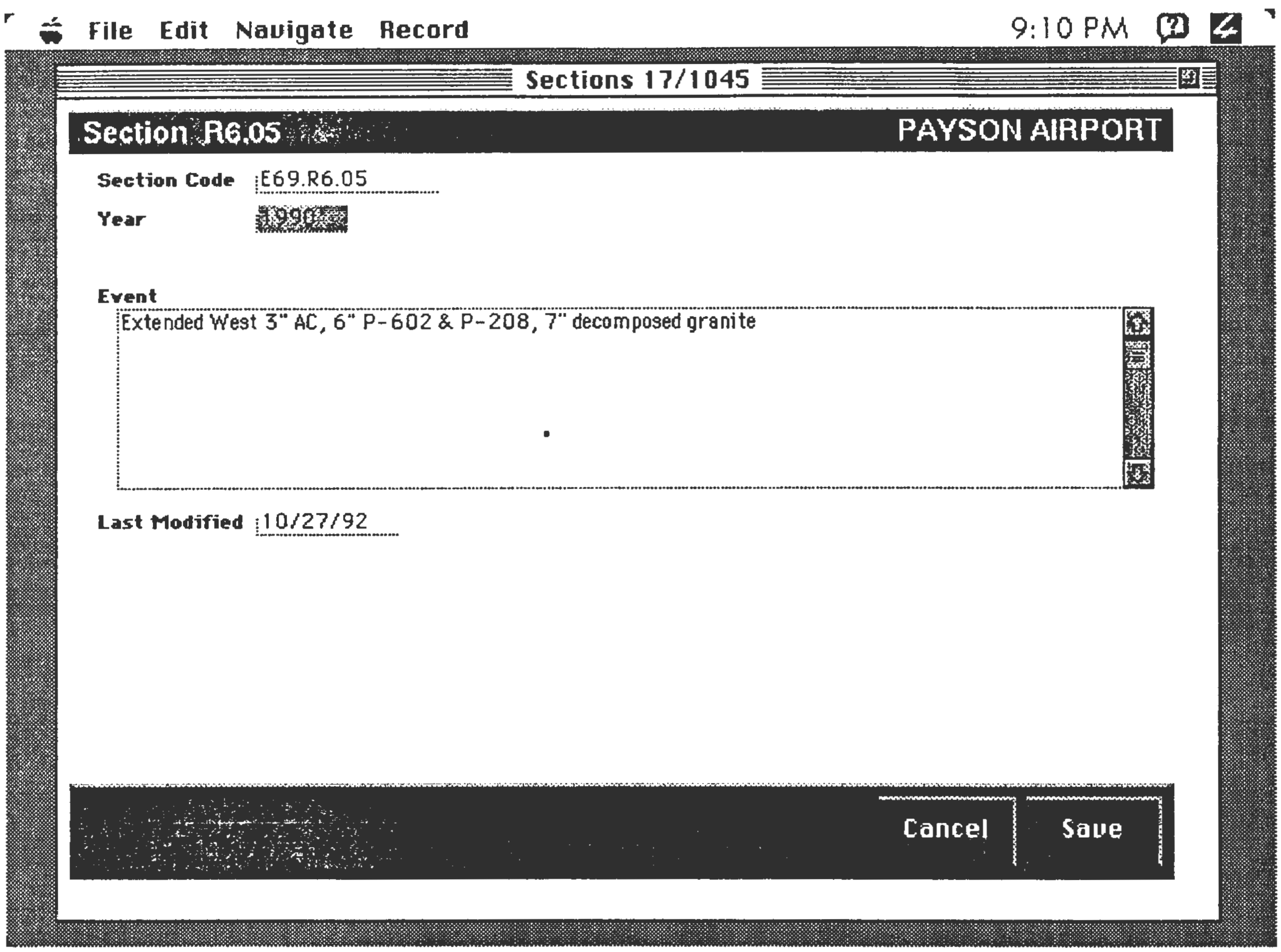

FIGURE 4 **Inventory data base.**

based budget for these projects on the basis of the pavement condition and deterioration rates. This information justifies the division's recommendations to the Arizona Transportation Board.

In addition to the primary objective, it is believed the system will improve interactions with the owners and operators of the primary airports because all recommendations by the division will be based on objective information about the condition of the pavements. Toward this end, the division is actively demonstrating the system throughout the state. For example, the PMS was demonstrated at the April 1993 meeting of the Arizona Airports Association.

The system resides at the Aeronautics Division headquarters in Phoenix. Airport owners and operators are encouraged to visit the headquarters and review the operation of the PMS. Staff engineers demonstrate the operation of the system for the owners and operators by using the data from their individual airports. Customized printouts are provided to the community when requested.

Conclusions

The Arizona Airport PMS was developed with some unique constraints. Field use has shown that these constraints have resulted in a quick and easily used network-level PMS. The use of the Macintosh computer platform has enabled the integration of mapping, land use, noise, safety, and pavement management into a user-friendly system.

One important benefit of the development of the PMS has been the collection and assembly of all historical records of pavement construction into a centralized and easily accessed data base. This data base improves the division's ability to evaluate the pavement restoration and preservation needs and proposed designs to meet these needs. The system allows projects to be tracked from the time the need is defined until they are completed. The system also provides the ability to track costs and effectiveness of the different types of preservation projects.

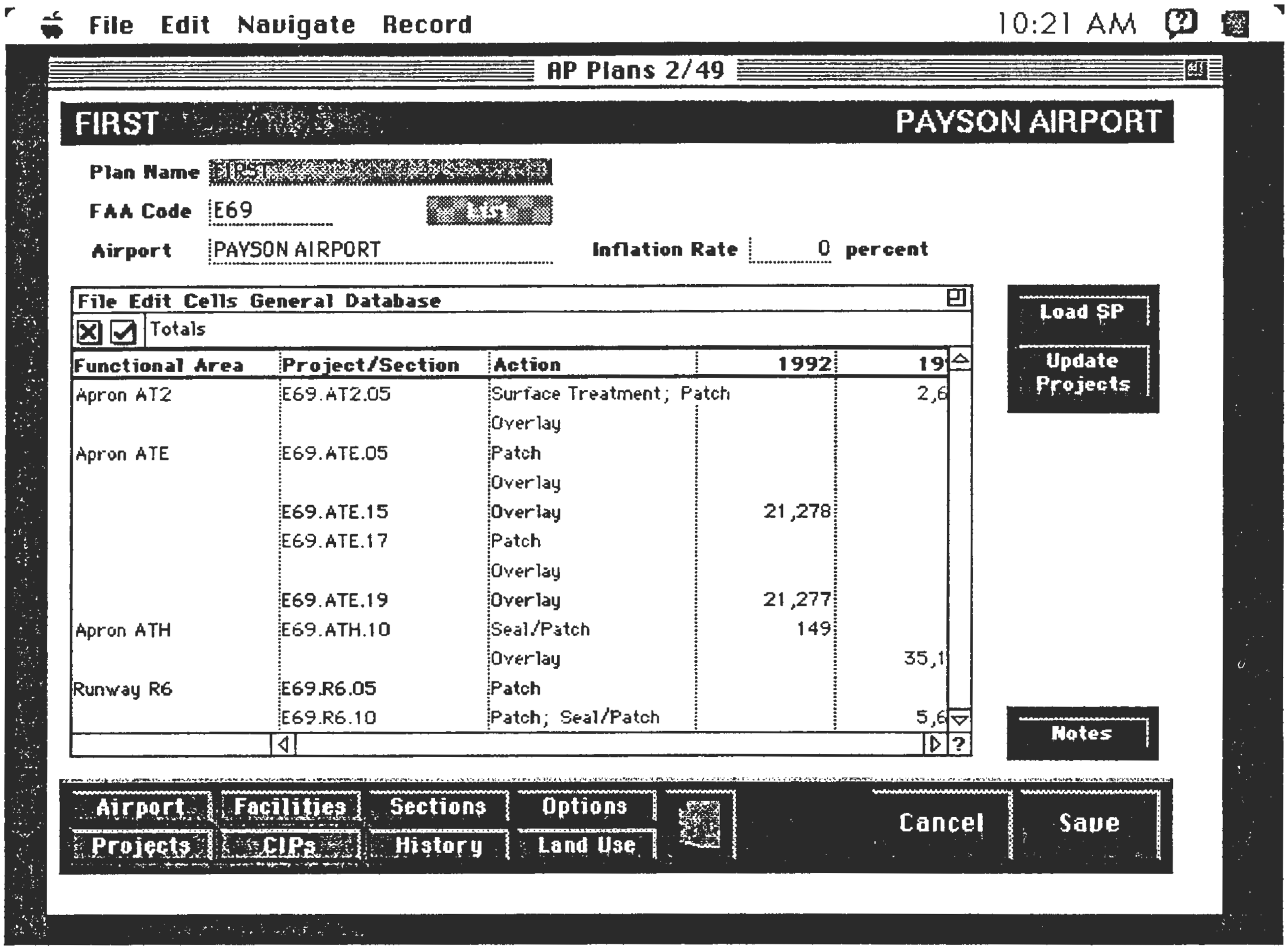

FIGURE 5 Capital improvement spreadsheet.

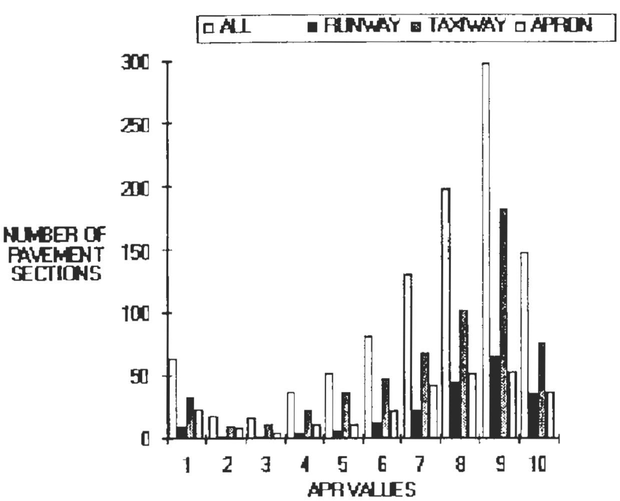

FIGURE 6 Distribution of APR values.

ACKNOWLEDGMENTS

The authors thank the ADOT Aeronautics Division for its assistance and efforts in developing this system. The efforts of Richard Trammel, of Barnard Dunkelberg Associates, in the development of software are also appreciated.

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Development of Pavement Maintenance Management System for a Road Network

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Pavement maintenance management system (PMMS) studies are required in order to program the investments in pavements of a selected road network so as to achieve optimal results. The results of a case study of PMMS carried out on the primary and secondary roads of the Bangalore Metropolitan Region Development Authority area in India are described. A simple approach to determine the most economical pavement maintenance strategy was been based on pavement evaluation and other data. Ways in which PMMS could be used and implemented in a developing country such as India and related issues such as problems in data collection, development of pavement deterioration models, and prediction of pavement life are examined. The problems encountered during the study are also examined. It is found that PMMS could result in considerable savings in road user costs and overall transportation costs.

The pavement maintenance management system (PMMS) in developing countries is in its infancy. Engineers in developing countries have been concentrating on new construction and maintenance of existing roads, but very little effort has been made to develop an appropriate maintenance management system that considers the several issues that are to be encountered in its use and implementation.

With an increase in the number of vehicles in developing countries, even a small saving in vehicle operation cost can justify very large investments (*1*). Competing demands from limited resources dictate that low-income countries such as India must search for optimum maintenance program (*2*). This involves analysis of different maintenance strategies and trade-offs between pavement maintenance and rehabilitation expenditures. To utilize effectively the merits of various investment alternatives, an important requirement is to project the future pavement performance of the different types and thicknesses of overlays used for strengthening or resurfacing existing pavements, because the performances of these overlays are dependent on several factors.

In addition, the financial constraints in developing countries such as India warrant stage construction. The growth in traffic of different classes of vehicles is found to have a significant effect on the savings in vehicle operation cost computations and in decisions about the appropriate type and thickness of overlay for construction. The optimal maintenance requirements of highway pavement could be quite different in developing countries, because of the reasons mentioned previously.

It has been difficult to develop pavement deterioration models and to predict the performance and service life of pavements in India because of the following reasons:

1. Most pavements on rural and urban roads have been not designed and constructed in a scientific way but constructed and strengthened in stages depending on the availability of funds, among other factors.
2. Several stretches of these pavements are structurally inadequate, with widely varying deficiencies in thickness.
3. Most of the earlier constructions suffer from major deficiencies such as improper subsurface drainage, insufficient height of embankment, improper compaction of fill

and subgrade soil, and improper use of boulder stones in subbase material.

4. Overloading of commercial vehicles has occurred, with wheel loads often exceeding the legal limit by up to 120 percent.

5. Several additional problems are prevalent in urban roads; they include the leakage of water from the water supply and sewage pipe lines that have been laid under the pavement in many instances, and the frequent cutting of the pavement across the road to take service lines (such as water supply, sewage, electricity, and telephone) from one side to the other and not properly compacting and refilling these "cross cuttings" in the pavement.

Therefore, the pavement deterioration models and the PMMSs that are available in developed countries cannot be used in India.

Scope

An approach is presented for the development of an appropriate PMMS for urban roads in a city in India with the use of data collected by simple conventional equipment such as the Benkelman beam and Bump Integrator. The paper focuses on (*a*) the manner in which the PMMS has been adopted and related issues such as problems in data collection and prediction of pavement life, (*b*) implementation of the system and the problems that were encountered, (*c*) road user acceptance issues and needs, and (*d*) effectiveness of PMMS in the funding of decisions.

Site Appraisal and Problem Identification

General Deficiencies in Bangalore Road System

Preliminary studies conducted on the existing arterial, primary, and secondary roads in the Bangalore Metropolitan Region Development Authority (BMRDA) area revealed several deficiencies, including those related to the road geometrics, drainage system, pavement, and other roadway amenities. One of the primary objectives of this study is to evaluate the extent of deficiency in road pavements of the existing primary and secondary roads in the BMRDA area and to suggest measures required to bring these to a desired minimum level of improvement and then to work out appropriate pavement maintenance strategies.

Deficiencies in Existing Road Pavements

The deficiencies in existing road pavements have been generally classified into five groups in this study; their characteristics of each category follow:

1. Structural inadequacy;
2. Poor riding quality;
3. Adequate structural capacity and satisfactory riding quality, but isolated pavement failures;
4. Drainage system, edges of the pavement, and the shoulders improperly maintained; and
5. Large-scale damage frequently caused by road cuttings across the pavement for providing new service lines, pavement cuttings along the road to repair service lines underneath, digging of trenches along the centerline of the pavement to provide new road medians, and leakage of water at some locations from pipe lines underneath the pavements.

The study included the road networks in BMRDA area (approximately 160 km in length) for which condition status reports and cost estimates for rehabilitation and maintenance were not available. A task force was set up to do the visual inspection survey for identification of roads network that needs improvement, rehabilitation, and maintenance. The paper discusses the issues and barriers encountered during the planning, development, and implementation of PMMS.

Field Studies

Field studies were planned to evaluate the structural and functional conditions of the selected stretches of roads for the road rehabilitation and maintenance studies. It was decided to carry out rating studies to determine the present serviceability rating (PSR) values and Bump Integrator studies for the measurement of the unevenness index (UI) on all the selected stretches. The Benkelman beam rebound deflection studies and skid resistance studies were planned and conducted on only a limited sample of stretches.

As many as 164 stretches of road with a total length of about 160 km were identified during reconnaissance for conduction of detailed studies of pavement surface condition by rating.

Additional studies were conducted to (*a*) estimate the quantity of materials required for profile correction of the road pavements, (*b*) find the deficiencies in the drainage system and the requirements for improvement, and (*c*) determine the need to raise the level of curbstones and footpaths in view of the rise in levels of pavements.

Analysis of Data and Identification of Stretches in Need of Different Maintenance Measures

Rating Values

The rating scale used in the study is 0 to 10, as given here:

- Very good: 8 to 10,
- Good: 6 to 8,
- Fair: 4 to 6,

- Poor: 2 to 4, and
- Very poor: 0 to 2.

The PSR value of a road stretch was taken as the average rating value assigned by the six raters for that stretch. When the 164 stretches of road were grouped into the five class intervals, it was found that only 3 stretches qualified as "very good" and 39 as "good."

UI Values

UI values were calculated from the Bump Integrator counter readings obtained from the left and right wheel paths, and the average value of each stretch was calculated in millimeters per kilometer. The road stretches described earlier were grouped by UI value into six categories, namely less than 1500, 1500 to 2500, 2500 to 4500, 4500 to 6500, 6500 to 8500, and above 8500 mm/km. No stretch was found to be in the UI category less than 1500, and four were found in the range of 1500 to 2500 mm/km.

Benkelman Beam Rebound Deflection Values

The rebound deflection values obtained at each point with the use of Benkelman beam values were analyzed. The characteristic deflection, Dc, values were calculated as

$$DC = (\bar{D} + 2s)$$

where D and s are the values of the mean and standard deviation deflections, respectively, in each stretch. Appropriate correction factors (*3,4*) for temperature and subgrade moisture were applied. It was found that the corrected characteristic deflection values varied from 0.64 mm, which indicated structurally adequate pavement, to 4.14 mm, which indicated highly inadequate pavement.

Identification of Stretches of Road That Require Priority Maintenance

The following general guidelines were formulated for fixing priorities for strengthening and resurfacing of pavements under a first-stage road improvement program.

Stretches with high values of corrected characteristic deflection and heavy traffic loads are to be strengthened on high priority. Stretches with high UI values or low PSR values and high traffic volume are to be resurfaced on high priority. For example, stretches with corrected deflection values of more than 2.50 mm with very heavy commercial/bus traffic on arterial roads and corrected deflection values over 4.00 mm with medium to heavy commercial or bus traffic on subarterial roads were given first priority for strengthening. Similarly, stretches with UI values over 8500 mm and PSR values less than 3.0 on arterial roads with high traffic volumes and UI values greater than 10 000 mm and PSR values less than 2.0 on other roads were given first priority for resurfacing to improve the surface condition. Similarly, stretches were divided into groups for second and third priorities for strengthening and resurfacing.

Maintenance Requirements Based on Importance, Traffic, and Road Condition

Classification of Road Stretches Based on Importance and Traffic

The selected 164 road stretches have been classified into the following three categories based on their importance and traffic volume, for the purpose of deciding the overlay or resurfacing thickness required over the existing pavement:

- Category 1: primary corridors consisting of arterial roads,
- Category 2: secondary corridors consisting of subarterial roads, and
- Category 3: secondary corridors consisting of other roads.

First-Stage Improvement Measures

Because the structural and surface conditions of pavements of most of the road stretches were far from satisfactory, it was decided that the pavement of all the stretches should be upgraded by strengthening or resurfacing to an acceptable level of serviceability or structural adequacy that it would be possible to apply one of the pavement deterioration models for predicting future requirements.

The overlay thickness required to strengthen the existing pavement was determined with the use of the following equation:

$$Ho = 550 \log_{10} \frac{Dc}{Da} \quad (1)$$

where

Ho = overlay thickness in granular equivalence (mm),
Dc = characteristic deflection corrected for temperature and moisture (mm) = $\bar{D} + 2s$,
$\bar{D}$ = mean value of Benkelman beam rebound deflection of pavement in stretch (mm),
s = standard deviation of rebound deflection values in stretch, and
Da = allowable value of rebound deflection (0.75 mm).

The granular equivalence values of 2.00, 1.75, and 1.50 have been assigned to the commonly used overlay materials such as bituminous concrete, dense bituminous macadam (including semidense bituminous concrete), and bituminous macadam, respectively.

For determination of the thickness of resurfacing course, *Hs,* to improve the surface condition to the required level, an equation was developed in terms of UI values of the pavement before and after resurfacing, and on the basis of some limited data collected for this purpose, given by

$$Hs = 350 \log_{10} \frac{\mathrm{UI}p}{\mathrm{UI}a} \tag{2}$$

where

Hs = thickness (granular equivalence) of resurfacing required to upgrade surface condition to desired level (mm),
$\mathrm{UI}p$ = present value of UI (mm/km), and
$\mathrm{UI}a$ = expected UI of the resurfaced pavement, taken as 2500 mm/km.

The first-stage improvement consisted of correcting the surface profile of existing pavements, strengthening or resurfacing to upgrade the pavement to the desired extent, improving the drainage system, shifting existing water supply and sewage pipe lines that run under the roadway, providing all the service lines on both sides of the carriageway, and raising the levels of sidewalks and curbstones to the desired extent.

Deterioration Models

Suitable deterioration models that were developed to predict the growth of deflection and UI values of the pavement are given next:

Deflection Growth Equation

$$D = Do\left(1 + \frac{0.125 * \mathrm{CSA}}{\log_{10}(H)}\right) \tag{3}$$

Unevenness Growth Equation

$$\mathrm{UI} = \mathrm{UI}o\left(1 + \frac{0.35 * \mathrm{CSA}}{\log_{10}(H)}\right) \tag{4}$$

where

D = increased deflection after application of traffic loads (mm),
CSA = cumulative standard axles of traffic load (million standard axles),
Do = initial deflection of pavement (mm),
H = overlay thickness in granular equivalent (mm),
UI = increased UI after application of traffic loads in terms of CSA (mm/km), and
$\mathrm{UI}o$ = initial UI (mm/km).

For each period of intervention that is considered, the subsequent requirements of strengthening or resurfacing have been worked out. For the additional thickness of pavement overlay or resurfacing obtained, different combinations of material, composition, and layer thickness have been examined, and a final choice is made, with the following taken into consideration: (*a*) total cost of construction, estimated rate of deterioration, and service life of the overlay/resurfacing; and (*b*) overall thickness and its effect on the level of pavement surface to avoid reduction of effective curb or sidewalk height and consequent drainage disorders. The scope of resorting to recycling of bituminous pavement surface course during subsequent periodical maintenance was also given due consideration.

Economic Analysis of Type and Thickness of Overlays and Frequency of Overlaying

The pavement deterioration models given in Equations 3 and 4 were used to estimate the service life of each overlay considered in the analysis. The factors taken into consideration are the volume of heavy commercial vehicles and their rate of growth, estimation of CSA, the changes in vehicle operation costs from time to time due to different rates of pavement deterioration in each stretch, the disruption to traffic flow during the periodic maintenance operations, and additional vehicle operation cost. The maximum allowable deterioration level of pavement before the next periodic maintenance work is given in terms of terminal UI of 4500 mm/km. The overlay thickness required to decrease the characteristic deflection to 0.75 mm and resurfacing thickness required to decrease the UI to 2500 mm/km were worked out, and the higher of the two values was adopted in each case.

For the remaining life of the 20-year period considered (i.e., 20 years minus the life of the first-stage improvement/strengthening), overlay thickness requirements at three different periods of interventions, namely, 3, 5, and 7 years, have been considered.

The net present cost of the alternative maintenance strategies, including the cost of first-stage improvements, was worked out, and the strategy with the lowest value of net present cost was selected as the least-cost solution.

Cost Appraisal

First-Stage Improvement of Primary Roads

The primary corridors consisting of total road length of 85.1 km were identified in the BMRDA area for road improvement work on first priority. These roads serve relatively heavy traffic including buses operating within the city. As already discussed, apart from strengthening and resurfacing of pavements to upgrade them to an acceptable level, other works such as raising and resurfacing of sidewalks and improving the drainage system were included under the first-stage improvement program. The total costs of various items of works for the primary corridors are given here:

Particulars	*Total Cost ($)*
Profile correction and first-stage strengthening	1,975,000
Improvement of sidewalk and drainage system	431,800
Shifting of main pipelines and service lines	3,115,715
Total	5,522,515

First-Stage Improvement of Secondary Corridors

The secondary corridors identified for improvements consist of road system and various connecting links of a total length of 89.3 km. The secondary corridors have been classified further as Classes 1 and 2. Class 1 secondary roads of a total length of 46.7 km cater to a heavy traffic volume including buses, whereas Class 2 consists of connecting road links of a total length of 42.6 km, which do not form main bus routes. The summary of costs for the various items of works for Classes 1 and 2 of secondary road system are given in the following:

	Cost ($)	
Particulars	*Class 1 Road*	*Class 2 Road*
Profile correction and first-stage strengthening/ resurfacing of pavements	848,570	700,000
Improvement of sidewalk and drainage	211,450	177,140
Shifting main pipelines and providing new pipe lines	2,808,570	1,034,280
Total	3,868,590	1,911,420

Thus the total cost of improving the secondary roads is $5,780,010 (Classes 1 and 2). The total cost of subsequent maintenance of the three categories of road systems of a total length of 174.4 km for the 20-year period after the first-stage improvement comes to $8,285,715. The total maintenance cost divided into 5-year periods are given next:

5-Year Block	*Total Maintenance Cost ($)*
First	957,150
Second	3,462,850
Third	2,494,285
Fourth	1,371,430
Total for 20 years	8,285,715

Issues in Implementation of PMMS

The success of the PMMS program depends on the efficiency of its implementation. Whatever may be the precision adopted in data collection, development of deterioration models, and economic analysis of different maintenance strategies, unless the selected strategy is put into practice, the significant work in a definition of an optimum pavement maintenance strategy is wasted (*5*). The implementation phase can be (*a*) implementation of and putting into practice a PMMS or certain selected components of a system, and (*b*) construction or maintenance of an actual pavement strategy or decision.

The issues that have been considered for implementation after the development of PMMS are presented. Noteworthy perceptions of the maintenance management problems include

- Lack of availability of data on pavement condition, construction practices, and maintenance details;
- Lack of knowledge by the engineers of appropriate pavement construction, maintenance, and data base management; and
- Unavailability of information on various pavement maintenance treatments and performance of the different overlays.

Several common deficiencies in implementing PMMS were identified from discussions with local practicing engineers.

The major steps to be considered in implementation of PMMS involve identifying specific deficiencies in existing maintenance management practices, namely, administrative and technical procedures. The maintenance practices have not been standardized by BMRDA or the city corporation, and no effort is being made by these organizations for timely maintenance of distressed pavements. At many stretches, it was found that failure starts from localized weak spots caused by leakages in underground water and drainage mains, cuttings in pavements, and so forth.

The maintenance of surface and subsurface drainage systems has received minimum attention. This is probably one of the major causes for early failure of the roads in BMRDA area. There is no coordination between different components of road maintenance work; for example, the maintenance of drainage systems is often undertaken long after the completion of pavement resurfacing work and even after the passage of one monsoon season. In secondary roads, frequent cuttings across and along the pavement for provision of service lines (sewage, water supply, electricity, and telephone) to consumers have resulted in damage and deterioration of the pavement at a very rapid rate particularly because the refilling of these cuts is seldom done properly. In addition to losses caused by damaged roads, vehicle users are also subjected to high degrees of discomfort, accidents, and increase in vehicle operation costs because of the presence of frequent humps and depressions across the roads.

Various investigators have developed pavement deterioration models to predict rates of structural and functional deterioration of pavements in time. However, it is impossible to develop reliable pavement deterioration models if damage is caused by unpredictable occurrences such as leakage of water supply and sewage lines and improper compaction at road cuttings.

A complex PMMS may not be the system that is required for a developing country such as India. Working PMMS manually to determine the least-cost solutions and priorities for implementation is cumbersome and time-consuming. Therefore, a user-friendly maintenance management system computer software has been developed. Field engineers have used the interactive computer software to decide the appropriate maintenance management strategy within limited available resources.

The road network in the city has been coded as nodes and links. The data on existing pavement composition and periodicity of strengthening, rehabilitation, and resurfacing have been computerized for each link of the city. The resources are allotted through objective mechanisms based on specific requirements of the system and policy decisions related to the quality or level of maintenance desired.

As a first step, the arterial roads of the city have been taken up for first-stage improvement to bring all the road stretches to a minimum level of structural condition. However, it is not certain whether funds would be made available to implement the maintenance schedule according to the proposed program. It may take a few more years before authentic conclusions are derived about the efficiency of the PMMS that has been developed.

However, the PMMS system that has been developed has helped in creating a comprehensive data base, computerizing the data, and training the field engineers in appropriate road construction and maintenance practices. The maintenance feedback data now being collected will help in reanalyzing and modifying project needs for maintenance or rehabilitation in the years to come. Old and obsolete pieces of equipment will be modernized, and premature failure of pavements because of poor road construction practices will be eliminated.

User-Related Issues

Successful PMMS considers user-related issues or functional performance of pavements. The road user is concerned with the functional behavior of pavements such as good riding quality, comfort, less delay, good skid resistance, and safety. As the serviceability of pavement decreases, costs of vehicle operation—including that of travel time—increase because of poor pavement surface conditions and reduction in travel speed. Similarly, when frequent rehabilitation measures are to be taken up because of premature failure or the adopted maintenance strategy, it involves high travel time costs because of traffic delays and diversions. It has been found that road users prefer a maintenance strategy that offers a long life with better riding quality and comfort, along with good skid resistance and high serviceability.

However, in a developing country such as India, where fewer resources are available than in other countries, the maintenance strategy that is preferred is stage construction, even though it involves more delay to road users. The least-cost solution has been worked out within a set of such boundary conditions.

Impact of PMMS on Funding Decisions

The PMMS program that has been developed is found to be effective in decisions for funding. The program was developed to plan the maintenance strategies among primary corridors that consist of arterial roads and among secondary corridors that consist of subarteries and other roads of the city. The primary corridors service relatively heavy traffic including buses operating within the city.

Earlier the city corporation was undertaking maintenance measures, based on volume of traffic, on stretches of road that are badly deteriorated. As an outcome of the present study, it has been possible to apportion the budgetary allocation effectively and more economically to the different categories of roads with consideration for structural and functional conditions as well as for traffic.

Conclusions

1. Wherever possible, maintenance needs for the road network in a region or a city should be undertaken with consideration for long-term needs. Maintenance strategies and priorities should be decided based on the results of PMMS studies for the network. This approach could result in considerable savings in road user cost as well as overall cost, as compared with the age-old method of undertaking maintenance work of each road link when it is found to be unavoidable.

2. It is very desirable to collect as many data as possible from most of the important stretches of road in the

country so as to develop a comprehensive data base about pavement behavior and deterioration caused by different contributing factors and under different maintenance strategies. Structural evaluation data about flexible pavements could be obtained with the use of simple methods such as Benkelman beam rebound deflection studies and surface condition evaluation data accumulated by the Bump Integrator.

3. Various alternatives should be considered before a decision is made on the type and thickness of pavement overlays for resurfacing and the intervention periods, so that the total transportation cost is minimum.

4. There is a need for coordination among different service agencies in cities so that frequent road cutting can be avoided, which will increase the life of the pavement structure.

5. PMMS has been found to be very effective in decisions for funding.

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Burlington Road Infrastructure Management

Sam Sidawi and Tom Eichenbaum, *City of Burlington, Canada*

The city of Burlington, with a population of 120,000 in Ontario, Canada, faced increased road rehabilitation needs and funding cutbacks. The city recognized the need for an integrated approach to maintain and improve its road infrastructure and achieved this with a pavement management system (PMS) in conjunction with asset capitalization and total infrastructure assessment. In 1990 the city initiated a complete review of its organization to reassess priorities, address functional deficiencies, and develop a long-term infrastructure management strategy. The city now makes effective use of PMS to determine the present status of the road network, predict performance, and determine an optimum long-term rehabilitation program. The system assesses the condition of each road, predicts the year in which each road section will fall below a minimum pavement quality index, and recommends when cost-effective rehabilitation should optimally occur. City staff recognized, however, that PMS tends to be biased toward high-volume arterial roads at the expense of low-volume local roads. To address the management of the entire road network, staff developed an innovative, integrated approach that incorporates both asset capitalization and total infrastructure management needs determination to complement the PMS. The road asset capitalization model uses the pavement quality index as the proportionate percentage of the remaining asset value, and it takes into consideration performance prediction curves as well as the life cycle of a road. The city has also developed methods for determining local street reconstruction priorities. Burlington has succeeded in introducing its PMS and integrating it into a cost-effective budgeting process. In view of this integrated approach to road infrastructure management, the city's program is viewed as a highly effective, proactive one that will assist the municipality in avoiding a road infrastructure crisis.

The city of Burlington, a municipality with a population of 120,000, is west of Toronto, Ontario, Canada, and is situated on one of the busiest railway and highway corridors in the country. The city has approximately 1 400 lane km of urban and rural roads, which carry a full range of traffic volumes. Initially, Burlington was largely a suburban community, but over the past 20 years it has become a key commercial and residential community in the Toronto/Niagara urban corridor.

Burlington, like most municipalities across North America, currently faces both declining infrastructure conditions and funding cutbacks. Despite this, the city has made great advances in its infrastructure management capabilities and in raising the understanding and priority of pavement and infrastructure management at a political level. This has resulted in increased funding and a strategic commitment by the city to rehabilitation of its roads and other municipal services. The success of the city's program can be attributed to achievements in the following areas:

- Organization and staffing,
- Innovative use of its pavement management system (PMS),

• Development of a prioritization method for the reconstruction of local streets, and
• Effective communication with city politicians.

This paper presents the way Burlington has implemented a highly regarded road infrastructure management system.

Organization and Staffing—Past Limitations

The city began investigating the need for and merits of a computerized PMS in the early 1980s. In 1985, the engineering department received the city council's approval to acquire PMS and undertake an extensive road condition survey. Once acquired, the system became the responsibility of staff members in the project, design, and construction section of the engineering department. The system, however, was generally viewed by staff as secondary to project responsibilities; consequently, staff training was minimal, and use of the system was only sporadic. Involvement of the city's road maintenance staff with the system was minimal.

In addition, preparation of the public works capital budget was also viewed as a secondary responsibility by the project, design, and construction staff, which resulted in cursory cost estimates and fairly simplistic project prioritization decisions. Project prioritization was viewed as very subjective and often political. Staff and city council faced difficulties in balancing PMS road condition ratings and rehabilitation recommendations against residents' demands for road repairs and reconstruction.

In the late 1980s, declining grants for road projects from senior levels of government, reduced revenues from developers, and tightening municipal budgets increased demands on engineering staff to become more involved in the budgeting, cost control, and management of the infrastructure. All that time the city faced the following problems in terms of infrastructure management:

• The highly sophisticated PMS was underused;
• Budget preparation was rushed, and priority decisions were based on subjective factors;
• There was a lack of communication between engineering and maintenance staff; and
• Council lacked an informed, objective plan to deal with either short- or long-term road infrastructure issues.

Staff and council recognized the serious nature of these problems and the need to effect change in order for the city to properly manage its infrastructure.

Changes

In 1990 Burlington began a complete review of its organization. This review provided the engineering department with an opportunity to reassess priorities and address functional deficiencies. One of the department's main goals was to resolve the serious inadequacies of its pavement management program, budgeting, and cost control and to develop a long-term infrastructure management strategy. The engineering department initiated the following changes based on this goal.

Creation of a Transportation and Engineering Planning Division

In the past, PMS and capital budget had been a secondary responsibility of project engineering staff. Long-range transportation planning and traffic engineering, however, was the responsibility of city staff in another department. It was decided that all these functions—pavement management, capital budgeting, transportation planning, and traffic engineering—should be within a single engineering division, because they all related to a planning function. This consolidation resulted in the creation of a new division, called Transportation and Engineering Planning. The effects of this change have been very successful because (a) pavement management and capital budgeting have been elevated to primary responsibilities and (b) traffic and transportation planning staff are more aware of the long-term costs of expanding road infrastructure.

In addition to merging these functions, this new division has also significantly enhanced the department's role in developing a broader infrastructure management strategy for the city and in dealing with overall financial issues.

New Staff Positions

This reorganization resulted in the creation of two new positions for the Transportation and Engineering Planning Division. The supervisor of Budgets and Engineering Planning has the following responsibilities, in order of priority: PMS implementation, capital budget preparation, overall infrastructure management, and long-term land use and services planning for the city. An assistant helps with the extensive technical and financial analyses required for this function. Although these positions were created less than 2 years ago, their scope and importance have been completely validated. The success of the positions has been greatly enhanced by the applied technical and computer skills that the employees brought with them to these positions.

Burlington PMS

Initially, PMS was used as the only means to program pavement rehabilitation. The system's routines could determine the present status of the road network, predict performance, and determine the optimum long-term rehabilitation program. The optimization routines and linear programming techniques that maximize benefits within given constraints. User benefits, influenced by the road's traffic volume, are one of the major factors in the cost-benefit analysis. Consequently, through the use of this objective analysis, the recommended rehabilitation program tends to be dominated by high-volume arterial roads, rather than by low-volume local roads. This neglect of the low-volume network may be cost-effective in terms of maximizing user benefits, but it may also lead to a loss in the total value of the city's road assets. In addition, neglect of local roads may negatively affect safety, aesthetics, and the perceived quality of life in those neighborhoods.

To address the management of the entire network, the city uses an integrated approach that incorporates both asset capitalization and total infrastructure needs determination. To achieve this, the city has developed in-house systems that establish the capital asset value of roads for various budget scenarios as well as assimilate the condition of subsurface facilities in conjunction with safety and environmental needs in the overall decision-making process.

The use of PMS, in conjunction with asset capitalization and total infrastructure assessment has proven to be an effective tool for programming road rehabilitation. This integrated approach has been used successfully to demonstrate to city council the need to manage road rehabilitation effectively.

Traditional and Innovative Road Infrastructure Analyses

The Burlington PMS program has evolved to the point where rehabilitation programming decisions are made based on several analyses, which include:

1. Traditional pavement management needs and priority analyses,
2. Innovative analysis best described as asset capitalization, and
3. Local streets reconstruction priority method.

These analyses, which will be discussed in later sections, have been found to be essential tools in an effective and comprehensive PMS.

Pavement Management Analysis

The most recent pavement management analysis, conducted in 1993, used field data collected in 1991 to establish the present status of the road network and determine an optimum long-term, pavement rehabilitation program. Present-status analysis is the initial analysis that establishes the condition of each road section at the time of field testing. It reflects the roughness, structural, and surface distress condition of a road. These indicators determine an aggregate pavement quality index (PQI), which is used in further analyses.

Once the present status of the city's network had been established, the next step was to predict the year in which each road section would fall below a minimum acceptable PQI level. This date, known as the "Needs Year," is considered to be the optimum point at which cost-effective rehabilitation should occur. By the use of performance prediction models developed by the city, an analysis was conducted to predict the Needs Year of all sections under consideration. The results predicted that 30.5 percent would fall into this category by 1993 and 56.3 percent by 2002.

The Needs Year distribution results reflected the growth of the city's road network. The city's roads were constructed primarily in several phases, each corresponding to a high-growth period. Consequently, the deterioration of large areas of the network would be expected to occur at the same time that each neighborhood area would need rehabilitation. Therefore, it is imperative that rehabilitation be planned and implemented in order to avoid a peak accumulation of needs.

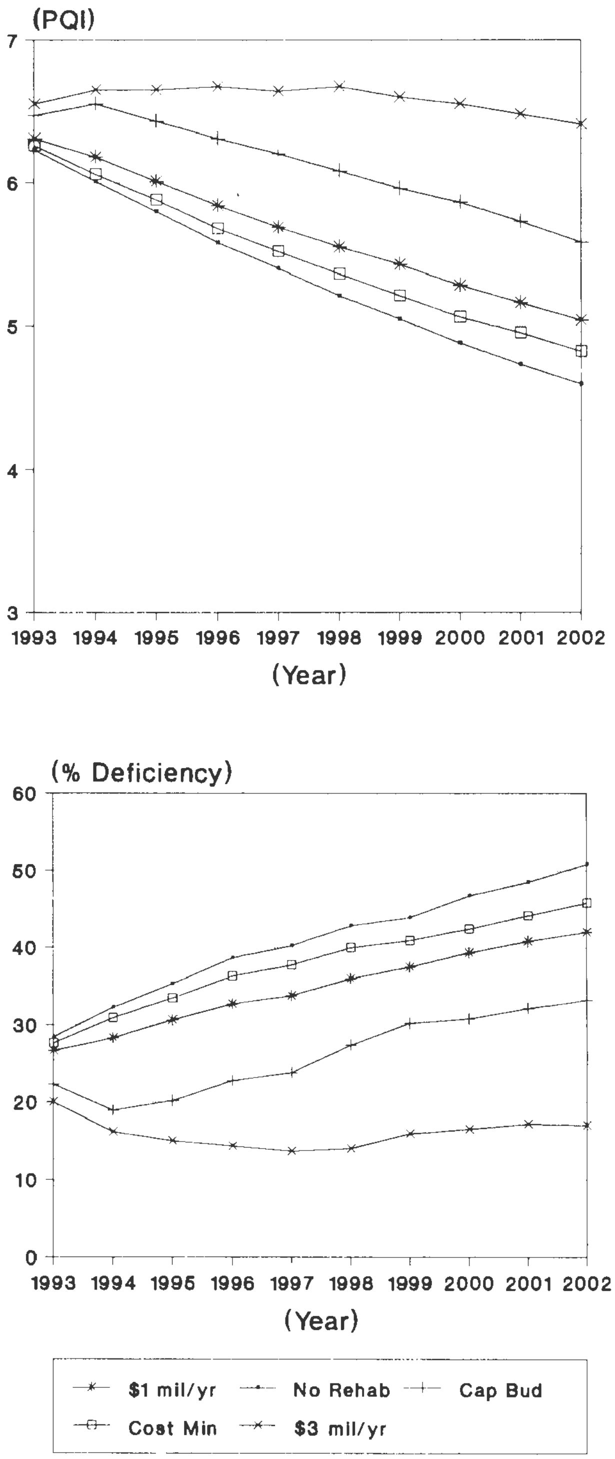
Ideally, the most cost-effective strategy would be to implement road rehabilitation in the actual Needs Year for a given section. However, fiscal conditions do not make this feasible for most municipalities. Therefore, all rehabilitation projects must be prioritized in order to maximize the returns of the program. The city's PMS uses several successive procedures to determine the optimum road rehabilitation program. First, the system employs an Expert program that uses field information and analysis results to simulate a professional's recommended rehabilitation for each of the Need sections. Second, the program calculates the associated benefit to cost for each section for several rehabilitation alternatives, with user benefits and maintenance cost reductions taken into consideration. Finally, the program optimizes the combination of projects to maximize benefits for the given constraints, in terms of funding limitations or level of service targets.

In the city's most recent review, four road rehabilitation scenarios were investigated and found to be sufficient for determination of the long-term performance of the road network and establishment of the appropriate funding level to maintain a satisfactory level of service. The four scenarios were

1. Net annual budget of $1 million,
2. Pavement expenditures equal to the city's 1992 roads capital budget of $16.3 million over 10 years,
3. Maintenance of the service level of arterial roads at minimum cost, and
4. Net annual budget of $3 million.

In these analyses, the annual budget represents the net anticipated annual expenditures for pavement-related rehabilitation work only. Therefore, costs related to drainage, curbs, sidewalks, sewers, and watermains have been excluded.

The results of these analyses are given in Figure 1. These results indicate that, over 10 years, the scenario with an annual budget of \$3 million will expend \$26.6 million and result in the highest network average PQI of 6.41 at the end of the programming period. The estimated network PQI average in 1993 is 6.3. The capital budget scenario will expend \$16.3 million and result in a network average PQI of 5.58 in the last year of the programming period. The \$1 million scenario, however, will



Network Average PQI

Year	No Rehab	\$1 mil/yr	Cap Bud	Cost Min	\$3 mil/yr
1993	6.23	6.31	6.47	6.26	6.55
1994	6.01	6.18	6.55	6.06	6.65
1995	5.80	6.01	6.43	5.88	6.65
1996	5.58	5.84	6.31	5.68	6.67
1997	5.40	5.69	6.20	5.52	6.64
1998	5.21	5.55	6.08	5.36	6.67
1999	5.05	5.43	5.96	5.21	6.60
2000	4.88	5.28	5.86	5.06	6.55
2001	4.73	5.16	5.73	4.95	6.48
2002	4.59	5.04	5.58	4.82	6.41

Percent of Network with Deficient PQI

Year	No Rehab	\$1 mil/yr	Cap Bud	Cost Min	\$3 mil/yr
1993	28.4	26.6	22.2	27.6	20.0
1994	32.2	28.3	18.9	30.9	16.1
1995	35.3	30.6	20.1	33.5	15.0
1996	38.6	32.7	22.7	36.5	14.3
1997	40.2	33.8	23.7	37.7	13.6
1998	42.8	36.0	27.4	40.0	14.0
1999	43.9	37.5	30.2	40.9	15.9
2000	46.7	39.3	30.8	42.4	16.5
2001	48.5	40.8	32.1	44.1	17.1
2002	50.8	42.0	33.2	45.8	17.0

FIGURE 1 Performance prediction.

expend approximately $10 million and result in a PQI average of 5.04, while the cost minimization analysis will expend $7.5 million, with a PQI average of 4.82 as a result. These results represent the service levels that will be precipitated by the various expenditure amounts.

In addition to varying service levels, each budget will affect the way a road network will be rehabilitated. For budgets with limited funds, the program will usually recommend that most funds be allocated to high-volume arterial roads that result in the greatest user benefits. As more funds become available, the program will include more local and collector roads. This trend is shown in Table 1, which indicates that the $1 million budget will result in rehabilitation of 26.3 percent of the arterial roads and 4.4 percent of the local roads. The $3 million budget, however, will result in the rehabilitation of 31.3 percent of the arterial roads and 53.4 percent of the local roads over the same period. In addition, the lower budget will rehabilitate approximately 13.9 percent of the total network, the capital forecast scenario will rehabilitate approximately 29.2 percent, and the highest budget will rehabilitate approximately 46.4 percent.

The combination of sections recommended for rehabilitation and the corresponding strategy will obviously depend on the scenario analyzed. The selection of projects is greatly influenced by the funds available to carry out the work. It should be noted that as the budget increases, so will the amount of sections recommended for major maintenance and overlay strategies. This correlation is evident in Table 2, where the $3 million budget contains a high percentage of sections recommended for resurfacing and maintenance. This higher percentage is justified because these strategies are cost-effective and prevent the need for the premature and costly reconstruction of road sections.

The ability to manage a pavement network effectively is primarily based on the presumption that pavements are rehabilitated at the optimum point in their life cycles. In some cases a minimal delay of 3 to 5 years can render resurfacing ineffective, thereby accelerating the need for reconstruction. This delay can increase the cost of rehabilitating the pavement by as much as three- to fivefold. To illustrate this, an analysis was conducted with the use of 1992 construction prices to determine the reconstruc-

TABLE 1 Recommended Rehabilitation Summary Based on Road Classification

	10 Year Total			
Recommended Rehab	Scenario 1 $1mil/yr	Scenario 2 Cap Budget	Scenario 3 Cos Min	Scenario 4 $3mil/yr
Arterial				
Lane-Km	107.19	133.31	103.35	127.45
% of Arterial	26.3	32.6	25.4	31.3
% of Network	7.6	9.4	7.3	9.0
Collectors				
Lane-Km	54.60	92.43	12.14	106.75
% of Collector	25.0	42.4	5.6	48.9
% of Network	3.9	6.5	0.9	7.5
Locals				
Lane-Km	34.77	186.64	0.95	422.07
% of Locals	4.4	23.7	0.1	53.4
% of Network	2.5	13.2	0.1	29.6
Total				
Lane-Km	196.55	412.58	116.44	656.27
% of Network	13.9	29.2	8.2	46.4

TABLE 2 Recommended Rehabilitation Summary for Alternative Funding Scenarios

	10 Year Total			
Recommended Rehab	Scenario 1 $1mil/yr	Scenario 2 Cap Budget	Scenario 3 Cos Min	Scenario 4 $3mil/yr
Maintenance				
Lane-Km	47.98	159.72	10.53	227.48
% of Network	3.4	11.3	0.7	16.1
Overlay				
Lane-Km	51.15	106.93	31.88	242.92
% of Network	3.6	7.6	2.3	17.2
Reconstruct				
Lane-Km	97.43	145.94	74.04	185.87
% of Network	6.9	10.3	5.2	13.1
Total				
Lane-Km	196.55	412.58	116.44	656.27
% of Network	13.9	29.2	8.2	46.4

tion cost of sections of the network with PQI less than 3.0. These sections are generally considered to have deteriorated beyond a point at which resurfacing would be of any benefit. The results, given in Table 3, clearly indicate that the backlog of sections requiring reconstruction could grow beyond funding capabilities. For example, under the cost minimization scenario, required funds would grow to $80.5 million by 2002. In comparison, the $3 million budget would result in a backlog of $21.7 million. For an investment perspective, an additional $19.1 million over 10 years could have a cost avoidance of $58.8 million or 308 percent.

As discussed earlier, pavement management analysis identifies the magnitude of each scenario's cost reduction in relation to the required routine maintenance, such as crack sealing and pothole patching. As a result it is expected that higher budgets result in lower routine maintenance costs. This saving is verified by the results of the analysis, which indicate that the 10-year total maintenance cost saving of the $3 million budget versus the cost minimization budget is projected to be $2.26 million. This amount, in combination with the previous cost avoidance amount of $58.8 million, will total $61.1 million.

The preceding traditional PMS analysis has been critical in development of an overall road infrastructure assessment and strategy for Burlington. The analysis shows that increased road rehabilitation funding throughout the city's 10-year forecast will be necessary to maintain the current road network condition and to avoid acceleration in need for costly road reconstruction.

Road Network Asset Capitalization

As indicated in the previous section, one indicator of the performance of a scenario is the resulting overall network average service level. Because these levels are affected by traffic volumes, they tend to be biased heavily by arterial sections. Therefore, low-volume local roads with poor service levels would minimally affect the overall network PQI average if arterial roads are in excellent condition. This could potentially lead to the neglect of low-volume roads, which would result in a total loss of the capital invested in the local road infrastructure. That is, if a strategy based entirely on systemwide benefit-cost were implemented, many local roads might be neglected to the point of total pavement failure (poor ride, excessive potholes, cracking, etc.). This neglect could result in a dramatic rise in the city's liability for accident and damage claims. This risk cost is not accounted for in the system modeling methods but clearly needs to be part of the city's pavement strategy. To ensure that capital investment in local roads is not neglected, the capital depreciation of all road sections should be monitored and evaluated. There-

TABLE 3 Estimated Cost of Reconstruction Needs

Year	No Rehab	$1 mil/yr	Cap Budget	Cost Min	$3 mil/yr
1993	$21.4	$20.7	$17.2	$21.2	$17.0
1994	$28.4	$25.7	$16.3	$28.1	$15.8
1995	$36.5	$33.3	$20.2	$36.1	$18.1
1996	$42.6	$37.4	$21.2	$41.3	$17.7
1997	$49.7	$43.1	$23.9	$48.4	$18.0
1998	$58.2	$49.4	$27.8	$57.1	$17.2
1999	$66.3	$55.5	$32.2	$64.0	$17.8
2000	$72.7	$60.8	$35.2	$69.8	$17.7
2001	$78.7	$66.0	$39.6	$75.5	$17.5
2002	$85.4	$72.0	$47.3	$80.5	$21.7

fore, depreciation of the city's road network, or capitalization of the road asset, must be investigated for each pavement management scenario.

The asset capitalization of the city's road infrastructure is no different from the capitalization of any other asset owned by the city. This method primarily identifies the investment life through performance prediction models and, in turn, the annual cost of maintaining the total asset value. It can also be applied to other city assets such as buildings, pools, sewers, or any facility with an average predicted life expectancy. For roads, life expectancy is defined by the performance prediction models used in the pavement management analysis.

The road asset capitalization model that has been developed by Burlington uses PQI as the proportionate percentage of the remaining asset value. The PQI level for a projected year is determined by performance prediction curves, which in turn reflect the life cycle of a road. Therefore, at the completion of construction, a road section would have a PQI of 10 or 100 percent of its asset value. Over time, and in accordance with the respective performance curve, the section will decline to a PQI of 5 or 50 percent of the asset value and eventually to a PQI of 0 or total loss of asset value. Because the PMS can predict the sectional PQI value for a given scenario in each year of the programming period, it is possible to estimate the total network asset value for that year. This value is equal to the sum of each section's corresponding PQI percentage, multiplied by the section's replacement cost.

The results of the asset capitalization analysis are given in Table 4 and Figure 2 and indicate that the replacement cost of the pavement portion of the city's road network is approximately $370 million, of a total cost of more than $750 million in road infrastructure. However, based on the current network PQI status, the estimated 1992 asset value is approximately $217 million. If the city implements the $1 million annual road rehabilitation budget, at the end of the programming period the road asset value will depreciate to $183 million. The $3 million annual budget, however, will lead to an asset value of $221 million in the last year of the analysis period. The results clearly indicate that none of the scenarios will restore the initial investment; however, the $3 million budget is the only budget that would eliminate the further decline of the city's overall road asset value. This analysis further confirms that in order to protect the existing city's road asset value, increased funding is necessary.

Local Street Reconstruction Priorities

Because of reduced funding for road infrastructure rehabilitation, arterial roads generally consume more than their proportionate share of available rehabilitation funds. In fact, traditional PMS analyses also are based on a form of benefit-to-cost analyses that tend to shift rehabilitation priorities to higher-volume roadways (i.e., arterial roads instead of low-volume local streets). Local streets, however, usually include approximately 85 percent of the total road system. Many local streets have deteriorated so that cost-effective rehabilitation such as resurfacing is no longer viable, and reconstruction is necessary. City staff believe that local street reconstruction cannot be neglected indefinitely, because of increased insurance risks to the

TABLE 4 Asset Capitalization Analysis Summary

Scenario	Capital Asset Worth in millions (Total Asset Worth of $370 Million)			
	Projected 1993	Projected 2002	Total Decrease	Percent Decrease
$1 million per year	219.3	183.1	186.9	50.5
Capital Budget	223.2	198.1	171.9	46.5
Cost Minimization	218.3	176.7	193.3	52.2
$3 million per year	225.2	221.1	148.9	40.2

municipality, excessive maintenance demands, and residents' valid concerns. In view of this, the city has successfully introduced the following two measures for dealing with local street reconstruction needs.

Dedicated Local Street Reconstruction Program

The city has reformatted its capital budget to introduce a specific program for local street reconstruction. An annual funding level of approximately 20 percent of all road reconstruction expenditures has been designated for local street reconstruction for the 10-year capital forecast period.

Local Street Reconstruction Priority Method

The number of local streets that require reconstruction far exceeds the total number that can be reconstructed within the 10-year period. This has resulted in debate over which local streets should be given priority. In the past the PQI rating of PMS was usually the only quantitative and objective criterion used when these decisions were made. Clearly, however, factors other than pavement condition have been recognized to affect the need for local street reconstruction. These factors may include pedestrian safety considerations, reconstruction needs of other services and utilities, roadway drainage concerns, and facilities required for new development. City staff faced the problem of quantification of these factors in order to make the process of prioritization as objective as possible.

To achieve this, in 1992 staff developed a simple 10-point rating system that included pavement condition ratings from the city's PMS and other relevant factors (see Figure 3). All non-PMS criteria were based on directly quantifiable factors, such as age of storm sewers and traffic volumes, or on a numerical ranking of qualitative observations, such as the adequacy of surface drainage. The system was intentionally set up to minimize information-collecting efforts and to avoid unnecessary complexity. All non-PMS information for ranking 25 of the more critical local streets in 1992 was collected as part of a field review of these streets by both engineering and maintenance staff. The data were recorded in a data base file for analysis and tabulation.

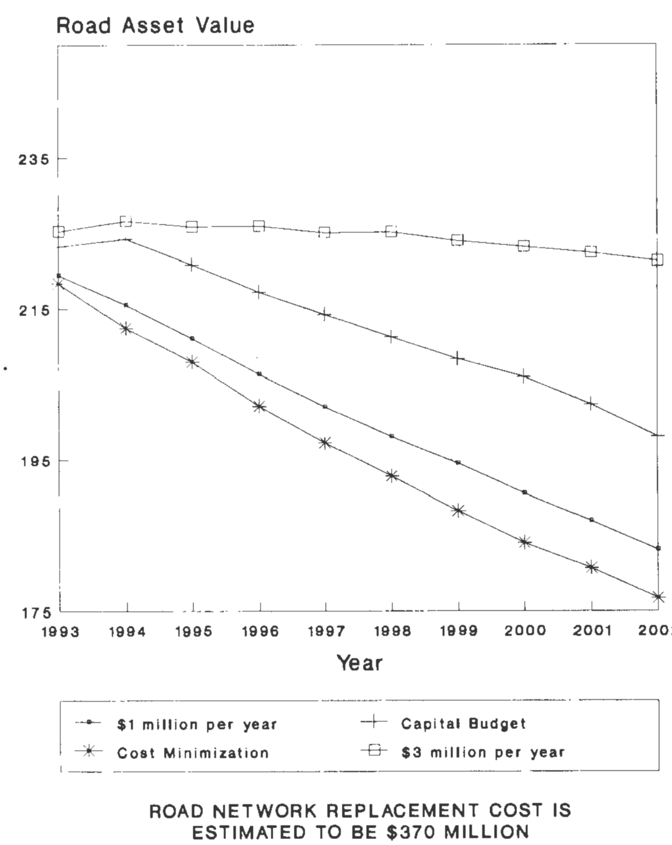


FIGURE 2 Remaining road asset value.

STREET NAME AND LIMITS	STRUCTURAL ADEQUACY INDEX (from PMS) [10]	PAVEMENT QUALITY INDEX (from PMS) [10]	TRAFFIC VOLUME AADT [10]	TRAFFIC & PEDESTRIAN SAFETY [10]	SURFACE DRAINAGE (Pavement Surface) [10]	CONDITION OF STORM SEWERS OR DITCHES [10]	CONDITION OF SIDEWALKS [10]	REGIONAL NEEDS (Watermains) [10]	REGIONAL NEEDS (Sanitary Replacement) [10]	DEVELOPMENT NEEDS (And other utilities where applicable) [10]	TOTAL (Lowest number is highest need) [100]
			LOCAL STREET 10-[(AADT/1500)*10] Maximum desirable volume for local street is 1500 vpd COLLECTOR 10-[(AADT/5000)*10] Maximum desirable volume for a two lane collector street is 5000 vpd MINIMUM VALUE = 0	No traffic or pedestrian accidents or Police O.R. on record 10 Isolated traffic accidents or pedestrian accidents have occurred but not attributable to road condition 8 Isolated traffic accidents and quality of traffic (trucks, thrutraffic) is incompatible with character of street (a few site obstructions) 5 Isolated traffic accidents directly attributable to the quality of traffic (trucks, thrutraffic) and many site distance problems 2 High incedence of traffic or pedestrian accidents on the street over the last 3 years 0	Good crown cross-fall and long drainage (no depressions) 10 Good crown cross-fall and long drainage but some depressions 8 Good crown & long slope but many depressions 6 Poor crown cross-fall but few depressions 4 Poor crown cross-fall and poor long slope and many depressions 2 Poor crown cross-fall and poor surface drainage 0	Storm sewers are new and functioning well 10 Storm sewers are more than 10 years old and functioning well or ditches are in excellent condition and work well 8 Storm sewers are more than 20 years old and some problems or ditches function fairly well 5 Storm sewers are old and have a few blockages or ditches require constant maintenance 2 Storm sewers are collapsed or ditches are extremely unfunctional 0	New sidewalks are in place on both sides 10 Sidewalks exist but are over 10 years old and require some maintenance 8 Sidewalks exist but are over 20 years old and need repairs or sidewalks only on one side 6 Sidewalks exist but are very old and are in bad shape (pitted, trip ledges) 4 No sidewalks but shoulder area or boulevard area can be used by pedestrians 2 No sidewalks and no shoulders for walking 0	New watermain and all new service connections 10 New watermain but some new service connections needed 8 Watermain 20 to 30 years old with some maintenance or minor repairs required 5 Old watermain with spot breaks and replacement required in 5 years 2 Old watermain, leaks and many breaks and service connection problems or fire flow is inadequate and must be improved as soon as possible 0	New sanitary sewer in place and no septic systems 10 New sanitary but some septic systems still in use 8 Sanitary system between 20 to 30 years old with regular maintenance 5 Sanitary system very old but still functions with some spot repairs 2 Sanitary system needs immediate replacement due to structural collapse or capacity problem 0	Road, storm water, sanitary or other major utility construction not required to serve any development 10 Road, storm water, sanitary or other major utility construction will be required to serve future development 5 Road, storm water, sanitary or other major utility construction must be done to serve a new development application 2 Road, storm water, sanitary or other major utility construction must be done to serve long standing development proposal 0	
RATING											

FIGURE 3 Enhanced local roads reconstruction prioritizing method.

A preliminary version of the Priority Method Table was found to overstate the importance of the condition of the pavement and other services compared with road and pedestrian safety factors. Accordingly, an adjustment was made to the weighting of these factors. When the system was presented to council, staff intentionally excluded provision of a ranking of all the streets inventoried with the proposed system. This required council to take an unbiased stand on the merits of the method and the soundness of the criteria. Except for one small adjustment to the traffic volume criteria, the method was unconditionally approved by council. Once accepted, the only difficulty was in terms of how it would be phased in. This was because certain projects that had been considered imminent before the method was introduced were now of a lower priority than some new candidates. Although many projects were immediately rescheduled because of the method, several projects that could have been deferred were already being designed and, thus, were not deferred. It is expected that this phase in will take at least 2 years, in terms of full realignment of the local streets' priorities.

This method has proven very effective in making the decision-making process to establish local street reconstruction priorities more objective. The method is viewed as an interim measure until a broader and more sophisticated expert system can be implemented to integrate all of the various infrastructure data bases and other decision-making factors.

Communication and Promotion

Although Burlington has taken important steps in advancing road infrastructure management through its reorganization, PMS development, and improved decision-making tools, this program would not have been as successful without the ongoing promotion and communication of the importance of these initiatives. Although technical agencies and engineers are often criticized for lacking communication skills, city staff have responded effectively to this challenge by taking the following actions to promote the infrastructure management initiatives:

- Annual PMS updates to council before budget deliberations, with slide presentations showing the fundamentals of the system, budget implications, and high-priority road sections;
- Involvement of residents with the field calibration of the PMS roughness index;
- Cross-departmental field review teams to assess and establish road reconstruction and establish resurfacing priorities;
- Successive infrastructure briefs to council that have stimulated council debate and attracted media attention; and
- Briefs to the provincial government and road associations on the city's PMS and infrastructure initiatives.

This persistent communication effort has resulted in infrastructure management becoming a top priority for both council and the community.

Summary and Future Directions

In the past 2 years Burlington has successfully reactivated its PMS and integrated it into a comprehensive and cost-effective budgeting process. But this is just the beginning of the challenges that face the city. Similar infrastructure management models need to be implemented for assets such as sewers, bridges, and buildings—all of which could possibly be integrated into a single expert type infrastructure and budgeting system. Initiatives have already begun to integrate the PMS data into the city's geographic information system. In addition to the technical and financial gains that result from the city's pavement management achievements, the initiative has elevated the knowledge and enthusiasm of council in management of the city's infrastructure.

Development of Effective Maintenance Strategies for Municipalities in Thailand

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There are approximately 200 municipalities in Thailand. Because of a very low tax base, most of the municipalities have insufficient funds to meet the basic requirements of the municipality, including health services and education, let alone have funds to maintain the road network to an adequate standard. Administration systems are generally simple with very few municipalities possessing computer systems. Australian development assistance was provided to assist municipalities to develop maintenance strategies that took into account the requirements of the municipality, the limited maintenance funds, and the training of staff. A pavement management systems (PMS) was implemented in Hat Yai and Park Praek municipalities in southern Thailand. The first task was to define the road network in a systematic manner—a road numbering system was lacking, and some roads were unnamed. Problems faced during the implementation, the expectations of the system, and user acceptance were examined. It is recommended that there is a need to develop a more systematic approach to maintenance, including training of the work force; there must be commitment and active involvement at the highest level within the municipality; there must be support within the government so that funding can be provided or local funding approved; and material must be provided in the local language.

CMPS&F Pty Limited of Australia and Pichai Taneeraranon, of Prince of Songkla University of Thailand, have been assisting municipalities in Thailand to improve their effectiveness in the maintenance of their road networks. This has involved presentations at training centers in key locations in Thailand and the implementation of a lower-level pavement management system (PMS). To date, PMS has been implemented in one major city (1991) and in one rural town (1992) with implementation to begin in Bangkok shortly.

The Thailand highway network is relatively young with pavement conditions comparable with those in the United States, Europe, and Australia. In the municipalities, however, the maintenance budget is very low, and maintenance techniques are not always effective. The problems arise from a very low tax base and, at times, a poor understanding of road maintenance. The latter is often caused by the bureaucratic nature of the municipality where the mayor is the key council officer and the engineering staff are engaged in many tasks other than road maintenance.

PMS is a new development in Thailand, where the level of computer and technical knowledge is low but rising gradually in municipalities. This paper describes the implementation of PMS into two municipalities (Hat Yai and Park Praek) and includes successes, failures, and future strategies.

The Need

There are approximately 200 municipalities in Thailand, which cover all major concentrations of population, except for Bangkok, which has its own administration. Each municipality is small and administers a small but diverse road network. Except for Bangkok, most of the population lives in rural areas.

Because of a very low tax base, most of the municipalities have insufficient funds to meet the basic requirements of the municipality, including health services and education, let along have funds to maintain the road network to an adequate standard. Administration systems are generally simple, and very few municipalities possess computer systems.

CMPS&F, Prince of Songkla University, and the Australian International Development Assistance Bureau (AIDAB) identified the need to assist municipalities to develop maintenance strategies, which took into account the requirements of the municipality, the limited maintenance funds, and the training of staff. To this end, AIDAB provided a grant to the other two parties to implement PMS in Hat Yai, a large regional city in southern Thailand. It was decided that any system to be implemented must meet the needs of the municipality and be relatively simple to operate. It was considered that the system should have three elements, namely

1. A data base that includes road inventory, roadside furnishings, traffic type, planning zones, and so forth. (At the stage of the second implementation, the mayor wanted PMS to include location of services, street markets, etc.)
2. A condition rating system that was objective and comprehensive, yet simple to understand and apply.
3. A data manipulation program that would allow the following questions to be answered:
   - –How long is the road network?
   - –How much of the network is in a particular condition?
   - –What are we doing well?
   - –What are we doing poorly?
   - –How much will it cost to maintain the network?
   - –How much will it cost to improve the network?
   - –Where are the problem areas?

The PMS needs were considered to be met by the Roads and Traffic Authority of New South Wales (RTA), Australia PMS. The two lower-level modules, Road Register Local (RRL) and Condition Management Information System (CMIS), were used. In more extensive networks, for example, Bangkok, the addition of optimization modules would be appropriate. After the initial implementation, the parties were engaged to implement PMS in Park Praek Municipality at Thung Song. This implementation was funded by the municipality.

The Clients

Hat Yai Municipality

Hat Yai Municipality is a thriving urban area in southern Thailand and one of the largest cities outside Bangkok. It has a population of around 150,000 living in an area of approximately 22 km^2.

The Hat Yai road network consists of 461 roads, which range from very heavily trafficked thoroughfares with traffic volumes of around 90,000 vehicles per day (approximately 50 percent motorcycles) to very minor *soi* (lanes). At the time of the implementation (1991), the 250-km network consisted of four pavement types, namely:

- Macadam with double surface treatment (46 percent),
- Asphalt (19 percent),
- Cement concrete (8 percent), and
- Unsealed (27 percent).

For rating purposes, the road network was divided into 569 segments.

Administratively the municipality is under the control of the mayor, who is a local businessman. For PMS implementation the work was delegated to the engineering division, where a senior engineer was appointed as project manager. The project manager was not the engineer responsible for road maintenance.

Because of the rapid growth of the city, staff only allocate minimal time and engineering resources to road maintenance. At the time of PMS implementation, all engineering calculations and budget preparation were undertaken manually, because the engineering division did not have a computer. Most of the staff were not computer literate but were keen to learn.

In this case, the client was identified by PMS implementors and AIDAB for PMS implementation because it was considered to be amenable to change, and funds were provided through international assistance. The municipality was also keen that other municipalities learn from its experience; it conducted a seminar during the implementation and provided staff to visit other municipalities.

Park Praek Municipality

Park Praek Municipality is a small municipality in Thung Song, a rail junction town also in southern Thailand. It has a population of around 25,000 living in an area of approximately 7 km^2. The Thung Song road network consisted of 97 roads that ranged from fairly heavily trafficked thoroughfares to lightly trafficked *soi*. Traffic was predominantly cars and motorcycles because heavy traffic bypassed the town. At the time of the implementation (1992), the 41-km network consisted of five pavement types, namely

- Double surface treatment (14 percent),
- Asphalt (46 percent),
- Cement concrete (1 percent),
- Cement concrete with asphalt overlay (1 percent), and
- Unsealed (limestone, laterite, earth, soil) (38 percent).

The mayor sees PMS as a systematic approval to road maintenance including development of accurate records of the inventory and location and cost of repairs. PMS is used for advanced planning. With up-to-date records, the mayor is able to better manage road maintenance.

For rating purposes the road network was divided into 132 segments. Administratively, the municipality is under the control of the mayor, who is a local medical practitioner and ex-army officer. Because the municipality is relatively small, the mayor and deputy mayor (infrastructure) are directly involved in day-to-day operation of the engineering division. It was the mayor who introduced computers into the municipality and set up the computer department by initially providing his own computers. The mayor initiated the project and traveled to Bangkok to argue the case with the Department of Local Government when approval was initially refused. A number of staff were computer literate, and a computer was used in the engineering division.

Arrangement of Engineering Functions

Local government in Thailand is an extension of the central government. This means that senior staff are liable for transfer on a regular basis (usually at least once every 5 years). Although each municipality is organized slightly differently, there are common features. Each municipality has a director of engineering, a chief engineer, and a senior technician. In the case of Hat Yai, there were three engineers at the chief engineer (class 7) level, one of whom was responsible for road construction and maintenance. In Park Praek Municipality, there was only one class 7 engineer.

Each municipality is divided up into a number of zones: four in the case of Park Praek and six in the case of Hat Yai. Each zone has an engineer and one or more technicians who are responsible for all engineering functions within the zone. The advantage of the zone system is that the engineers and technicians become very familiar with their road network and the problems associated with it. This greatly assisted with the implementation of PMS.

In general, engineering records in all municipalities in Thailand are fairly simple with the road inventory kept in a handwritten register. In one or two cases, the records are kept in a computer data base. At the time of implementation of PMS in Hat Yai, the only PMS operating in Thailand was the mainframe computer system operating at the Thai Department of Highways. There appeared to be very little interaction between the Department of Highways and the Department of Local Administration, which means that the advanced construction and maintenance techniques available to the Department of Highways have not been introduced to local government.

Issues Associated with PMS Implementation

Why Implement PMS?

At Hat Yai the driving force behind PMS was a need to prepare budgets to (a) determine budget to maintain current condition, and (b) determine budget to improve area network to desirable condition.

Throughout, the municipality tended to restrict the maintenance options to a few tried options—some of which were used with varying success.

At Thung Song the driving force behind PMS was a desire to bring objectivity and a systematic approach to road maintenance. The mayor wanted to introduce state-of-the-art maintenance materials and techniques. The mayor wanted to be proactive in that he wanted action to be taken concerning pavement defects before public complaints were lodged. Unfortunately, many of the more advanced materials such as polymer-modified binders are unavailable in Thailand and are unlikely to be available in the short to intermediate term.

In areas like Bangkok, the need is to ensure that funding is needs-based across the Bangkok Metropolitan Administration (BMA). At present it is very difficult to quantify needs among the various districts, because the condition of the network is not systematically measured, and uniform intervention levels have not been adopted. The need is for a sophisticated system that optimizes both funding and treatments. A maintenance code of practice is also needed. In view of this, the BMA has set up a PMS task force and approved the budget to implement a PMS in the 1993/1994 fiscal year. The reasons can be seen, therefore, behind the decision to implement PMS. Once the decision is made to implement PMS, there are a number of issues to be addressed.

What Is the Road Network?

The basis of any road management system is a good knowledge of the extent of the road network. The initial road construction is undertaken by the municipality or by a subdivider/developer and then handed over to the municipality. Extensive discussions with staff from many of the municipalities in Thailand indicated that network information that is included in road lists and on maps of municipalities is generally incomplete. This is not meant to imply that staff did not know the total road network—they certainly did.

Thailand's Department of Highways has a very logical and consistent road numbering system. Unfortunately, this type of numbering system has not flowed into the municipalities. Many but not all of the roads had street signs in Thai and usually in English. In both municipalities, some of the roads and lanes had no names. Neither municipality had a road numbering system and the municipal maps were incomplete.

To develop an up-to-date and logical road numbering system, it was decided to use a three-number system with the first letter signifying the zone in which the road commenced. After the system was explained to the staff in a training session, it was left to the staff in each zone to draw up the numbering system, mark all the road numbers on the maps, and update the maps to show all the road network since the original maps were drawn up. This approach proved highly successful with the staff taking full and proprietary responsibility for the system.

What Data Should Be Collected?

At the time of the implementation, neither municipality had an accurate inventory or method of evaluating the condition of the inventory items. It was also clear that one of the key items from both a pavement point of view and a public health point of view was drainage.

In common with most areas of Thailand, the same drainage system is used for run-off water, sewage, and sullage. In the more built-up areas, drainage is by means of covered concrete-lined drains. In the less built-up areas, the drainage is an open surface drain. The latter were more common in Thung Song than in Hat Yai. Blocked drainage, particularly of the open drains, can cause moisture ingress into the pavement and is a potential source of disease. Therefore, drainage condition is a key component of the management system.

At Thung Song, street markets occupied part of the roadway. Pavement requirements in such areas are different from those where the shoulders are used as through lanes. Similarly, pavement requirements vary depending on road use and traffic volume. To assist in the process, the data base incorporated details of bus routes, traffic volumes, and the like.

What Parameters Should Be Measured for PMS Input?

It is clear that the rating parameters must be straightforward and cost-effective to collect. At this stage of the evolution of maintenance planning in Thai local government, the use of structural testing cannot be justified at a network level.

From discussions with municipality staff, it was apparent that the types of defects and maintenance problems would be adequately characterized by evaluation of the following features:

- Rutting,
- Cracking,
- Surface defects,
- Surface wear,
- Concrete stepping,
- Joint sealant condition,
- Edge condition,
- Surface condition, and
- Shoulder condition.

Available Maintenance Treatment

The range of available maintenance treatments in Thailand is limited. Often the range is further restricted by the restricted experience of the staff. Table 1 shows the list of treatments and unit costs for Park Praek Municipality. The list is more extensive than is the case in most municipalities. In fact, it is more extensive than those available at Hat Yai. Even where a large number of treatments are available, additional staff training is required to make them fully effective. Training in such techniques should be a key element of any PMS implementation, particularly in recently industrialized countries.

Training

Pavement rating was to be undertaken in accordance with the procedures described in the RTA ROCOND90 Road Condition Manual (*1*). The features described in the manual were discussed in each case with the municipality staff and found to be appropriate to the local situation. Training was given in English and Thai with key features of the manual translated into Thai. Translation into Thai was not quite as simple as one might expect, because some of the English words had no direct equivalent in Thai. In fact, some of the terms became a mix of English and Thai.

TABLE 1 Cost of Maintenance Treatments, Park Praek Municipality, 1992

Treatment	Unit	Unit Cost (Baht)#
Grade & Trim Shoulder (both sides)	m^2	20,000
Grade & Trim Pavement	m^2	10
Gravel Overlay (100 mm thick)	m^2	400
Patching	m^2	300
Heavy Patch Pavement	m^2	400
Heavy Patch Shoulder	m^2	400
Replace Concrete Slab	m^2	450
Seal Cracks (Flexible)	m^2	300
Seal with Single Surface Treatment	m^2	125
Seal with Double Surface Treatment	m^2	200
Asphalt Overlay (500 mm thick)	m^2	250
Cold Mix Overlay (500 mm thick)*	m^2	250
Cold Mix Asphalt (50 mm thick)*	m^2	250
Clean Table Drain	km	100
Clean Drain Inlets	km	2,000
Repair Concrete Footpath	m^2	250
Repair Paving Block Footpath	m^2	400
Patch Concrete (with Concrete)	m^2	450
Patch Concrete (with Asphalt)	m^2	400
Seal Concrete Joints	m^2	20
Repair Kerb & Gutter	m^2	250

As at 1991 $US = 25 Baht, $AUS = 20 Baht
* Extension of existing technology as used by the Municipality

The key to the successful implementation of any PMS is the training of the staff. In view of this, it was given considerable emphasis. This training took place in the office and the field. Staff were completely inexperienced in the tasks involved, so more time than expected was spent in the training. There was a need to identify each of the distress types and collect all the inventory information. At times staff became overly cautious in evaluation and measurement. This meant that data collection became too slow and was too accurate for the order of accuracy of the system. This will have to be addressed more fully in further implementations. Staff were also trained in maintenance planning and techniques.

Brief Description of System

As mentioned earlier, the PMS modules implemented were part of the Roads & Traffic Authority NSW PMS. The modules are

- Road Register Local (RRL) (2), and
- Condition Management Information System (CMIS) (3).

RRL allows the municipality to enter all road inventory and condition information and to interrogate the data base. The software is written in OPENACCESS data base language. At the stage of the implementation, the software and data input were in English with instructions in Thai. Data input is possible in Thai, but difficulty was found in using 3 of the 44 Thai characters. As a result, English was preferred by municipality staff. However, daily work instruction in Thai is essential because the technical field staff are not familiar with English. This was initiated for the Thung Song implementation. For future implementations, it is proposed to use an English/Thai conversion program to allow the software screens and key data to be in Thai, although the actual manipulation programs will remain in English.

CMIS allows the municipality to interrogate the data base using a decision tree type process where road segments of a particular type and in a particular condition can be chosen and listed. Of more importance to the municipality are the features that allow the development of budgets. The information required as input are (a) pavement or inventory condition level and corresponding treatment, and (b) treatment unit cost.

The appropriate pavement or inventory condition level and corresponding treatments are chosen with municipality staff. The specified condition levels and treatments can then be varied until the proposed maintenance budget meets the available budget. The process takes minutes, whereas the existing processes took days and would require many iterations to determine the appropriate works program. For the relatively simple road networks and lack of computer sophistication, the use of optimization techniques was considered inappropriate at this stage.

Condition of Road Networks

General

One the key requirements of PMS is the ability to determine both maintenance priorities and suitability of existing treatments and practices. In this section it is proposed to discuss briefly the results of the condition rating and implications for the future. The problems identified appear to have widespread application to all municipalities throughout Thailand.

Hat Yai

Most of the roads exhibited insignificant rutting or cracking, and approximately half the road segments exhibited little or no patching or surface defects. Approximately 30 percent of the segments showed flushing or stripping of the surface. Closer analysis revealed that most pavement distress occurred in macadam pavements.

Many defects in the macadam pavements resulted from inadequate construction processes rather than wear and tear caused by traffic. If the macadam pavements were constructed and surfaced to a higher standard, many of the current maintenance problems would disappear. Similarly, if patching techniques were improved, the amount of bleeding and flushing because of excessive application of bitumen would be reduced. Concrete pavements were generally in good condition except for the joint sealant, which was defective. It was suggested, therefore, that

- The initial application of the sealant may have been incorrect,
- The joint sealant is inappropriate for the harsh weather conditions in Thailand, and
- The time interval between replacement of the sealant may be excessive.

It was suggested that this be investigated further by the municipality so that the most cost-effective solution can be found before the structural integrity of the concrete pavements is destroyed. Unsealed roads were considered to be in a condition that was fit for use based on observed traffic volumes and traffic loading.

Drainage, particularly surface drainage such as table drains, was being given inadequate attention and could lead to pavement failures. It was noted that extensive drainage works are being undertaken. It was clear that the number of alternative maintenance treatments could be increased and that some may indeed be inappropriate. Nevertheless, it is considered that it will take some time for the municipality to address these issues.

Park Praek

Most of the roads exhibited insignificant rutting and cracking. Where cracking occurred, it was considered to be age-related rather than to be an inherent weakness in the construction and maintenance techniques. Although 66 percent of the road network showed little or no patching, significant areas (10 percent) showed a patchwork quilt effect where small-scale patching or asphalt resurfacing appeared to be preferred to larger-scale rehabilitation or resealing, or both. Little attention appeared to have been paid to the cost-effectiveness of the approach that had been adopted. It was clear that maintenance techniques could be improved in pothole repair and patching. These issues were addressed during PMS implementation.

The limited length of concrete pavement showed some cracking, but the major defect, as at Hat Yai, was the poor condition of the joint sealant. Stepping at joints also indicated that greater attention needed to be given to the construction techniques adopted. Unsealed roads were generally fit for use with the better materials that were used on the more highly trafficked roads. Culverts and concrete drains were essentially in fair to good condition, but open drains were generally in poor condition. The latter were essentially blocked with little or no flow. Because the drains are used for both runoff and waste water, it is essential that the drains be kept clear. Of all features assessed in Thung Song, the drainage was by far of most concern.

Benefits of PMS Implementation

The situation in Thailand is no different from other countries where the benefits from PMS depend on the level of commitment at the highest level. In one case there was enthusiastic commitment and daily involvement at the highest level; in the other there was commitment and delegation. This has resulted in one municipality (Park Praek) fully committed to daily use of the systems and desire to improve construction and maintenance practices. In the other (Hat Yai), there will be gradual changes, and the system requires renewed enthusiasm to ensure that it is fully used. The original project manager was in the process of further development of the system when he was transferred.

Because of the tight budgetary situation in each municipality, it is very difficult to increase the maintenance budget. In most municipalities, the budget does not even cover routine maintenance requirements. The ongoing benefit to Hat Yai and Park Praek will probably be more in terms of the better use of the available maintenance funds rather than an increase in the budget.

In Hat Yai, where funds are more plentiful, trial maintenance budgets were prepared based on (a) best use of available funds and (b) funds required to improve the condition of the road network to very good condition.

These budgets were based on a code of practice in which each level of distress activates a specific maintenance treatment. Maintenance treatments were those already used by the municipality. Details are given in Table 2.

The trial budget of 23,154,000 baht would address most of the pavement requirements of the network. Such a budget would maintain the road network at a high level. It has the potential to reduce substantially the rate of network deterioration by treatment of pavement cracking, improvement of pavement drainage, and restoration of joint seals in concrete pavements. Adoption of this option would involve the implementation of some new maintenance technology and methods. The formation height of unsealed roads would not be increased.

The trial budget of 16,913,000 baht would also address most pavement maintenance requirements. The standard at which the network is maintained should be lower, with treatment only for road sections that have a poor rating for rutting, surface wear, and unsealed pavements. This option would involve the implementation of the same new technologies as in trial budget 1.

Trial budgets 3 and 4 were based on existing budget levels and existing treatments. Budget 3 provided a higher level of service on sealed roads and treated poor unsealed pavement condition. Budget 4 provided a lower level of service on sealed roads and unsealed pavement condition but offered a latvite overlay on unsealed roads susceptible to flooding in the rainy season.

The development of such trial programs improved the effectiveness of maintenance planning, because it allowed the municipality, for the first time, to

- Ascertain the budget required to bring the network up to a superior standard,
- Tailor the program to allow best use of the available budget,
- Ascertain the effect of different intervention levels on maintenance spending, and
- Reallocate funds to provide an overall improvement in network condition.

Before implementation of PMS, the municipality did not have the technology or training to undertake such a task. PMS allowed the case to be made for an increase in maintenance funding of more than the existing $14 million budget.

The trial programs were used as the basis for the 1991/1992 financial-year maintenance program. Because of staff changes, PMS was not used as the basis for the 1992/1993 budget. It is hoped that, through continued encouragement, PMS will be used as the basis for future programs.

At Park Praek the emphasis moved away from budgetary requirements to maintenance best practice. The rating techniques developed during PMS implementation were implemented on a daily basis. Again, a code of practice was provided so that each level of distress activated a specific treatment. The maintenance treatments were developed with the use of existing best practice from the municipality together with input from the PMS implementation based on best Australian practice. Allowance had to be made for treatments unavailable in Thailand.

Almost all of the suggested treatments used existing materials and practices. The costs of various treatments are given in Table 1. The cold mix treatments were suggested as an extension of techniques recently introduced in the municipality. Cleaning of drains and drain inlets that established practice was recommended but on a more regular basis. The use of a stress-alleviating membrane was recommended as a new technology not yet introduced in Thailand.

A budget of million baht 8.4 would address most pavement membrane requirements of the network. Allocation of such a budget would maintain the service level at a higher level of service than the current level. It would also substantially reduce the rate of network deterioration by treating pavement cracking, improving pavement drainage, and restoring joint seals.

TABLE 2 Trial Maintenance Programs for Hat Yai Municipality

Trial Budget No.	Number of Treatments	Approximate % Network Treated	Budget (Baht)
1	11	37	23,154,000
2	11	24	16,913,000
3	6	13	14,748,000
4	7	12	14,394,000

In 1991 $US1 = Baht 25, $AUS1 = Baht 20

The implementation at Park Praek was effective in that it allows the municipality, for the first time, to

• Quantify maintenance problems and condition evaluation,
• Be objective in application of maintenance treatments across the network,
• Maintain maintenance intervention levels with changes of staff and staff experience, and
• Apply the technology on a daily basis.

Arguably the major benefits of the PMS implementation came in the area of the management of maintenance, including the questioning of existing practice. Part of the stimulus for this came from the fact that the implementors brought different ideas based on their knowledge of maintenance practices outside Thailand. In other municipalities throughout Thailand, staff appeared to lack a basic knowledge of road maintenance techniques and information on such aspects as routine pothole filling and patching, especially in a low-funding environment.

THE FUTURE

It is clear that the following factors are necessary for the future implementation of PMS in Thailand (and other recently industrialized countries):

• Commitment and active involvement at the highest level within the municipality. This will accelerate as the level of computer and technical knowledge increases within municipalities as the staff with low-level technical certificates are replaced by more highly trained university graduates. The latter will be more concerned with efficiency and effectiveness.
• Support at the highest level within the government department so that funds are available or local funding is approved to allow sufficient funds for PMS implementation. Local authority finances are often very restricted.
• Suitable implementation material and software in Thai.

There is also great need for training of municipality staff throughout Thailand in basic road maintenance techniques and systematic condition rating and treatment selection. Much of this can be undertaken by carefully selected local staff with specialized input as required. Seminars have already been held for municipalities throughout Thailand, and further action is planned.

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Road Surface Management System

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A road surface management system configured for small- to-medium-sized road networks is presented. The approach includes procedures to handle a road network inventory, a windshield survey, a set of repair strategies, and analysis options. Thirteen parameters per road are contained in the inventory, seven surface distress characteristics are observed, more then 25 repair alternatives are suggested, and a series of budget analyses is included. Decision trees are used to associate repairs with observed surface distresses. A decision tree is associated with each surface distress; default or user-defined alternatives are assigned to the distresses. A network condition rating is calculated from the repair strategies identified for a road network. A description of the software and hardware is presented with an estimate of implementation costs.

Road surface management is the application of pavement management principles as a means of determining the best use of public funds to maintain public roads.

Local public roads are commonly maintained by municipal or county highway department personnel. Their training consists primarily of on-the-job experience; they learn to view surface distresses, associate repairs with surface distresses, and perform maintenance repairs. They are proficient in performing these responsibilities; the difficulties they express are to simultaneously recall the surface condition of all their roads, to recollect the maintenance history of each road, to assess traffic volumes and traffic type to prepare a prioritized maintenance plan for municipal budgets. Road pavement management systems (PMS) are available to manage data and prepare reports. These systems are generic so that they are applicable to a wide variety of municipalities. To develop a maintenance plan for a municipality a management system must be tailored to maintain the local road network inventory, manage surface distress conditions, and identify acceptable repairs. These types of road surface management systems are being adopted by municipal governments to maintain highways at the highest possible quality of service by systematically selecting the best use of maintenance dollars.

Objective

Desirable pavement management system characteristics expressed most frequently by local officials as they evaluate the use of pavement management for their community are

- Low system acquisition, implementation, and operation costs;
- Compatible with existing road inventory files;
- Easy to learn and operate for novices and experienced users;
- Use commonly observed distress characteristics, (those pertinent to selecting appropriate repairs);

• Responsive to locally used and historically effective repair alternatives and associated costs; and
• Responsive to the public and political needs of a municipality.

In selecting a road surface management system municipal officials should look for the following characteristics:

• Flexibility to model the highway practices of their local municipality (i.e., repair practices, associated costs, priority parameters);
• Ease of recording road inventory and condition survey data;
• Relationships between observed surface deterioration characteristics and repair practices must be specifiable;
• Maintenance planning reports and budget schedules must be able to be produced from a set of user-specified parameters;
• General maintenance strategies must be identified (i.e., further engineering may be required before a final decision can be made);
• Software must be compatible with existing hardware or required hardware is cost-effective; and
• Training and support is offered by the distributors of the package.

IMPLEMENTATION

The Road Surface Management System (RSMS) was designed to be used by small- to medium-sized municipalities. It is presently being used by such diverse groups as

• Covert, New York, with 23 mi of asphalt paved roads and 22 mi of gravel roads and very limited staff;
• Dover, New Hampshire, with 125 mi of asphalt paved roads and an engineering and planning department;
• Manchester, New Hampshire, with a population of over 100,000;
• County or townships, such as Yellowstone County, Montana, and Carrol County, Maryland, each with several hundred mi of paved and unpaved roads;
• Technology Transfer Centers (T^2 Center), such as the Maine Local Roads Center;
• Nonmunicipal organizations, such as regional planning commissions and private consultants; and
• Regional planning commissions conduct RSMS for towns that lack the resources or capability to manage maintenance activities.

Before implementing a PMS system, long-term maintenance goals should be established. For example, the town of Covert, New York, established the following goals in their 10-year plan:

• Restore all failed pavements to good condition,
• Maintain pavements now in good condition,
• Maintain aggregate surfaced roads, and
• Avoid paving aggregate roads.

Two levels of management are suggested for implementing a road surface management program in an urban or rural area. The first level of coordination is at the region or state level by an established institution or agency. Their responsibilities should include maintaining continuity, training, technical support, and data exchange. The second level is implementation on the local/municipal/county level (i.e., those performing the condition surveys).

An FHWA T^2 center, or similar organization, having established communications either through newsletters, workshops, or similar functions, serves best as a coordinator for the first level. It offers the continuity not always present at the local level because of the high turnover of personnel and typically small staffs. Responsibilities include initial training and refresher courses that must be offered regularly to assure uniformity in the condition survey data as well as in the use of the program. Technical support should be available for assistance by phone or in the field. New users must get their questions answered quickly or they will become frustrated and give up.

At the second level, the primary user of RSMS, surface distress data can be observed and recorded by a two-person survey team at a rate of approximately 30 to 60 roads/day (i.e., 40 to 60 mi of road). Additional time is required to verify road identification information when a road network is being evaluated for the first time. To minimize travel time, surface condition raters should plan the condition survey routes before entering the field. Routes can be easily noted on a municipal map with colored pencils and then sequenced in the computer. It is advantageous if one of the team members is familiar with the road network, because it helps in developing or verifying the road inventory file as well as establishing the sequence for performing the road network condition survey. The primary user should either be familiar with the repair alternatives and associated costs for the road system or have access to them. The more familiar the primary user is with this information the more accurately a pavement management program can be tuned to represent local conditions.

One of the most common problems encountered in installing a PMS is the lack of a complete road inventory. Time spent verifying information such as road name, surface type, width, length, or location must be accounted for in the survey process. It should be noted that it is only necessary to collect inventory information the first time PMS is conducted. In subsequent years, only the road surface deterioration information is collected. For example, the first year that the city of Dover, New Hampshire, Engineering Department conducted RSMS, a two-person crew spent 1 full week verifying inventory information and slightly more than 2 weeks evaluating road surface conditions. In the process of verifying the inventory, two roads, with a total length of approximately ⅜ mi, were found that were not shown on the town map. In a smaller town, Covert, New York, 1 day was spent verifying the road inventory and 5 days were spent conducting the road surface condition survey. Several Transportation Technology Transfer Centers, such as those in Maine, Kentucky, New Hampshire, and New York, have conducted training and refresher sessions to familiarize maintenance personnel with the road surface distress rating process. Other agencies have used a common group, such as the county surveyor, to rate all road distresses.

Costs incurred using RSMS are personnel time, travel costs, and computer use. Personnel time may be estimated for a 150-mi road network as follows:

- Road inventory file: 2 to 3 person-days,
- Condition survey: 5 to 10 mi/day, and
- Tune RSMS and generate reports: 1 to 2 person-days.

Travel costs can be estimated as being equal to cost per unit mile, times 2.5, and times the number of road miles to be surveyed. This accounts for the travel to and from the start and end points for each road.

To eliminate conflict between those responsible for road maintenance and those in charge of finances, some towns bring in an outside consultant, such as a regional planning commission, to conduct the RSMS surveys and to recommend repairs. For example, Salem, New Hampshire, contracted the Rockingham County Planning Commission to conduct RSMS. Unfortunately, there is occasionally a credibility problem when using outside personnel to rate roads. The Rockingham Planning Commission found that if it brought along a town maintenance official to observe the initial portion of the survey process, the results of the survey were less likely to be disputed. There are two main reasons for this increased tendency to accept the survey results. First, during the observation of the survey, the town official develops a more thorough understanding of the distress rating system, and second, the credibility of the evaluators is established.

Computer use is required for each phase of RSMS; however, all the work does not necessarily have to be on the same computer. Developing the road inventory file and generating the RSMS reports can be completed on any IBM-compatible personal computer. Road surface condition survey information is input by using a digitizing tablet and a fifth wheel. Many RSMS users have no computer experience and in many cases the first introduction to computers is through RSMS training. These people need technical support until they become proficient with the program and RSMS hardware environment.

Small towns, particularly in rural areas, often do not have adequate documentation to support budget requests for road maintenance and improvements. Steve Burritt, Public Works Director for the Town of Henniker, New Hampshire, reported in 1991 that the Town Board was so impressed by the thoroughness of the RSMS reports that the Public Works Department received the entire amount that had been requested for road work. (However, it should be noted that this was possibly the first time that a public works director had presented a written budget report to the town board.) The presentation of an itemized list of projected repairs, showing what appears to be an enormous amount of money, occasionally has an overwhelming effect on those involved in the budget making process. For example, in small towns with extremely limited funds the goal for implementing RSMS may not be how to make all roads perfect, but rather where to best use limited resources. The use of RSMS does not automatically result in increased funding for road maintenance. Instead, it provides tools to make the best use of the available funds. One small town decided that a gradual increase in spending on preventive maintenance would be more than paid for in the long run.

Road Surface Management Data

Road surface management systems use three categories of data: (*a*) road inventory, (*b*) surface condition survey, and (*c*) repair alternatives and associated costs. Road inventory and condition survey results are entered by the user. Complete editing of the road inventory file allows users to update, and limited editing capability of the condition survey results restricts adjusting of field data. Users should have the option of entering or adjusting repair practices and associated costs to represent their maintenance practices and costs. A pavement service index can be calculated to denote the quality of a road network. Decision trees can be used to associate repair practices with surface deterioration characteristics; users should have the option of adjusting the trees to represent their decision-making practices.

Road Inventory Files

These files contain information for each road in a municipality. An inventory file includes the following typical information:

- Road name,
- Travel direction,
- Traffic volume group,
- Starting mileage,
- Pavement width,
- Surface type,
- Inventory number,
- Town maintained (Y/N),
- Year last inspected,
- Ending mileage,
- Number of lanes, and
- Shoulder type.

Road inventory information can be ascertained from existing road inventory data files (if they exist), road maps, field observation, and highway personnel.

Associated with each road name is a unique set of data. If multiple entries are to be made for a single road, such as changing road width, the user can store the road under two or more unique names (e.g., Main Street-1, Main Street-2). Private and state-maintained roads can be stored and denoted in the file and denoted as not being maintained by a municipality.

A traffic volume group can be used to order the roads in a prioritized repair table. Because of the difficulty and cost of obtaining traffic counts, traffic volume groups can be used to estimate average daily volume. If traffic count data are available such data can be used, otherwise volume estimates can be assigned on the basis of the road classifications given in Table 1.

Surface Condition Survey

Condition surveys can be conducted by using data entry sheets that use a graphical representation of each road surface distress. To facilitate the condition survey, descriptive scales can be used instead of a numerical scale. These descriptive scales record the severity and extent of a distress.

The use of descriptive scales allows the use of survey personnel with less training or experience and also tends to produce more consistent results. In addition, the use of descriptive scales in distress evaluation reports conveys more information to those not directly involved in the survey process. In small towns, where financial managers may have no road maintenance experience, it is of utmost importance to communicate using terms that are understandable by all personnel involved in the decision-making process.

Road surface conditions commonly observed on flexible pavement surfaces are alligator cracking, edge cracking, roughness, longitudinal/transverse cracking, patching/potholes, drainage, and rutting.

Values for each distress characteristic can be assessed by severity of distress and the extent of road surface having the distress, or by relative condition of the distress. The ranges representing the severity and extent of flexible pavement surface distresses used by RSMS are given in Table 2. The conditions representing the relative pavement surface distresses are given in Table 3.

Road surface deterioration characteristics commonly observed on unpaved surfaces are primary distresses (improper cross section and inadequate roadside drainage) and traffic-induced distresses (corrugation, potholes, dust, loose aggregate, and rutting).

Unpaved road distresses represented by severity and extent are given in Table 4. Unpaved surface distress conditions represented by a relative characteristic are given in Table 5.

Each of the severity, extent, and condition ranges can be defined so that a condition surveyor can recognize a distress and its range while driving up to 20 mph. The specifications for severity state the size of a deterioration; as an example, the definition for moderate alligator cracking would be as follows: "Easily discernible cracking with measurable crack widths through ⅛ in. and some breakup. Pavement pieces, while loose, are still interconnected." Similarly, the extent of a distress is defined by ranges that are easily discernible to a rater. An example of less than 10 percent longitudinal or transverse cracking (low extent) is as follows: "When overall length of longitudinal cracking is less than 10 percent of the section length and/or transverse cracks are greater than 50 ft apart."

It is important for raters to distinguish primary distress from secondary. As an example, the primary distress can be longitudinal cracking. The secondary distress could be alligator cracking appearing around and between the longitudinal cracks.

TABLE 1 Estimated Traffic Volume

Road Classification	Traffic Volume Group
Arterial	High
Collector	High-Moderate
Feeder	Moderate
Urban Residential	Low-Moderate
Rural Residential	Low

TABLE 2 Pavement Severity and Extent Characteristics

Distress	Severity	Extent
Alligator	Low, Mod. High	<10%, 10%-30%, >30%
Edge Cracking	Low, Mod. High	<10%, 10%-30%, >30%
Longitudinal/ Transverse Cracking	Low, Mod. High	<10%, 10%-30%, >30%

TABLE 3 Pavement Relative Characteristics

Distress	Condition
Roughness	Good, Fair, Poor
Drainage	Good, Fair, Poor
Patching/Potholes	Low, Mod, High
Rutting	None Visual, Visual (<1") (>1")

TABLE 4 Unpaved Road: Severity and Extent Characteristics

Distress	Severity	Extent
Corrugations	Low, Mod., High	<10%, 10%-30%, >30%
Potholes	Low, Mod., High	<10%, 10%-30%, >30%
Rutting	Low, Mod., High	<10%, 10%-30%, >30%
Loose Aggregate	Low, Mod., High	<10%, 10%-30%, >30%

Roads are sectioned by homogeneity with respect to surface deterioration. Only one rating per distress is used per road section; thus multiple sections must be defined when changes in deterioration characteristics occur. The decision to make multiple sections is made at the time a condition survey is conducted. There is no limit as to the number of sections into which a road can be divided.

Data entry to PMS software packages can be by keyboard, digitizing tablet, bar code reader, or light pen (see Figure 1 for the pavement condition survey overlay used by RSMS).

Repair Strategies

The flexible pavement repair techniques commonly used on local roads fall into seven basic categories.

- Defer maintenance,
- Seal cracks,
- Patch,
- Repair drainage,
- Surface coat,
- Overlays, and
- Reconstruct.

Unpaved road repair techniques also fall into seven basic categories:

- Defer maintenance,
- Dust control and stabilization,
- Spot addition of material,
- Roadside drainage maintenance,
- Reshaping,
- Regrade existing material, and
- Reconstruction.

Representative repair practices and estimates of associated costs are included in most management packages. When available, actual historical project costs should be entered by the user to upgrade the default values.

Various repairs can be listed within each repair category; the decision of which repair to use is left to the discretion of the highway personnel, for example:

- Category: patch—(*a*) Cold patch: life span 1 year, (*b*) Hot patch: life span 2 to 3 years, (*c*) Infrared patch: life span 2 to 5 years.

Associated with each repair strategy is a unit cost (e.g., dollars per square foot, per linear foot, or per square yard). Care must be taken to include all secondary costs associated with a repair such that the repair costs repre-

TABLE 5 Unpaved Road: Relative Characteristics

Distress	Condition
Cross-Section	Good, Fair, Poor
Roadside Drainage	Good, Fair, Poor
Dust	Light, Medium, Heavy

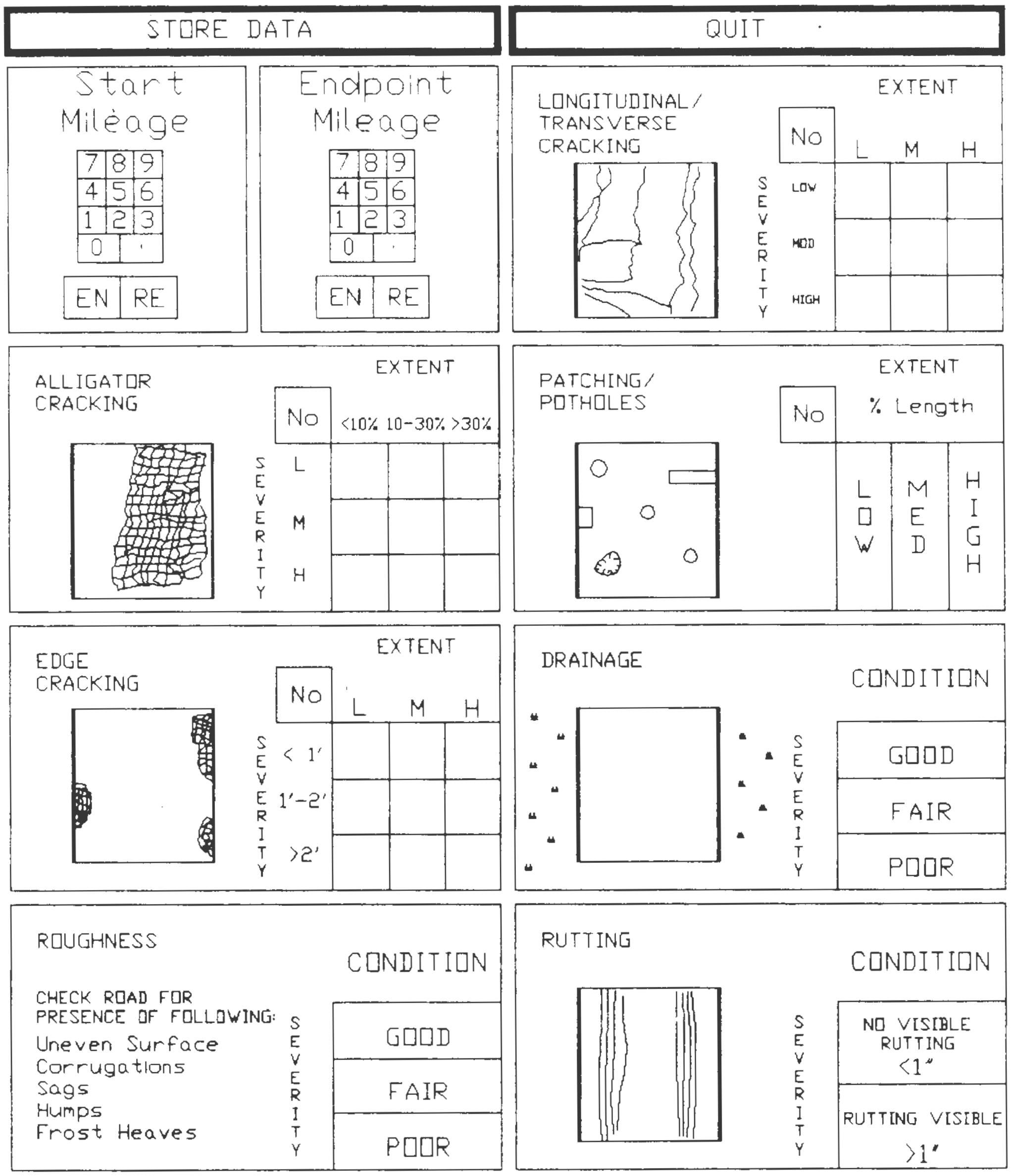

FIGURE 1 Pavement condition survey sheet.

sent total project costs. Engineering, management, and other secondary repairs must be included in the unit cost to give a representative total project cost.

Decision trees can be used to associate repairs to surface distresses. Each of the distress categories should be associated with a decision tree. Trees should be adjustable to represent the decision-making policies of a user (see Figure 2 for the alligator cracking decision tree).

Reports

Road surface management packages offer a series of lists and reports to present data, such as

- Road inventory list,
- Repair techniques list,
- Road survey sequence list,

- Road surface condition survey results,
- Project repairs, and
- Budget reports.

A road inventory list consists of the attributes that identify the road segment (i.e., road name, road width, etc.) and can be presented either in alphabetical order by road name or in ascending order by road inventory number. A repair techniques list contains default and user-specified repair alternatives and costs that are associated with surface distresses. A road survey sequence list is used to identify the order in which roads will be surveyed and the direction of travel for conducting the survey. Road condition survey results are tabulated per surveyed road. These results can be requested one road at a time or the road network can be listed by road name or inventory number. Projected repair reports can be listed either in alphabetical order or in prioritized order. Prioritization can be based on the following factors: (*a*) traffic volume, accounting for 33 to 99 percent of the prioritization value; (*b*) road surface roughness, accounting for 1 to 66 percent of the prioritization value; and (*c*) road condition (represented by the projected required repair category) accounting for the remaining 0 to 33 percent of the prioritization values. The total of these three factors is normalized to 100 percent.

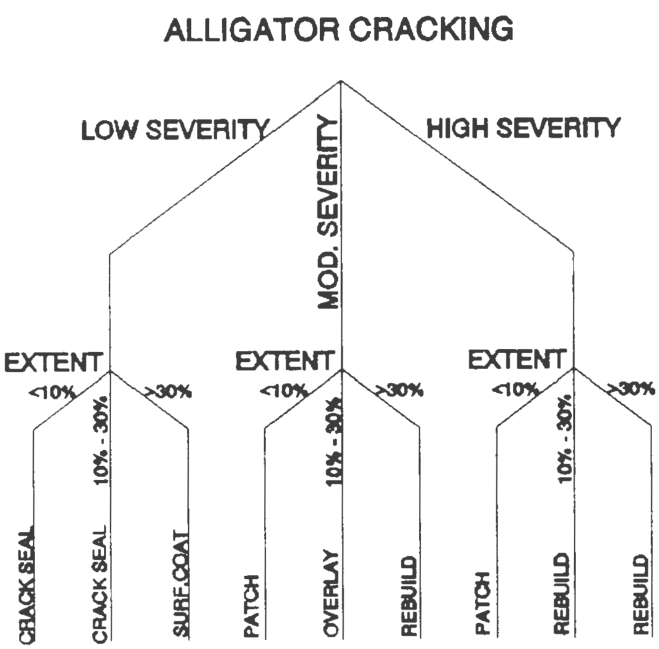

FIGURE 2 Decision tree.

Training

Road surface management training should consist of two parts (*a*) software and hardware training for computer systems and (*b*) road surface condition surveyor training. The first part introduces a user to the software and the hardware configuration. The package should be thought of as a tool and this part of the training simply covers the use of the tool. The second part introduces the rater to the road surface condition survey parameters. Each of the seven parameters should be explained using a reference manual, slides, and videotape. The second session should include field experience during which the participants conduct a survey on a prescribed set of roads. The objective of this session is to standardize the participants' ratings. To maintain uniformity of data it is suggested that users take a refresher course once a year.

Conclusions

The items identified for consideration in selecting a PMS are many and vary between municipalities or regions. Some of the unusual but important considerations are

- Is it desirable to have same equipment used to gather surface condition information and produce reports?
- Do field notes have to be reentered in the office?
- Are sufficient data maintained to adequately manage the road network?
- Are the surface distresses required by the system sufficient to identify repair strategies?
- Are the reports complete enough for substantiating budget requests?

Towns benefit from using PMS through improved infrastructure and better use of repair dollars. Infrastructure attributes that yield benefits are road inventory, condition survey, and prioritized maintenance schedules. A road inventory enables highway personnel, elected officials, and public works personnel to keep better records of the infrastructure. Condition surveys ascertain the rate of road deterioration and life spans of maintenance procedures.

PMS users are generating a data bank of repairs, costs, and life expectancies. In time, sufficient data will be collected to perform statistical studies on repair procedures and life cycle costs.

Implementation of Pavement Management Systems To Optimize Work Programs for Local Government Authorities in Australia

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The lessons learned in marketing and implementing pavement management systems (PMS) within state road authorities and local government authorities in Australia are discussed. PMS was developed by the Asset Control Technology Section of the Roads and Traffic Authority of New South Wales. This PMS has been implemented in over 40 local government authorities and four state road authorities in Australia as well as a number of government authorities in Asia. The system is modular and has been especially adapted for local government. Key issues are reviewed that have been identified as significant in the implementation of PMS to a wide sector of the road industry in NSW, particularly over the past 4 to 5 years. Local government technical staff have developed an increasing realization of the need for PMS technology but have exhibited some reticence to select and implement a system. The comprehensive implementation and training package provided with the PMS, at first considered daunting by some clients, has proven entirely adequate. It is now often cited as constituting a valuable management review, which is one of the main advantages of taking PMS technology to local government. In the areas of infrastructure renewal, effective asset management, and accountability for the capitalization of assets, PMS has been credited with significant short-term wins and significant medium- to long-term capabilities. Examples of the applications of PMS in these areas are described. A brief case study of the effective implementation of PMS in Dubbo City is provided. Interfacing PMS software with other information management systems requires considerable attention. The nature of the market place for PMS implementation is discussed in light of developments over the past 5 years in information management. In conclusion, there is a retrospective look at the projections made for PMS in Australia at the preceding conference, the degree to which they have been realized, and the lessons available from past PMS implementations from the viewpoint of the implementor and the local government client.

A pavement management system (PMS) is generally accepted in Australia as a method of information collection, analysis, and decision making designed to permit optimization of resources for the maintenance, rehabilitation, and reconstruction of pavements and related road assets. In Australia, road condition inspections developed out of the recognized need for measures of performance in road management in the middle 1970s and interest in extending procedures to PMS was initiated (*1*).

By the 1980s PMS was recognized as capable of a much greater contribution to road asset management. A road inspection procedure, ROCOND87, was developed and documented by the Department of Main Roads in New South Wales (now termed the RTA-NSW) and a 0–1 integer programming optimization procedure was being used, having been adapted from Texas A&M University (2). Since this early development was reported at the Second North American Conference on Managing Pavements in Toronto (3), legislative requirements and accounting requirements have provided timely catalysts to a program of development that has taken PMS off the mainframe and into a very user-friendly personal computer environment.

The Asset Control Technology Section of the RTA-NSW has been at the forefront of PMS and road asset management software in Australia, and the implementation of the RTA PMS software in local government is the topic of this paper (see Figure 1). There are, however, some 15 software packages available from consultants to local government in Australia. Two other systems, the Dynatest PMS system and the SMEC-Newcastle system, also provide for optimization of strategies. The remaining 12 or so systems provide information system functionality only. The Australian Road Research Board recently published a comparative study of PMS software available in Australia (*4*).

The RTA PMS can be considered to consist of seven modules that allow tailoring and staging of the application in a local government authority.

In Australia, local government authorities can be urbanized municipalities in a suburban environment of a large metropolis such as Sydney, Melbourne, Adelaide, or Perth, or they can be rural areas served by a number of townships and referred to as shires. Rural cities of significant population can warrant their own local government; Dubbo City, Tamworth City, and Armidale City are examples. All local government will be referred to as a council.

As can be expected, the extent, age, and mix of road assets in local government can vary significantly. The modular nature of the RTA PMS has allowed staging and tailoring of the PMS during implementation so that the varying needs and resources of local government are catered for.

Modules of RTA PMS

Road Location System

To serve both the PMS data base and other information systems in council, such as asset data bases, traffic accident

AUSTRALIAN STATE ROAD AUTHORITIES	1. Victoria 2. Tasmania	3. South Australia 4. Northern Territory
OVERSEAS ROAD AUTHORITIES	5. Shenyang City, Liaoning Province, China 6. Hat Yai Municipality, Thailand 7. Park Praek Municipality, Thailand 8. National Taiwan University (*Research*)	
AUSTRALIAN LOCAL GOVERNMENTS:		
New South Wales	9. Kempsey Shire 10. Hastings Municipality 11. Armidale City 12. Wollongong City 13. Dubbo City 14. Wollondilly Shire 15. Berrigan Shire 16. Camden Municipality 17. Greater Taree City 18. Cooma Monaro Shire	19. Wingecarribee Shire 20. Tamworth City 21. Tweed Shire 22. Shoalhaven City 23. Bega Shire 24. Gosford City 25. Port Stephens Shire 26. Bathurst City 27. Mosman Municipality 28. Woollahra Municipal.
South Australia	27. Mitcham Shire 28. Burnside City	
Victoria	29. Werribee City 30. Deakin Shire 31. Waranga Shire 32. Shepparton City 33. Rochester Shire 34. Traralgon Shire 35. Melton Shire 36. Broadmeadows City	37. Warrnambool City 38. Wycheproof Shire 39. Morwell City 40. Warrnambool Shire 41. Hamden Shire 42. Portland City 43. Karkarook Shire 44. Narracan Shire
Queensland	45. Maroochy Shire 46. Townsville City 47. Thuringowa City	

FIGURE 1 Implementations of the RTA PMS (as 1993).

data bases, and in recent times geographic information systems, a road location system that comprises road numbers, links, and nodes is required.

ROCOND90 Extended Inspection System

Concise data are required to quantify the road related assets and encode their condition. Each council can tailor the extent and nature of its data collection within guidelines built around the ROCOND90 procedure developed by the RTA for highway applications.

Road Register Local

A special data base called Road Register Local (RRL) is available to hold the condition and inventory data. It is a relational data base with menu-driven queries and reports. RRL is a special version of the RTA's own data base RR4. It caters to data required by councils generally and provides an additional 30 user-definable fields that can be configured for each client. RRL produces the American Standard Code for Information Interchange (ASCII) file CONDATA.TXT on which the other modules operate.

CMISPRO, Graphical Information System

CMISPRO is a specific application program that by graphical and menu interface provides the council with statistical reports, filters, queries, graphical data presentation, decision tree processes, data mapping, and convenient exporting and importing abilities for other asset systems.

TNOS, Site-Specific Treatment Optimization

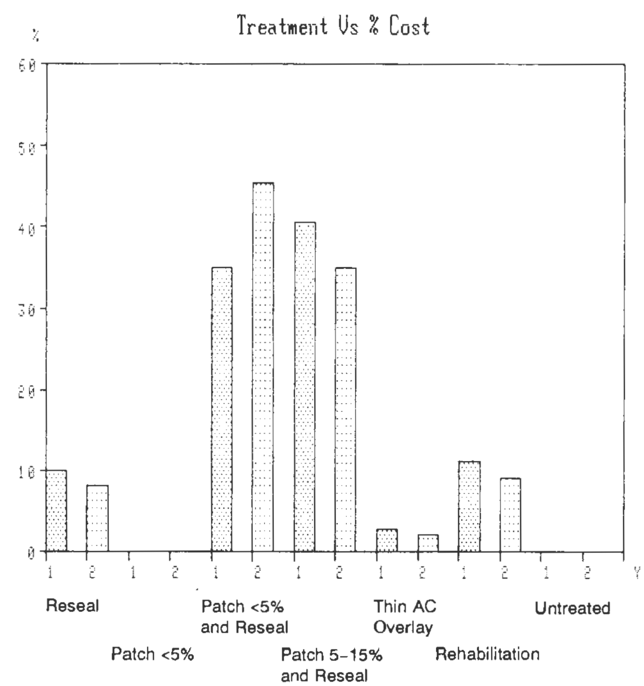
TNOS is a modernized PC version of the 0-1 integer programming software described by Yandell (2). Councils apply this module to road pavements. For a given budget TNOS optimizes a selection of pavement or surface treatments at particular road segments. Treatments and treatment performance models are selected by each council. (Dubbo City's 1992 choice is given in Figure 2. Figure 3 shows the flexibility of the system because Dubbo City has selected different treatments for 1993 modeling.)

FNOS, Strategic Budgetary Planning

FNOS is a PC-based software package developed by the RTA that allows a council to select various road condition targets and compute the budget requirement to meet these

TNOS DISTRESS TYPES (Dubbo City 1992/93)	Cracking Edge Break Pavement Deflection Rutting Roughness
TNOS TREATMENTS (Dubbo City 1992/93)	Reseals PMB Reseals Thin AC Overlay Thick AC Overlay Stabilise and Seal Reconstruction Minor Heavy Patching Major Heavy Patching

FIGURE 2 Treatments and distresses in TNOS analysis.



NOTE: The TNOS Analysis above indicates the percentage of budget allocated to the treatments Dubbo City has selected and modelled. Year 1 indicates the $1,200,000 budget Year 2 indicates a $1,500,000 as an alternative.

FIGURE 3 1992–1993 TNOS analysis for Dubbo City Council; budget $1,200,000 (Aust.).

targets and the general makeup of strategy types across the network over the time period set. FNOS uses probabilistic models. (Dubbo City's current FNOS parameters are shown in Figure 4.)

LCC, Life Cycle Costing Program

This program allows a council to further analyze the project-specific output of the other PMS modules. The user graphically builds a life cycle of treatments and routine maintenance providing costs in today's dollar values. The package proceeds to compute the net present worth and equivalent annualized cost for such life cycles at six different discount rates. The council can then provide further optimization of the life cycle strategy at a project level.

Implementation and Training Process

Statewide Roads Technical Management (SWR-TM) has developed the following implementation process with the

Council: ____________________ Network Area: 1 336 500 m^2

Model Description: LOCAL SEALED NETWORK

Treatment	Target Values % Area	Target Values % Budget	Target Values Average Treatment Cost	Model Output % Area	Model Output % Budget
Routine Maintenance	87	9	$0·06	86·8	8·8
Reseal	9	39	$2·20	8·2	42·6
Heavy Patching	3·4	20	$3·50	4·3	26·3
Reconstruction	0·6	30	$22·00	0·4	16·8
5th Treatment	0·1	2	$10·00	0·3	5·5
TOTAL COST	$800 000			$840 000	

Texture

		1	2
Routine maintenance	1	·93	·07
	2	0	1
Reseal	1	·99	·01
	2	·98	·02
Heavy patching	1	·93	·07
	2	0	1
Reconstruction	1	·99	·07
	2	0	1
AC Overlay	1	1	0
	2	·995	·005

Rutting

		1	2
Routine maintenance	1	·99	·01
	2	0	1
Reseal	1	·99	·01
	2	0	1
Heavy patching	1	·995	·005
	2	·02	·98
Reconstruction	1	1	0
	2	1	0
AC Overlay	1	1	0
	2	·94	·06

Cracking

		1	2	3
Routine maintenance	1	·91	·09	0
	2	·03	·84	·13
	3	0	0	1
Reseal	1	·995	·005	0
	2	·97	·03	0
	3	·75	·22	·03
Heavy patching	1	·92	·08	0
	2	·04	·84	·12
	3	0	·01	·99
Reconstruction	1	·99	·01	0
	2	·99	·01	0
	3	·99	·01	0
AC Overlay	1	·99	·01	0
	2	·94	·06	0
	3	·75	·22	·03

Pavement Defects

		1	2	3
Routine maintenance	1	·95	·05	0
	2	·05	·86	·09
	3	0	0	1
Reseal	1	·995	·005	0
	2	·50	·46	·04
	3	0	·15	·85
Heavy patching	1	·99	·01	0
	2	·93	·06	·01
	3	·20	·25	·55
Reconstruction	1	·99	·01	0
	2	·99	·01	0
	3	·99	·01	0
AC Overlay	1	1	0	0
	2	·60	·40	0
	3	·10	·45	·45

FIGURE 4 FNOS model summary.

RTA and other consultants acting as agents for the RTA PMS. The time frame of the implementation is adjusted to suit the council's rate of data collection and the relationship between the procedure and the council's financial year. The timing of each visit is therefore only indicative. Additionally it should be noted that visits are occasionally extended or repeated to ensure that all appropriate staff at the council are trained.

First Visit, Week 1 (1 Day)

- Seminar and interviews with council senior management, and
- Meeting with engineering staff involved in PMS implementation.

SWR-TM formalizes the road referencing location system, adapts road register and Condition Management Information System (CMIS) software to accept council customisation, and updates the ROCOND manuals accordingly.

Second Visit, Week 3 (2 Days)

- Office and field training in ROCOND road condition rating and data entry to road register.

Third Visit, Week 8 (2 Days)

- Review and audit partially completed ROCOND condition survey and data entry;
- Train PMS engineering staff in Road Register query and output, and in the use of CMIS software; and
- Introduce PMS engineering staff to Treatment Scheduling Network Optimization System (TNOS) and Financial Planning Network Optimization System (FNOS) logic and predictive modeling.

Fourth Visit, Week 10 (1 Day)

- Development of TNOS pavement performance models for all selected distress types and treatment types selected.

During the intervening weeks before the fifth visit, SWR-TM coordinates and establishes liaison with the PMS coordinator to develop the TNOS performance modeling. SWR-TM ensures that the newly developed TNOS model data are correctly installed and operational in the council's computer.

Fifth Visit, Week 13 (2 Days)

- Train PMS engineering staff in TNOS software operation;
- Project level treatment design and life-cycle costing are explained based on the draft schedule of works from TNOS analysis; and
- Development of FNOS probabilistic performance models.

During the intervening weeks before the sixth visit, SWR-TM coordinates and establishes liaison with the PMS coordinator in fine-tuning the FNOS probabilistic performance models. SWR-TM ensures that the newly developed FNOS model data are correctly installed in the council's computer.

Sixth Visit, Week 15 (1 to 2 Days)

- Train PMS engineering staff in FNOS software; and
- Review of CMIS and TNOS for engineering staff, including troubleshooting, further analyses, and graphical/tabulated output reports.

Note: Following this visit, SWR-TM prepares a State of the Road Network report with council staff.

Seventh Visit, Week 17 (1 Day)

- Presentation to council section heads and to other engineering staff on the use of PMS as a new management tool. Present State of the Road Network report.

Note: An agenda is forwarded in advance of each proposed visit. The agenda includes the proposed timetable, venues, and suggested attendees.

Appraisal of Implementation in Councils to Date

Some 35 councils have chosen to implement the RTA PMS in New South Wales (NSW), Victoria, Queensland, (QLD), and South Australia and most have now completed implementation. It is appropriate to review the performance of the implementation process. A case study below looks explicitly at Dubbo City Council in NSW. The following commentary is based on SWR-TM experience in NSW and QLD.

Data

Most councils have had little in the way of reliable and maintained road condition data. Building a new data base is not a problem and incorporating existing data has been typically undertaken as a keystroke process. Some file transfer has been used but less than was anticipated.

Some councils are actively pursuing a global information system built around a geographic information system

(GIS) and have shown some anxiety with regard to the PC-based PMS software. Typically this is based on an incomplete knowledge on the function of GIS and an historical leaning toward mainframe hardware in local government in Australia. This circumstance, however, emphasizes the need to involve a broad spectrum of council management in the first stage of implementation. It is less than ideal to consider the engineering department of council as the sole client responsible for all data. It is important, however, to identify all proposed data items with a management department of council. The engineering department is typically responsible for the maintenance of the bulk of the data critically related to PMS that is generally and correctly considered an engineering management tool.

The road location system and the extended ROCOND90 inspection procedure coupled with RRL (which has 30 user-definable fields above and beyond the standard local government fields) have not constituted a problem in implementation. Councils soon realize the commitment of resources necessary to collect and maintain data items and with a little guidance from the implementor are largely self-regulating, keeping the data volume well within the abilities of the software.

Staff Resources

Councils in Australia have undergone downsizing in recent years and the provision of appropriate staff for training and subsequent data collection is probably the most significant threat to a successful implementation. This problem is typically overcome by maintaining the enthusiasm of the staff selected as raters. The implementors need to be experienced engineers with knowledge of the real problems of road pavement inspection so as to recognize the problems of the raters and maintain their enthusiasm for PMS. Emphasis is placed on the short term (sometimes immediate) advantages of formal inspection of road assets as well as the longer-term value of database access.

Although SWR-TM encourages councils to target 8 to 10 weeks for data collection, more commonly this is spread over 3 to 6 months because of intermittent postponements while other tasks are addressed. This problem needs to be addressed for each council's subsequent inspections as a shorter duration for the inspection is desirable in terms of motivation of the raters and quality of the data. Automation of inspection to some extent is possible, though costly at this stage. This topic will receive attention at the PMS Users Conference programmed for Sydney and Melbourne in mid-1993.

Data Interrogation

There are extensive querying facilities in the RRL and CMISPRO packages—some more friendly than others. During implementation at least two officers are targeted as key students for the full use of these data base–type interrogation facilities. In some instances nominated officers for this role are not computer literate.

Generally the implementor finds that he or she is restricted in the ability to teach the processes until the council staff can realistically manipulate their own data. This is available 3 to 4 weeks into the implementation. More powerful use of such reports is often developed after the implementation period and examples of effective reports will be discussed at the User Conference. SWR-TM provides a state-of-the-network report at the end of the implementation, providing all the encouragement possible to ensure the council can build such reports into its annual management process.

Performance Modeling

The modules TNOS and FNOS are reserved for road pavement program and strategy development. They need performance models to be developed for treatments and condition distresses. Each council makes these selections.

It has been a surprise to both SWR-TM as implementor and the councils that development of preliminary performance models has not been a troublesome process.

Four to five key experienced practical engineers or foremen are called together for a modeling session led by the implementor. Although the TNOS module allows nine treatments and seven distress types to be modeled, typically Council choose six to seven treatments and four to six distress types. The model development has been described by several councils to be the equivalent of a review of the engineering department's decision-making processes—a review that is often direly needed but unlikely to be convened in any other context. Life curves are drawn up graphically and fully discussed by the group and compared for consistency before digitizing (Figure 5). While each council develops its own models and benefits by the process, the implementor must ensure that models are sound and stable based on prior experience with the TNOS analysis.

The strategic analysis FNOS is based on a Markovian probabilistic model somewhat similar to the Arizona Department of Transportation (DoT) analysis. Development of models here is dependent on quizzing the council about its dissection of budget among typically only four to five generic treatments and council's past records of treatment prompts related to typically four distress types (Figure 4). The process is more abstract and mathematical than the TNOS modeling; however, the results of analyzing with the matrix models so developed soon allow the numbers to model past performance. This credibility can then be applied to future budgets.

Councils are a little more sceptical of the FNOS models and analysis; however, they realize that the FNOS

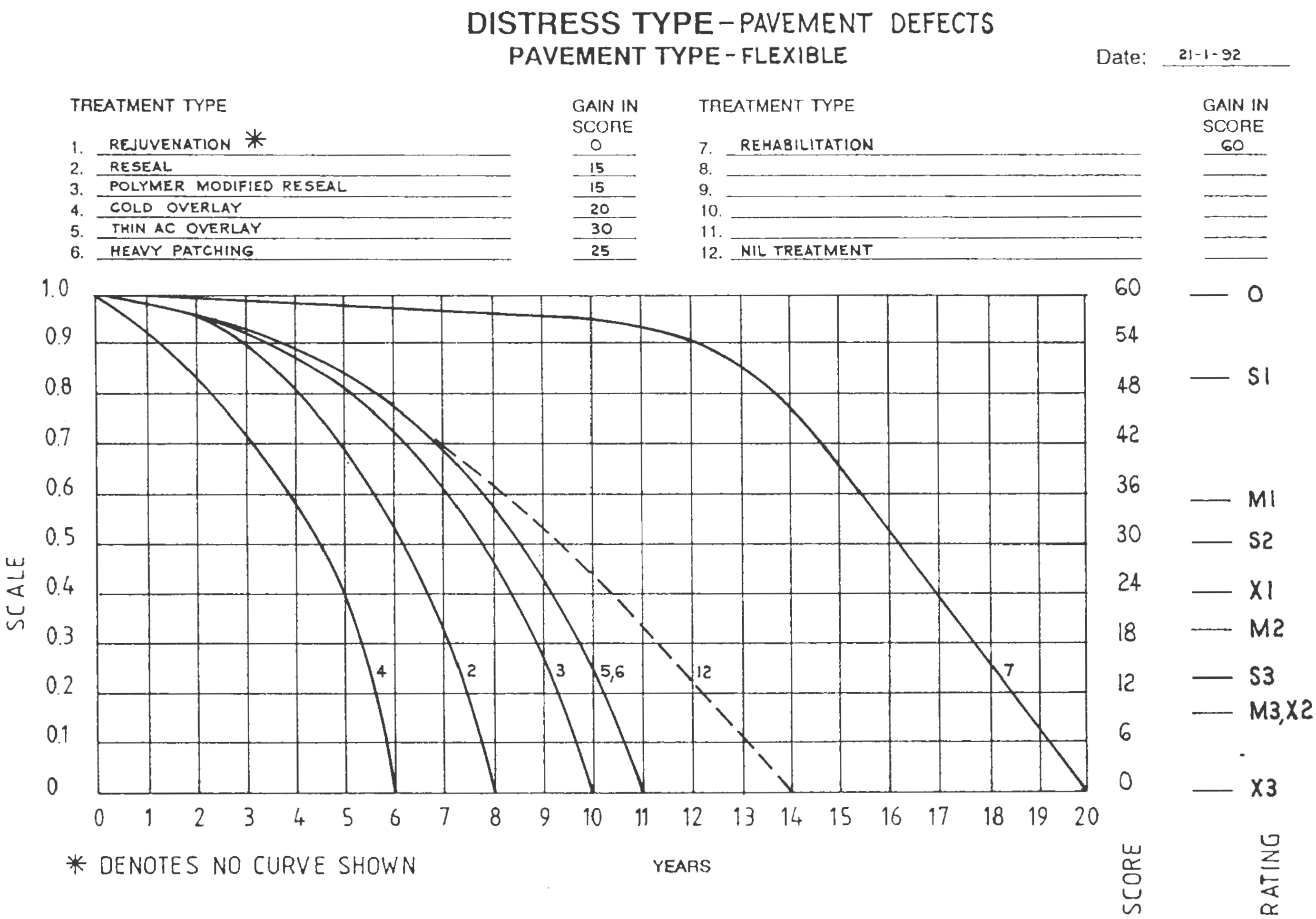


FIGURE 5 TNOS survival curves.

analysis is directly addressing the more important strategic management issues on the council floor.

Two key lessons learned in the implementations to date are that the development of these models needs to be related to the particular council's network data and that the implementor must be capable of relating the mathematical processes involved to the managerial processes of engineers. Accordingly the modeling must only commence when 50 to 75 percent of the network data are available and can only confidently be completed when the network data are 100 percent available. In addition, at the end of implementation the council staff must be fully aware of the way the models influence the analysis and be capable of modifying the models when required.

Project Level Studies

The development of the PMS in councils during implementation has led several councils to consider new treatment types and reconsider the wisdom of some treatments currently in use. Once the council can develop performance models for its selected treatments, it is more aware of the performance life of individual treatments and the likely cycles of future maintenance and rehabilitation. The LCC software enables the comparative life cycle costs of candidate treatments to be studied under the microscope even after the optimal generic treatment has been selected by TNOS analysis. Specialist treatments like microasphalt can be combined with initial treatments such as heavy patching. In situ recycling by cementitious stabilization is being considered more carefully because of its obvious advantages under PMS analysis, and its life cycle costs may influence the final decision on its use.

Marketplace Realities for PMS Implementation in Australia

At this stage the PMS marketplace in Australia can be perceived as made up of several categories of client in the local government sector as follows:

1. Councils that need PMS to complement other modern management initiatives such as asset capitalization, asset management, and management corporatization;

2. Councils that perceive PMS along with other management initiatives as superfluous to their needs and hampering their traditional flexibility in function;

3. Councils that perceive the need for PMS as in group 1 above but believe their road asset base cannot justify the investment required; and

4. Councils that are unsure of the value of PMS and prefer to leave the pioneering to others.

Those who consider themselves proponents for PMS over the past 10 years or so must consider that PMS is obliquely competing in the marketplace with maintenance management systems (work scheduling and costing systems, termed MMS in Australia), asset management systems (based on building and plant management but now broadly based), and comprehensive information management systems (generally associated with GIS in Australia).

Because of the rapid development in both the computer hardware industry and the computer software industry over the past 5 years or so councils are reticent to make bold decisions, fearful that the technology they adopt will not be compatible with management systems with which it needs to communicate. The priorities between these new systems and the logical order of introduction are problems that can have a negative effect on PMS implementation.

In Australia, councils in group 1 have signed up for a PMS Implementation or have budgeted to do so in the next financial year. They have no problem with the external cost of $30,000 to $70,000 (Aust); however, many are confused and wary about interfacing with other technologies.

Councils in group 2 are impressed principally with the information presentation available from road asset data bases and only wish to use selected information persuasively thereby retaining their flexibility in policy. They tend to choose the simple data base systems that are presented as PMS but do not provide optimization tools for engineering management. Their investment is between $3,000 and $6,000 (Aust) and training can be minimal and in some cases optimal. Unfortunately, this action typically delays the implementation of PMS even if the need for a more effective tool is recognized early.

Councils in group 3 have a tendency to choose the cheaper data base systems or may select to take up the first four modules of the RTA system with a view to progressively enhancing the system when resources allow.

Councils in group 4 reflect the conservative nature of government management. Their decision may be more straightforward in 1994. They will, however, be disadvantaged by every year they postpone the collection and recording of data valuable to PMS.

The authors' combined experience to date suggests that PMS needs to be proposed as a set of engineering tools that have value across the full spectrum of council management. It needs to be emphasized that the PC environment provides the most appropriate and flexible environment for the software because of the ease of import and export of files in the ASCII format and the speed of software development in this environment because of the level of open competition. PMS needs to be recognized as a forerunner of global information systems such as GIS. Care must be taken such that GIS is not seen as a substitute for PMS analysis or a prerequisite for PMS implementation.

Comprehensive implementation and training needs to be provided with the sale of PMS software. Councils have recognized the value of the SWR-TM implementation, which is a compulsory component of the PMS cost as required by the Asset Control Technology Section of the RTA.

Dubbo City Council—A Case Study

Dubbo is a major inland regional town in NSW with a population of approximately 37,000. For the last 10 years it has experienced a growth rate of 2 percent per annum. This growth rate, for a city council that has both an urban and rural community, has brought with it a number of problems. The expansion, although ensuring the survival of the city, has put heavy demands on its infrastructure. To the road engineer this has meant competing demands for money from many sectors ranging from parks and gardens and child care to community projects.

Investment

Before the implementation of the PMS, council was committed to asset maintenance and had a number of strategies to maintain the major assets. These included regular and frequent resurfacing of the road network as well as a committed rehabilitation budget. The program, however, was based simply on age so that the yearly required budget mimicked construction activity of a number of years previous. The engineering department is aware of a "bulge" in required budget that was coming up and the difficulty for council to meet that need.

The adoption of a computer-based decision-making strategy seemed like the best alternative. With it would come a better understanding of the network as well as a method by which progress and performance could be measured. The council budget for roads in 1993 is approximately $4,000,000 (Aust). A small increase in productivity was all that was necessary to cover the establishment cost as well as the ongoing cost of the development. Not all councils are as financially secure as Dubbo and for some an outlay of $70,000 is not possible. There is, however, the alternative of a partial implementation.

What Sort of PMS?

The alternative types of PMS have already been discussed. It is important, however, to understand why Dubbo Council went with the RTA option. To assess the alternative packages a list of features that were considered desirable was drawn up and included:

1. A detailed road register that would take over all the information that had already been collected;
2. A condition statement that detailed road condition both in terms of individual roads and the network as a whole;
3. The system was to model the degradation of the road in a form that was easy to understand and therefore easy to fine-tune as more information became available;
4. The system had to be compatible with what all levels of government wanted in terms of condition reporting; and
5. The system had to be accepted by the road industry.

Council had already been using the RTA PMS system on the classified road network. This allowed the opportunity to consider the aspects of it that would need to be changed to satisfy the needs of council. The RTA system met all the requirements of council. It had the distinct advantage that the modeling procedures are straightforward and when presented in graphical form give a visual picture of road deterioration.

It was important from the beginning that council accepted that there was an ongoing cost associated with the data collection and manipulation of the models.

Data Collection

Although the PMS has been modified to suit local government it started as a tool for a highway authority. It is important to realize that the perception of a road to such people is a straight line from one point to the next with scant regard for anything that exists outside the table drain. Councils have a slightly differing view where a lot more emphasis is paid to things like footpaths, street lights, signs, and even bus stops. The local government version of the software caters for all this. It is important not to get too carried away with peripheral detail as the cost of collection of this detail can soon outweigh its economic significance.

Dubbo was one the early councils to start using the PMS and the number of categories of data collected soon matched the number of available fields. Today many of these fields remain empty. The reason for them is still valid, and as resources become available the additional data will be collected. Eventually it is hoped that RRL will provide a representation of the current real network available at a terminal in the office. This will allow assessment of engineering problems and will also allow graphical representation through CMISPRO of relationships between collected data.

The collection of the road condition information is and will remain the most important side of the PMS. In Dubbo, it has been necessary to contract out the data collection, for a number of reasons.

First, it is important that the data be collected in as short a time frame as possible. This makes the representation of the network more accurate because it closely measures the condition state at a particular point in time. In Dubbo, roughness is the major distress modeled. At the moment this is the most easily measured and the most repeatable distress mode. It can also be argued that it is the most easily identifiable condition state for the consumer (i.e., the motorist).

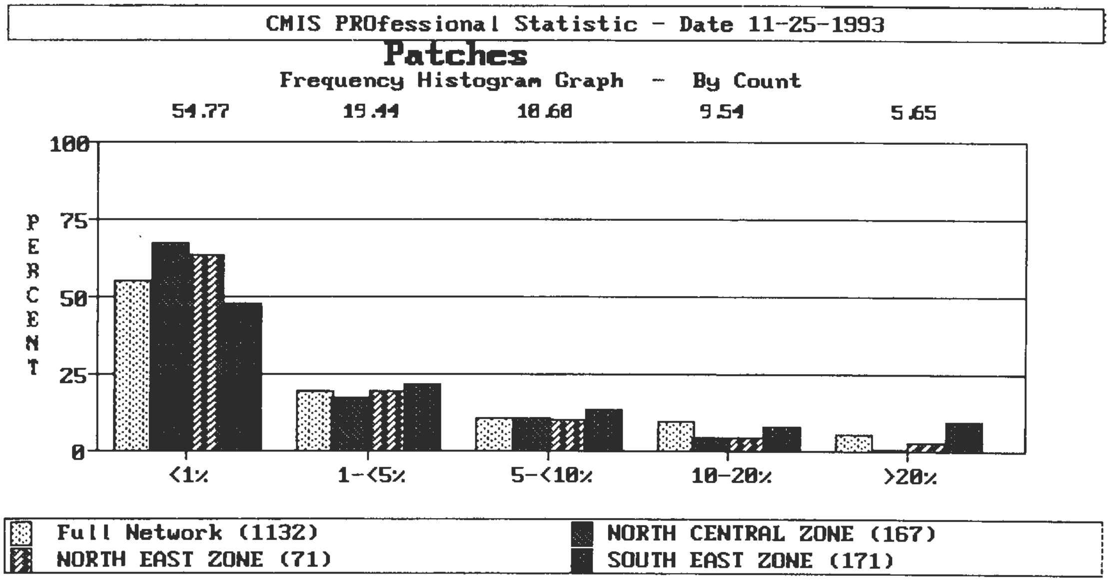
Second, the push toward contracting in council has meant that appointing staff to do data collection is becoming increasingly difficult.

Third, the need to have an independent person assess the network condition does away with local prejudices as well as influences because of knowledge of impending work.

While the ongoing collection of data is a major cost in the postimplementation stage the need for reliable information cannot be understated. At the present council does an annual survey and it is intended to continue this for at least another 3 years. After this the historical sequence of information will be reviewed with the possibility of going to a 2- or 3-year cycle. It is anticipated that by then the deterioration models will be sufficiently fine-tuned to accurately represent the whole of life curves.

Use to Date

Use of the PMS has been on three different levels. The first level was by engineering departments. The implementation stage caused the engineering department to look long and hard at what council did to maintain the road network, how council did it, and why council did it. The implementation process was done over a number of weeks and in association with a number of councils. This sharing of experiences further added to the review process and following on from this has changed some of the maintenance philosophies. More emphasis is now being paid on ride quality and patching crews are more aware of the impact they have on the network condition. Figure 2 gives the treatments and distress types modeled in TNOS analysis by Dubbo City Council. Figure 6 shows the current network statistics for roughness. Figure 3 shows the current optimized TNOS program of works as a graphical presentation rather than a listing. Figure 7 gives funds required and the nature of work anticipated to meet target condition states.



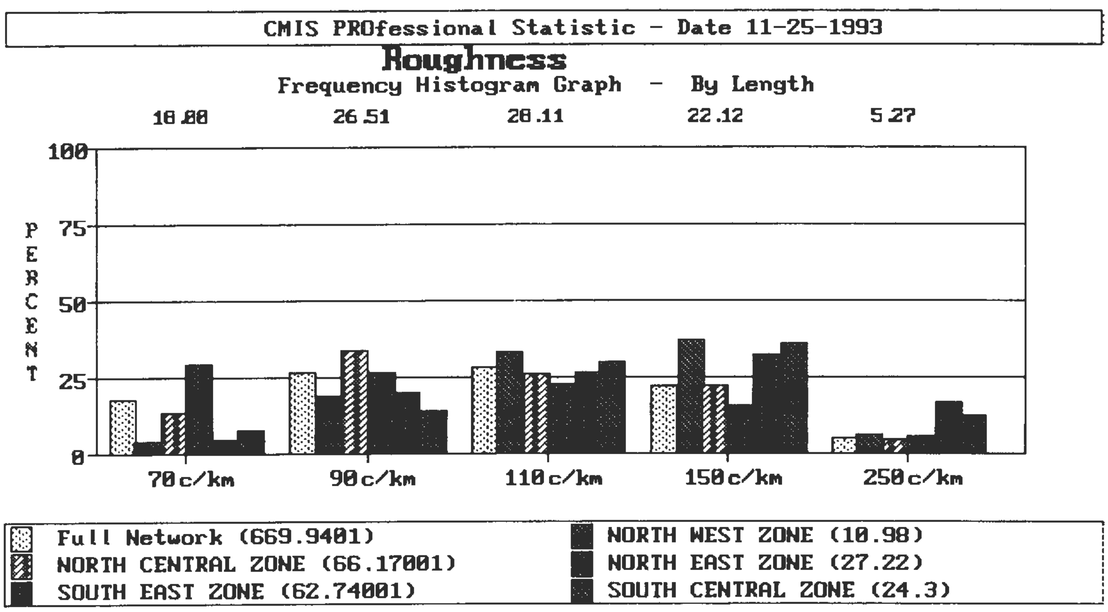


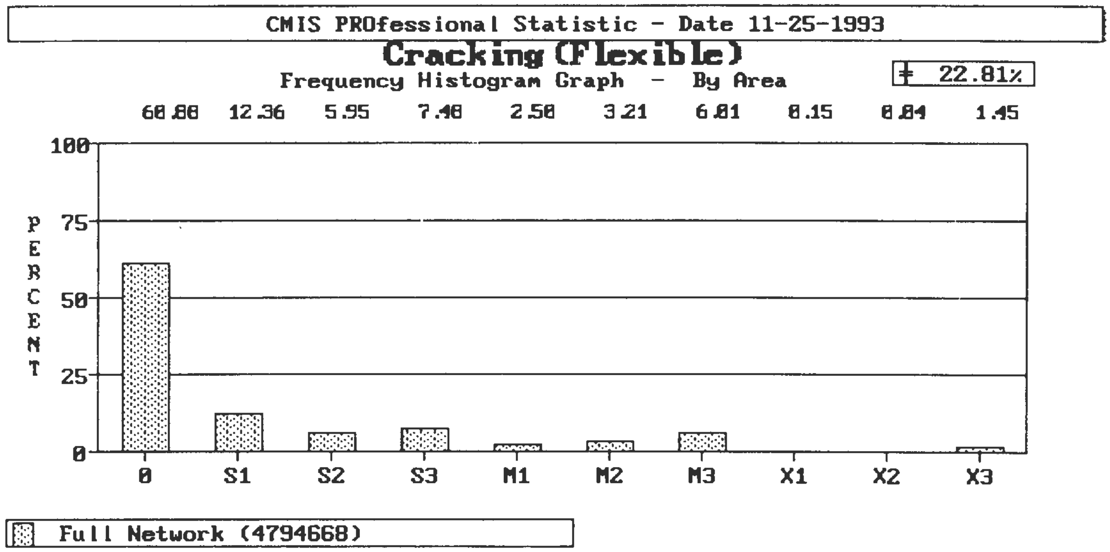
FIGURE 6 Some current network distress statistics including roughness (NAASRA) *(continued on next page).*

The management of council's major asset is the second level of use. The first year of use of the PMS saw a major shift in emphasis in council priority. In essence it was shown that the current level of funding did not allow for expansion of the sealed road network. It was therefore necessary to consolidate the existing roads and maintain them to a suitable standard and await additional funds for network expansion.

The third level is the political use of the PMS. In the first year of the PMS the elected members of the council were given a recipe for the future of the road network. It gave them an understanding they had never had of the condition of their roads and allowed them to make a more informed decision on resource allocation.

To reinforce the detail that was given to them a bus trip was organized to demonstrate:

- Segments that were identified for a particular treatment. This highlighted the need to maintain rather than rehabilitate the road asset;
- Segments that, having a deficiency, were being left for treatment in following years; and



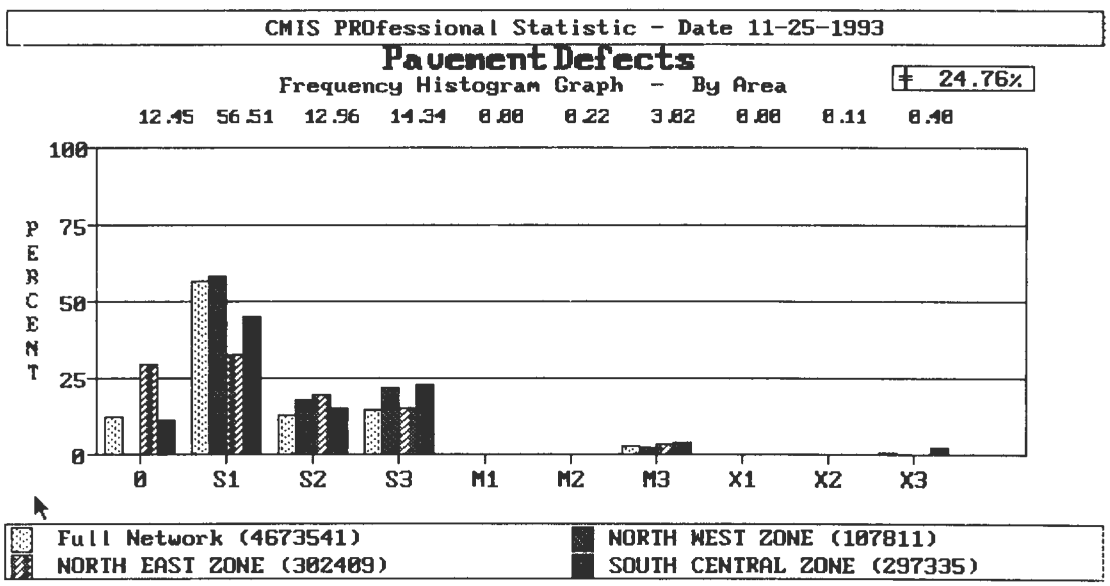


FIGURE 6 *(continued)*.

• Segments that were typical of the average condition of the road network. This gave council the opportunity to decide what standard they wished the network to be in.

With a full understanding of the road network condition and its relation to previous years, it is now possible for council to argue for a better distribution of funds from higher levels of government.

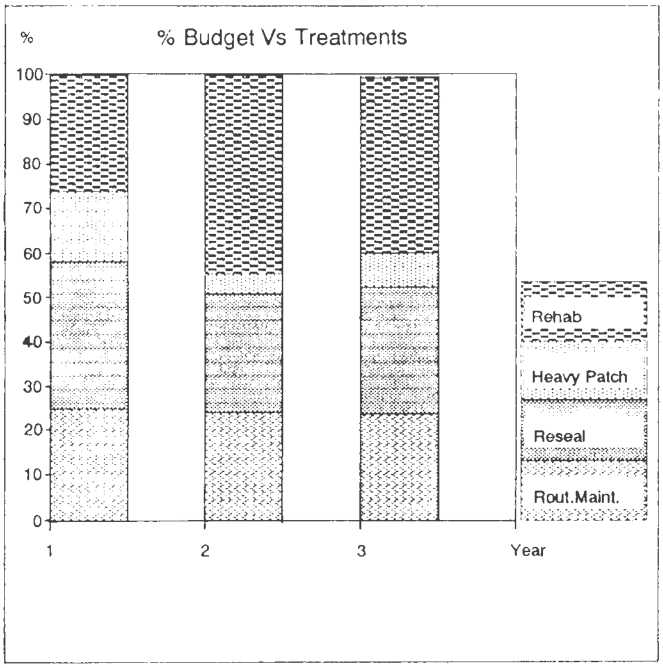
Information Management Systems

Councils have traditionally dealt with large software houses for computer advancement. As the accounting needs are being met there is a move toward other computing needs. GIS are being pursued as the basis for any information system by mainframe exponents. This will be the most likely outcome in years to come and there is no reason that PMS cannot be integrated with this facility. In the mean time the use of powerful PC-based systems will dominate the market place because they are cost-competitive and are continually improving.

Dubbo has invested heavily in a geographical mapping system that requires a high degree of accuracy. When this is complete it is proposed to integrate the PMS into it. The mapping abilities of the PMS are cumbersome by comparison and the addition of the mainframe mapping should greatly enhance communication abilities.

Dubbo City Council
Network: condata.txt

Run: 3 year analysis-Maintain
15/04/93 exist.conds-5% disc.rate



Dubbo City Council
Network: condata.txt
% Budget Vs Treatments

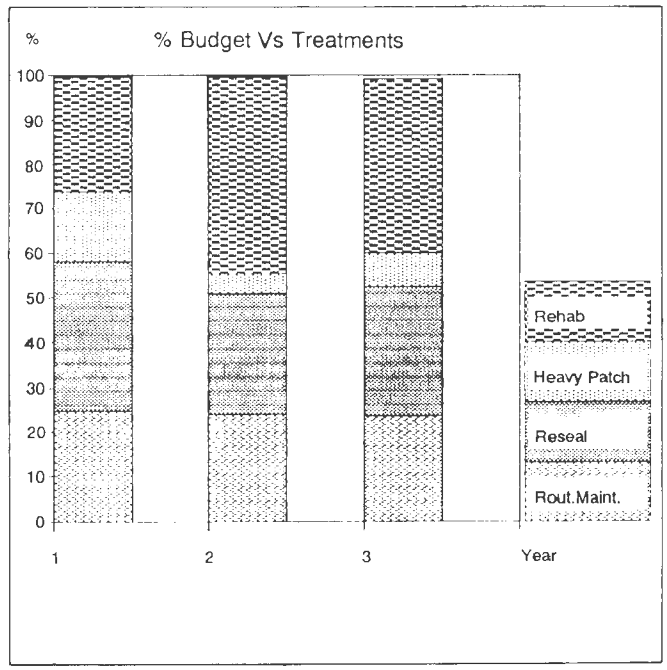
Run: 3 year analysis-Maintain
15/04/93 exist.conds-5% disc.rate

Treatment	Yr 1	Yr 2	Yr 3
Rout.Maint.	24.9%	24.1%	23.8%
Reseal	33.5%	26.7%	28.8%
Heavy Patch	15.8%	4.5%	7.6%
Rehab	25.8%	44.7%	39.8%
Total Budget	1890902	1992119	2000002

NOTE:
The FNOS Analysis above indicates that Dubbo City needs to increase its road upkeep budget for the current \$1.2M to \$1.9M in year 1 and \$2.0M in years 2 and 3 to maintain the existing network conditions.

Dubbo City Council
Network: condata.txt

Run: 3 year analysis-Maintain
15/04/93 exist.conds-5% disc.rate



Dubbo City Council
Network: condata.txt
% Budget Vs Treatments

Run: 3 year analysis-Maintain
15/04/93 exist.conds-5% disc.rate

Treatment	Yr 1	Yr 2	Yr 3
Rout.Maint.	23.8%	23.4%	25.5%
Reseal	27.3%	28.4%	33.2%
Heavy Patch	8.6%	12.9%	5.9%
Rehab	40.3%	35.3%	35.4%
Total Budget	2000002	2000002	-1876118

NOTE:
The FNOS analysis above indicates that in order to gain a margin improvement in roughness of the network over the next 3 years the upkeep budget should be set at \$2.0M in years 1 and 2 and may then be able to be dropped to \$1.88M in year 3. The new work would be rehabilitation replacing heavy patching.

FIGURE 7 FNOS analysis—Dubbo City Council.

PMS is only the start. The introduction of MMSs now being developed for councils will greatly enhance the use of the PMS. During implementation it became apparent that more accurate information on costing and resources programming would enhance PMS modeling. The MMS looks to provide such information as well as address the efficiency of operations.

Review

In any decision-making process it is important to undertake a review. Since deciding on the RTA PMS there have been many new and better PMS packages.

These new packages have been targeted at different-size councils, with cheap versions for small councils and more expensive ones for larger councils. The chosen package continues to be developed and is gaining more and more acceptance. It also has fitted into councils' needs to adopt accrual accounting.

The implementation of the package was time consuming and if it could be done again more engineers would have been involved. This would not only have shared the workload but also ensured a better long-term uniformity in the event of staff leaving.

It is important that, as with any computer program modeling, the human element be identified. In Dubbo City Council's case, a segment of road that was in extremely poor condition was not identified for treatment. The engineering reasons were easily explained, but the politics of the issue resulted in treatment. It is important that this be recognized from the outset.

These changes are inevitable but it is important that the elected members realize that such a decision does not compromise the usefulness or integrity of the modeling and that there will always be engineering or political decisions made outside the PMS model.

The Future

The council needs to continue the commitment to the PMS system. It holds the key to the future of the road network. A number of initiatives need to be investigated.

First the integration of the GIS, although done in isolation, would be improved by an overlay of the road register finally linking all of council's information systems.

Second, the implementation of the MMS will see the confirmation of the maintenance proposals put forward in the PMS. It will allow better correlation between future proposals and actual work and provide a more accurate checking system on the validity of council's models of road infrastructure performance.

Conclusion

PMS Implementor

1. The modular makeup of the software is valuable in providing for selective and staged implementation;
2. The information collected and the formats for peripheral data should be determinable by the client local government authority within basic guidelines;
3. The tailoring of the software and face-to-face training should remain as a compulsory part of the PMS sale to ensure adequate implementation and should continue at the same resource level;
4. It is advantageous to introduce cheaper and efficient mechanical means of data collection as soon as possible;
5. PMS information system elements need to be conveniently linked to other information packages such as GIS; and
6. The implementor should remain in touch with the client and preferably consult in other areas of road engineering such that valid applications of PMS are recognized after implementation.

Local Government PMS Client

1. The program needs to be owned and accepted as the method of asset management;
2. Council must be prepared to have an ongoing commitment to allocate resources for data collection;
3. The modular makeup of the software is important to allow various councils to invest in PMS appropriate to their needs;
4. Council should be confident that it gets what it wants from PMS;
5. The engineering department and council's elected members must be educated in PMS functionality and thus be able to understand the information available;
6. The PMS should not be seen as a totally correct and singular solution to the needs of the road network; and
7. The engineering department needs to be able to review the parameters that are input to the PMS and needs to have access to a consultant providing an update service on the system.

Postscript Discussion

At the Second North American Conference on Pavement Management Systems in Toronto, Canada in 1987, K. Porter reported that a national committee was formulating guidelines for the effective and hopefully uniform implementation of PMS in Australia. At that stage the focus was on state road authorities. A listing of aspirations for the 1990s was provided as follows:

1. Common pavement performance data, analysis logic, and reporting formats in a common approach to PMS;
2. Coordination of appraisal of new equipment for the mechanical collection of pavement performance data;
3. The definition of an Australian Pavement Serviceability Rating (PSR) and development of intrastate correlation to this overall condition parameter; and
4. The definition of a hierarchy of road classifications based on road use by volume, vehicle type, and axle mass statistics.

It is appropriate to reflect on current achievements in these areas in 1993.

1. The ROCOND90 procedure has become an unofficial standard for key performance and condition data in both state road authorities and local government. Analysis logic in the three optimizing PMS packages are different. Dynatest PMS and the SMEC-Newcastle systems use recalibrated versions of the World Bank HDM-III models; the RTA PMS uses client-generated models. Reporting formats vary but all are reasonably flexible.
2. Laser technology is available for mechanical measurement of rutting and roughness. Vehicles are available from RST Australia, Dynatest PMS, Australian Road Research Board, and RTA-NSW. Surface texture by laser is available from RST Australia. NAASRA Roughness (now AUSTROADS Roughness) is available by conventional

vehicles. Sideways Force Coefficient Routine Investigation Machine (SCRIM) skid resistance surveys are available to a limited extent. Falling weight deflectometer surveys are available and are becoming more popular in recent years. Video logging is available from Dynatest PMS and RST Australia. The cost of these mechanical surveys often prohibits more widespread use, particularly by local government on local roads.

3. Significant steps have been made to establish a pavement user rating a surface condition index (SCI), and a pavement condition index. Interim definitions have been developed and interstate trials undertaken. At this stage the concept is alive, and the final definition and implementation is expected during 1993.

4. Many local government authorities are undertaking road hierarchy classifications in conjunction with the implementation of information systems and PMS particularly. Unfortunately, the issue of a standardized road hierarchy has not been addressed at this stage.

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BETTER DATA QUALITY MANAGEMENT

New Zealand Experience in Comparing Manual and Automatic Pavement Condition Rating Systems

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The purpose of condition rating surveys is to measure and record defects along a section of road in a standard and objective manner. This provides a measure of the condition of each road section, which in turn can be used to assess routine maintenance and rehabilitation needs. In New Zealand, such a survey is presently accomplished by visual walkover on a 10 percent sample of the road network carried out by trained raters. As part of an effort to continually improve the quality of pavement condition data, a comparative study was undertaken to establish the degree of correlation between walkover survey data and data automatically acquired by the Swedish Road Surface Tester (RST) and Side Force Coefficient Routine Investigation Machine (SCRIM). The principal pavement distress modes of interest were confined to rutting, shoving, scabbing, and flushing. The main conclusion reached was that, although RST and SCRIM have value as survey tools, some form of visual assessment of the actual pavement condition is still required to fully identify surface related defects. In addition, it was demonstrated that for vehicle-acquired condition rating data, particular attention must be paid to selecting appropriate reporting lengths and intervention levels so that they are consistent with both the resolution of the measuring device and the minimum pavement length that justifies resurfacing or shape correction.

The role of experience and judgment in pavement design, construction, and maintenance is so great, given the need to use local materials in natural environments, that good engineering demands that the performance of all roads to be consistently evaluated (*1*). The aims of this evaluation are to

1. Check if the intended pavement function and performance objectives are being achieved;
2. Provide guidance for planning and rehabilitation;
3. Provide feedback for improvements to existing design, construction, and maintenance procedures;
4. Establish a data base on road performance for use by future designers and economic analysts; and
5. Detect condition changes from one year to the next.

The objective assessment of the present condition of a road requires the rating of the individual components that make up that condition. In New Zealand, a pavement management system (PMS) has evolved around manual surveys carried out on a 10 percent sample of the road network. This paper describes the condition rating procedures adopted and the results of a comparative study undertaken to establish the degree of correlation between manual survey data and data obtained by continuous measuring devices such as the Swedish Road Surface Tester (RST) (*2*) and the Side Force Coefficient Routine Investigation Machine (SCRIM) (*3*).

Description of Road Assessment and Maintenance Management System

New Zealand's road network comprises some 10 500 km of state highways and 83 500 km of local roads. Approximately 38 500 km of the network are unsealed. The majority of the sealed roads consist of a granular basecourse with a chipseal surface (bitumen with a one sized aggregate surface), although increasingly asphaltic concrete and porous friction course are being used on urban motorways and arterials.

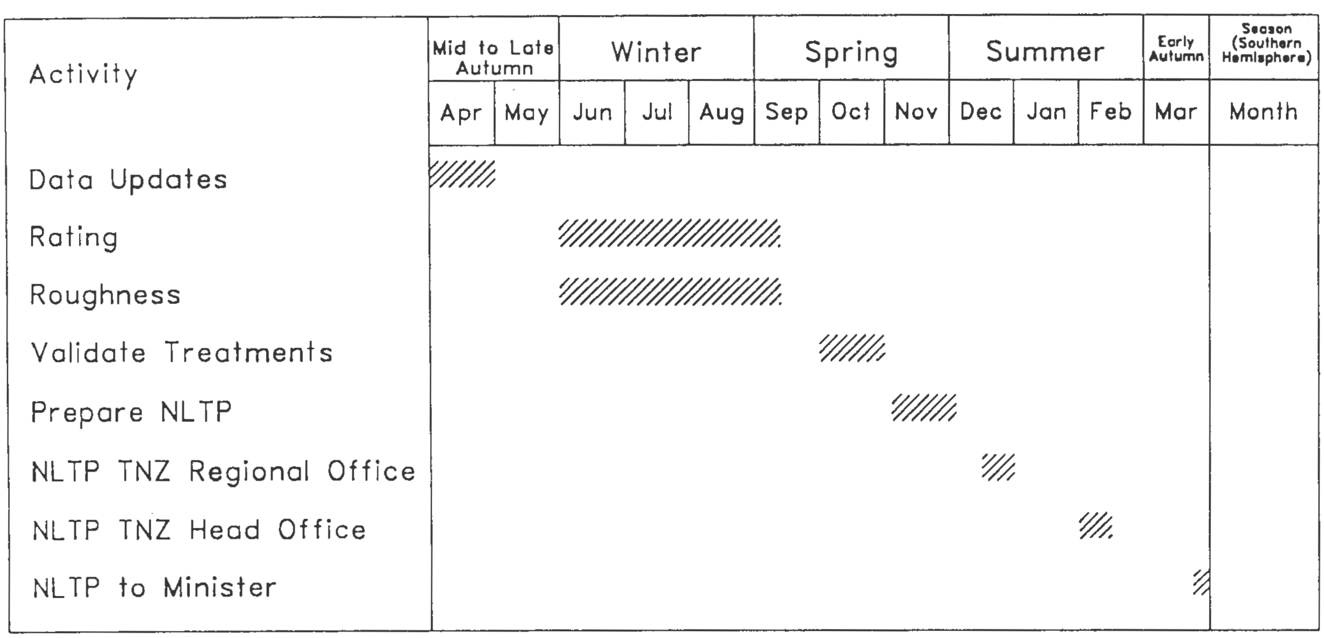
Transit New Zealand (formerly the National Roads Board) is the national road agency. It has the responsibility for managing the state highways and allocating funds (on average 50 percent financial assistance) to the local authorities. Government funding is obtained via road user charges, and gasoline tax, licenses and fees and made available to Transit New Zealand to disburse in accordance with an agreed annual land transport program. Therefore, to effectively manage the road network a PMS is required.

New Zealand's Road Assessment and Maintenance Management (RAMM) system was initiated in the mid 1980s by a local government group and supported by Transit New Zealand. The RAMM system is typical of PMSs in that it contains inventory data of the road asset, condition data including roughness, and an analysis module based on a benefit/cost approach to provide a priority list of treatments.

Central to the RAMM system are annual inspections concerned with pavement surface defects and longitudinal roughness measurement (ride quality). Information regarding surface defects is presently acquired by manual condition rating procedures whereby trained personnel inspect and record defects on a sample per segment basis. Typically this is a 50-m sample per 500-m segment for pavement defects and the full length for surface drainage because of the susceptibility of New Zealand pavements to damage initiated by water ingress. These manual surveys are conducted over the late winter months and are complimented by 100 percent sampling of the road roughness undertaken with the NAASRA roughness meter (*4*).

The schedule of activities must be tightly controlled to formulate the yearly National Land Transport Programme (NLTP). The timing is shown in Figure 1. Several points should be noted.

1. Significant pavement defects are most easily observed and measured at the end of winter before the summer construction season;
2. The data must be acquired by field survey, analyzed, and area treatments for proposed maintenance and reconstruction completed in time to advertise and let contracts for start and completion in the favorable summer season;
3. Typical 1993 unit costs of the various RAMM associated activities are:
   - Initial establishment of the various inventories: US$8.50/lane-km;
   - Subsequent annual inventory condition ratings, including field and office activities: US$5.00/lane-km; and
   - Road roughness survey: US$2.00/lane-km.



Note: NLTP = National Land Transport Programme

FIGURE 1 RAMM schedule of activities.

The pavement surface defects, as defined in the Transit New Zealand Road Condition Rating Manual (5), are summarized in Table 1 along with their units of measure. No scoring system is used, instead the actual measurements are recorded and used in the treatment selection analysis. The surveys are conducted by many teams of raters who have attended rating training workshops conducted on behalf of Transit New Zealand.

The RAMM system is now owned by Transit New Zealand, and development is progressed in consultation with local authorities via a RAMM advisory group. Several user groups have been formed to facilitate information exchange and liaison.

As at September 1993, only 6 of 74 local authorities had not undertaken to implement the RAMM system. A directive from the Minister of Transport to Transit New Zealand in June 1993 required all local authorities to have the RAMM system in place no later than June 30, 1994. The New Zealand Government requires all local governments to justify ongoing maintenance funding by means of the RAMM system. The intention is to provide a common benchmarked approach to asset management across all local authorities. The RAMM system is also a cornerstone of Transit New Zealand's assurances to government that budget levels, toward which financial assistance is made available, are set at equitable and efficient levels across the country.

Data Quality Management

To maximize the benefits of the RAMM system and ensure that valid comparisons of the condition of the highways from year to year and location to location can be made, accurate data must be gathered. Steps that may be taken to provide quality data are

- Documentation of measurement procedures;
- Training material and training courses and certification for raters;
- Introduction of quality control, tolerance limits and statistical checks on permissible variability for data;
- Calibration procedures and control procedures for the deployment of measuring equipment;
- Comparison of field data against existing data records to check for anomalies;
- Procedures to adopt when errors are encountered; and
- Quality assurance requirements incorporated in contracts for survey work.

All of the above steps have or are being implemented in New Zealand.

Because most of the data are gathered by the use of straight edges and other measuring equipment (e.g., tapes, wedges, wheels, etc.) uniformity of training is critical. A technical institute, Taranaki Polytechnic, works with Transit New Zealand to provide the course format and resource materials to accredited trainers. On state highways, the raters are employees of the consultants providing road network management services to Transit New Zealand.

The first condition rating survey was conducted on the state highway network in 1989. Training requirements were intensified in 1990, and from data comparisons between the first two years, quality assurance (QA) criteria were developed and tried in 1991. The QA criteria were reviewed and distributed to local authorities in 1992 and recommended for adoption.

TABLE 1 Surveyed Pavement Defects

Defect	Units
Surface	
Rutting	Linear metre > 20 mm from 2 m straight edge
Shoving	Linear metre in wheelpaths
Scabbing	m^2 > 10% chip loss
Flushing	Linear metre in wheelpaths
Alligator cracks	Linear metre in wheelpaths
Longitudinal and transverse cracks	Linear metre of crack
Joint cracks	Linear metre of crack
Potholes	Number > 70 mm diameter
Pothole patch	Number < 0.5 m^2
Edge break	Linear metre
Edge break patch	Linear metre
Drainage	
Blocked	Linear metre
Inadequate	Linear metre < 400 mm deep
Ineffective Shoulder	Linear metre of shoulder that prevents water discharge

From the experience gained in the QA process, limits of variation in the measurement (and recognition) of the defects were developed and issued in 1992. With further experience, these limits are likely to be refined further.

The changes in data brought about by the training procedures is illustrated in Figures 2, 3, and 4 for the length of edge break (reduction of the seal coat by more than 100 mm from the original line of the seal edge), scabbing (areas of chip loss), and alligator cracking. It can be seen that there was a major shift in the distribution of edge break from 1989 to the following years and it appears that the 1989 survey overestimated the rate of this dis-

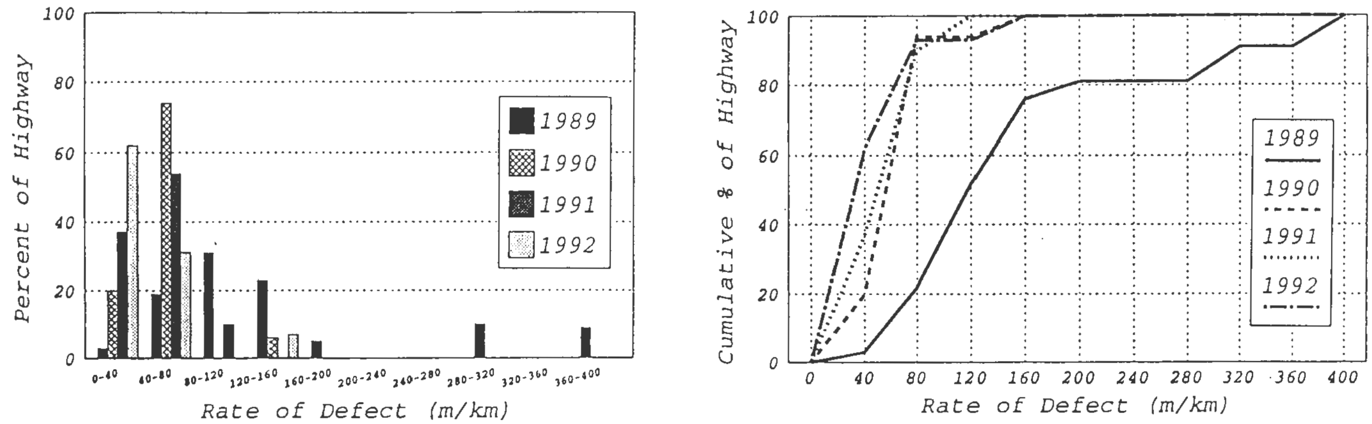


FIGURE 2 Variability of manually obtained edge break data, 1989–1992.

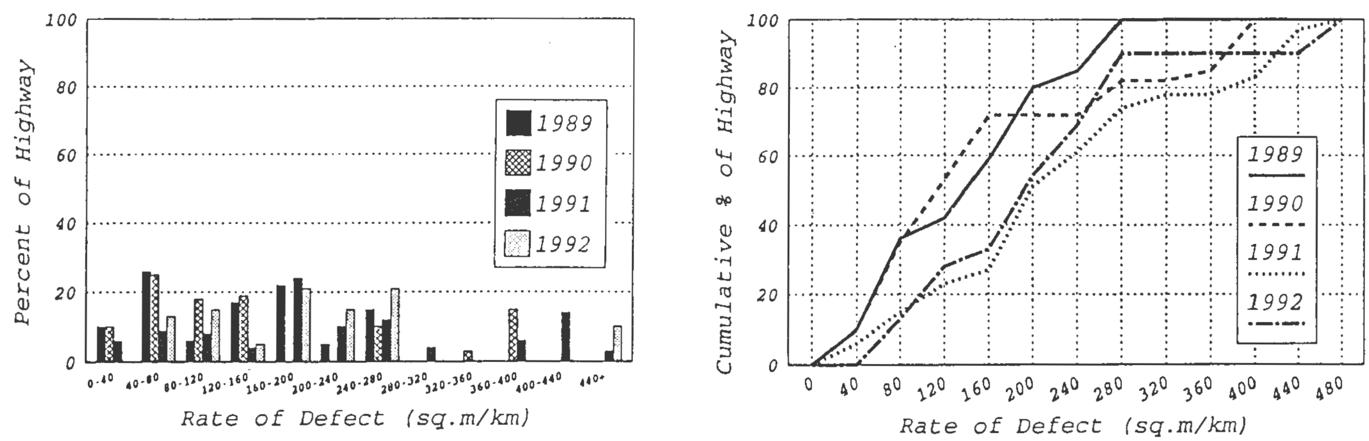


FIGURE 3 Variability of manually obtained scabbing data, 1989–1992.

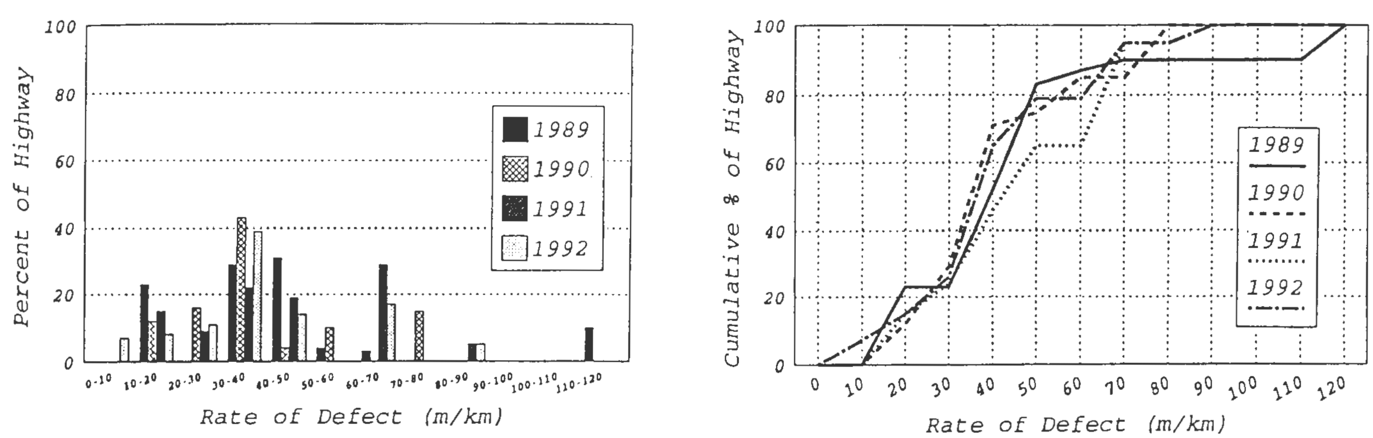


FIGURE 4 Variability of manually obtained alligator cracking data, 1989–1992.

tress. For scabbing, the data suggest that there was a significant change between 1989 and 1990 and 1991 and 1992 surveys. In this case the incidence of this form of distress has increased. Alligator cracking distribution does not appear to have change significantly.

The changes in the frequency of the different types of distress from year to year are greater than can be accounted for by road maintenance activities. It is considered that the closer distributions for all forms of distress that have occurred in the 1991 and 1992 surveys are due to the introduction of formal training and QA procedures.

Automatic Data Collection

Although visual surveys are a common and comparatively inexpensive means for collecting pavement defect information, there are a number of recognised problems with this method. These include the subjective nature of the visual surveys, transcription errors that inevitably occur, and consistency of the measured ratings that lead to a low correlation between raters and even among individual raters over time. As a direct consequence of these problems and in response to an increasing need for systematic, objective and safe means of acquiring pavement condition data for input into PMSs, a number of high output continuous measuring devices that can be operated at normal traffic speeds have been developed.

In an effort to determine the most appropriate means for acquiring surface defect information, the use of automatic data collection by vehicle based systems was investigated in 1988 when a RST was imported to New Zealand to demonstrate its suitability for use in gathering input data for RAMM, and again in 1990 when a SCRIM machine performed a survey of the New Zealand state highway network. The availability of 100 percent sampling of roughness, rut depth and surface texture by the RST, and skid resistance, as determined by the 50-km/hr side force coefficient (SFC), provided an opportunity to establish the degree of correlation with the walkover visual survey data stored in the RAMM database.

Agreement Between Automatic and Manual Condition Rating Procedures

Methodology

Five representative road sections varying in length from 2 to 7 km located on State Highway 1 North (SH1N), New Zealand's main highway, were selected from the RAMM data base. The RAMM data were derived from visual surveys conducted during June and July 1989. These road sections, along with the principal modes of pavement distress identified for each section, have been summarized in Table 2. These modes are briefly described.

- *Rutting:* longitudinal wheeltrack depressions. Only the length of wheeltrack exceeding 20 mm from a 2-m straight edge is recorded in RAMM.
- *Shoving:* horizontal displacement of the surface material, which causes a series of shallow transverse depressions resembling corrugations.
- *Scabbing:* removal of larger surface aggregates leaving craters (i.e., chip loss).
- *Flushing:* road surface has a slick, smooth appearance because binder has flushed (risen) to a level where surface aggregate is only just protruding or where binder has risen to be level with or over the top of the surface aggregate.

Rutting and shoving affect roughness, whereas scabbing and flushing affect macrotexture.

To establish the level of agreement between the walkover visual survey data sampled on a 10 percent basis with the RST and SCRIM data, a graphical approach was adopted. This entailed plotting 100-m averaged results of the RST and SCRIM surveys as a function of distance along the SH1N sections listed in Table 2. Superimposed on the plots, where appropriate, were the intervention/investigation criteria presently specified by Transit New Zealand, along with the locations of the manual inspections. In this manner, the condition of the road section with respect to a certain pavement distress parameter could be readily ascertained along with whether the severity level at the manual inspection location warranted recording by the rater. By way of example, resulting distribution graphs for a site (site 2 in Table 2) are presented in Figures 5 to 8.

Descriptive statistics were also calculated for both the RST and SCRIM data. These statistics were in turn compared with the results of the walkover visual survey data that was normalized with respect to the number of lanes and surveyed road length (i.e., lane-kilometers) to allow the condition of the sections to be ranked with respect to the various recorded distress parameters. The resulting normalized RAMM data are given in Table 3.

Only a summary of the principal findings of the comparative study will be given here; a detailed discussion has been given elsewhere (6).

Rutting

The RST calculates maximum rut depth by a mathematical method, which is analogous to a wire being stretched traversely across the road profile (2). Figure 9 shows the difference between straight edge (as used in manual surveys) and the RST wire surface measurement of rut depth.

A comparison of the RST rut depth distributions with the RAMM rutting ratings identified poor agreement between the measurement methods as to where significant rutting occurred along a road section. Furthermore, at no

TABLE 2 Representative SH1N Condition Survey Sections

Site No.	Section of SH1N	Approximate Location	Length (km)	Characteristic Surface Distress
1	393/9.16-15.97	Whangamarino	6.81	Extensive scabbing and flushing with some localised rutting at the middle and end of section
2	428/0.00-2.37	Huntly	2.37	Extensive scabbing with considerable rutting at middle of section
3	915/6.10-8.71	Manakau	2.61	Extensive flushing with considerable rutting at end of section
4	931/1.50-7.50	Waikanae	6.00	Flushing and shoving along last half of section
5	942/2.09-5.12	Paraparaumu	3.03	Localised scabbing, flushing and rutting

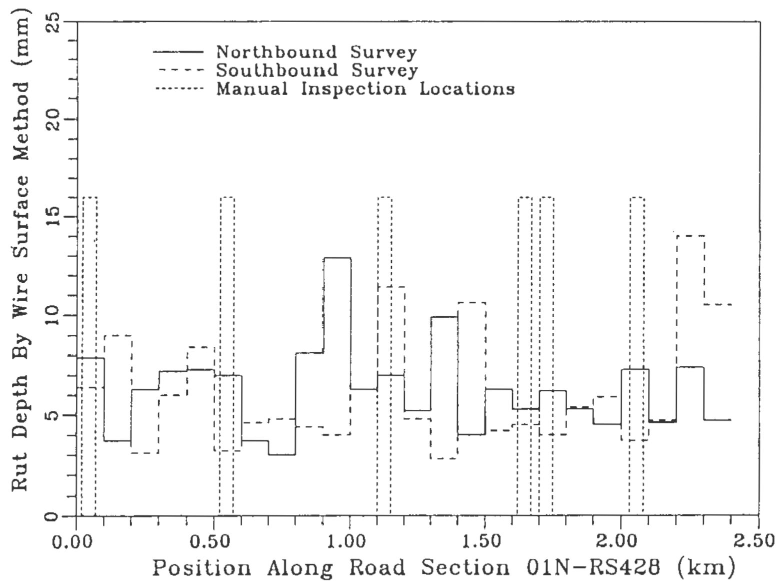


FIGURE 5 100-m rut depth distributions, site 2.

manual inspection location did the RST rut depth exceed the intervention level of 20 mm.

Table 4 shows that sites 1 and 2 have the highest average RST rut depth on the basis of continuous sampling. However, this is inconsistent with the rankings based on normalized RAMM pavement condition ratings given in Table 3 which indicate sites 2 and 3 as having the greatest extent of this type of pavement defect.

The poor agreement between RST rut depth and the manual survey is attributed to

1. Lack of significant correlation between RST and straight edge rut depth described by Jameson et al. (7);
2. The fact that in 1989, some raters gauged rut depth by eye rather than physical measurement—this has subsequently been addressed through training programs implemented since 1990; and
3. The difference in the way the rut depth measurement is presented, for example, an average over a 100-m reporting length (RST) compared with the accumulated length that exceeds a threshold level (manual survey).

Surface Deficiencies

The RST measures both fine and rough macrotexture using the output from laser cameras mounted over each wheelpath. Fine macrotexture covers surface profile

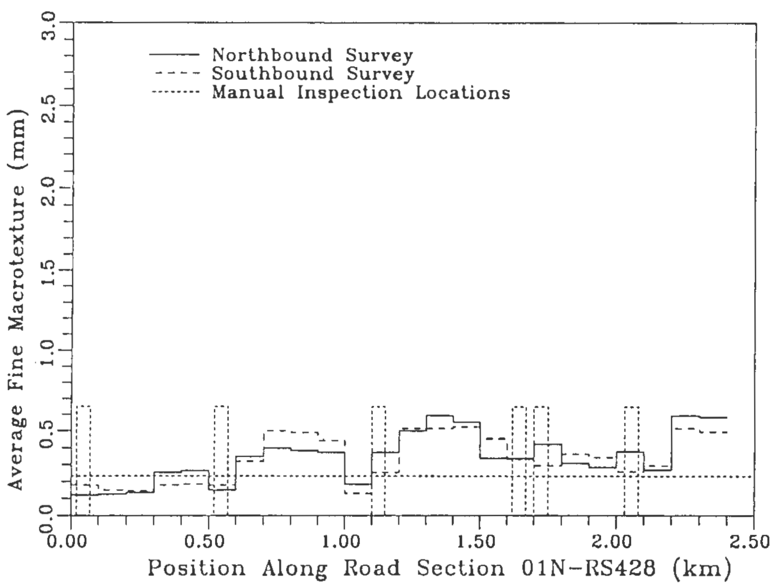


FIGURE 6 **100-m RST-RMS fine macrotexture distributions, site 2. (Broken horizontal line represents Transit New Zealand intervention levels.)**

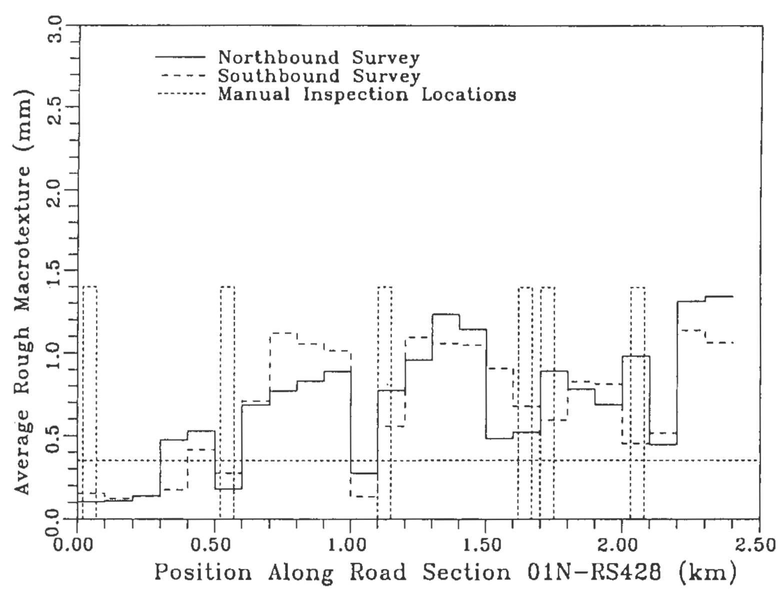


FIGURE 7 **100-m RST-RMS rough macrotexture distributions, site 2. (Broken horizontal line represents Transit New Zealand intervention levels.)**

wavelengths over the range 1 to 10 mm, constituting macrotexture roughness caused by very small chippings and the sharpness and angularity of chippings. Rough macrotexture covers wavelengths in the range 10 to 80 mm and describes surface roughness caused by large chippings, asperities, and other surface features, which, in the order of size, are less than the tire/road contact zone.

The principal surface deficiencies recorded in visual surveys are associated with scabbing, flushing, potholing, and cracking. In a work by Cenek (*8*) it was demonstrated that the RST could not reliably recognize cracking in chipseal surfaces. However, because both scabbing and flushing involve a loss of surface texture, it was expected that some surface defects could be identified by combining RST fine and rough macrotexture measures with SCRIM data. In particular, RST rough macrotexture should be sensitive to scabbing and potholing, and RST fine macrotexture to flushing. Therefore to establish the degree of agreement between automatic and manual survey procedures in identifying defects in the surface texture, the 100-m averaged RST fine and rough RMS macrotexture and SCRIM skid resistance distributions for the five selected SH1N sections

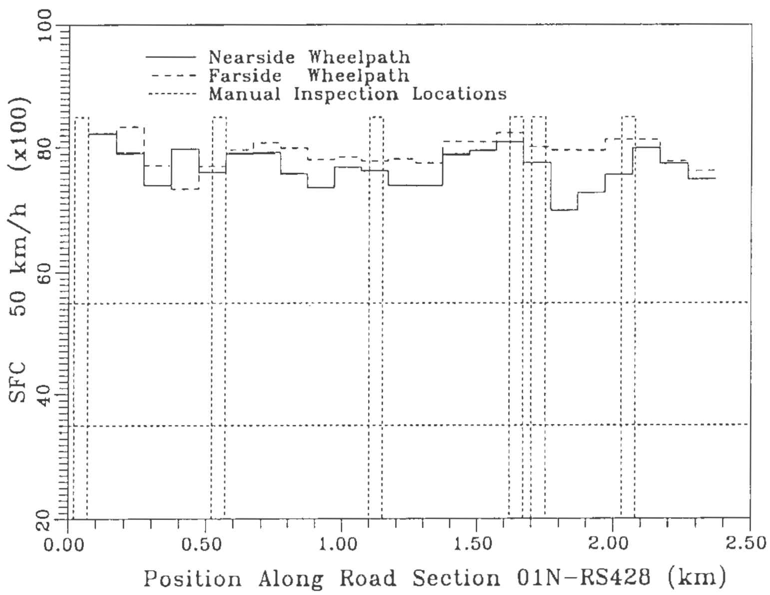


FIGURE 8 100-m SCRIM SFC_{50} distributions, site 2. (Broken horizontal line represents Transit New Zealand intervention levels.)

TABLE 3 Normalized RAMM Pavement Condition Ratings

Site No.	Description	Rutting (m/lane-km)	Shoving (m/lane-km)	Scabbing (m^2/lane-km)	Flushing (m/lane-km)
1	RS393/9.16-15.97	9	0	474	218
2	RS428/0.00-2.37	108	5	400	168
3	RS915/6.10-8.71	110	4	4	286
4	RS931/1.50-7.50	0	61	15	210
5	RS942/2.09-5.12	16	0	16	28

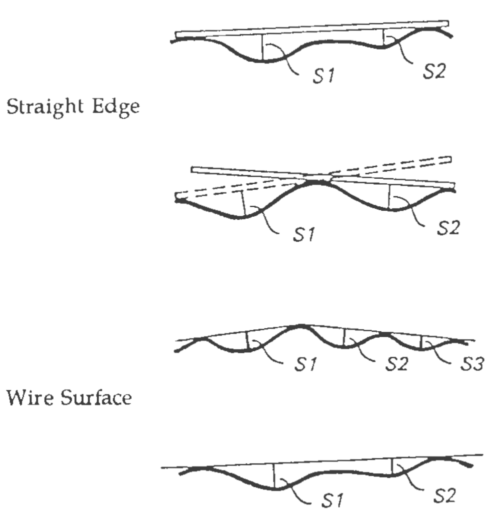


FIGURE 9 Cross-profile measurements; rut depth is the largest value of S1, S2, S3, and so forth (2).

were considered. The associated statistical descriptions for each section are given in Tables 5 to 7.

The distribution graphs showed that only very few 100-m lengths fell below the intervention/investigation criteria for texture depth and skid resistance. Site 2 had the greatest loss of macrotexture, with 1.2 lane-km below the minimum acceptable texture depth, followed by site 3 (0.2 lane-km) and site 4 (0.1 lane-km). Both RST fine and rough macrotexture measures showed the same location and extent of surface texture loss. By comparison, only site 4 had sections where the measured skid resistance fell in the range requiring investigation.

As with the rut depth analysis, there was poor agreement between the RAMM scabbing and flushing ratings and the RST and SCRIM data as to where significant texture defects had occurred along each SH1N section investigated.

Table 5 to 7 show that site 2 has the lowest average texture depth. Of particular interest is the very little difference

TABLE 4 SH1N Descriptive Statistics for RST-Measured Rut Depth

Site No.	Direction	Rut Depth (as Derived from Wire Surface Method), mm						
		Mean	Median	Std Dev	Min	Max	Q1	Q3
1	Northbound	7.14	6.10	3.13	3.20	15.60	4.80	9.50
	Southbound	7.10	6.30	3.06	2.80	16.20	5.10	8.18
2	Northbound	6.35	6.30	2.15	3.00	12.90	4.75	7.30
	Southbound	6.11	4.80	2.98	2.80	14.00	4.05	7.90
3	Northbound	5.42	4.35	3.39	1.60	17.90	3.38	6.35
	Southbound	4.67	4.55	1.61	1.90	8.70	3.50	5.95
4	Northbound	4.27	3.60	2.52	1.00	10.60	2.10	5.75
	Southbound	5.33	4.60	3.31	1.30	15.90	2.50	7.40
5	Northbound	3.26	3.10	1.43	1.20	6.60	2.20	3.93
	Southbound	4.67	2.75	4.91	1.30	23.60	2.08	4.40

TABLE 5 SH1N Descriptive Statistics for RST-RMS Fine Macrotexture

Site No.	Direction	RST-RMS Fine Macrotexture (1-10 mm wavelengths), mm								
		Wheelpath Averaged Statistics							Individual Wheelpath Mean Values	
		Mean	Median	Std Dev	Min	Max	Lower Quartile	Upper Quartile	Outer	Inner
1	Northbound	0.85	0.89	0.10	0.58	0.99	0.83	0.92	0.84	0.85
	Southbound	0.77	0.78	0.09	0.51	0.93	0.73	0.83	0.76	0.77
2	Northbound	0.33	0.34	0.14	0.12	0.60	0.20	0.40	0.33	0.33
	Southbound	0.33	0.33	0.14	0.13	0.53	0.18	0.49	0.33	0.35
3	Northbound	0.52	0.50	0.14	0.24	0.75	0.43	0.65	0.53	0.52
	Southbound	0.49	0.52	0.13	0.19	0.68	0.43	0.58	0.47	0.64
4	Northbound	0.94	0.60	0.67	0.26	2.54	0.47	1.11	0.95	0.94
	Southbound	0.60	0.58	0.20	0.22	1.01	0.44	0.72	0.58	0.61
5	Northbound	0.55	0.56	0.08	0.36	0.75	0.53	0.59	0.54	0.57
	Southbound	0.56	0.57	0.06	0.46	0.70	0.49	0.59	0.55	0.57

TABLE 6 SH1N Descriptive Statistics for RST-RMS Rough Macrotexture

Site No.	Direction	RST-RMS Rough Macrotexture (10-80 mm wavelengths), mm								
		Wheelpath Averaged Statistics							Individual Wheelpath Mean Values	
		Mean	Median	Std Dev	Min	Max	Lower Quartile	Upper Quartile	Outer	Inner
1	Northbound	1.61	1.64	0.15	1.19	1.84	1.55	1.71	1.55	1.66
	Southbound	1.45	1.46	0.16	0.97	1.83	1.38	1.55	1.40	1.51
2	Northbound	0.64	0.69	0.36	0.11	1.32	0.32	0.89	0.63	0.65
	Southbound	0.67	0.70	0.37	0.13	1.14	0.31	1.00	0.65	0.69
3	Northbound	1.18	1.22	0.35	0.46	1.65	0.92	1.47	1.19	1.18
	Southbound	1.11	1.11	0.31	0.35	1.64	0.93	1.31	1.09	1.12
4	Northbound	1.35	1.11	0.52	0.47	2.13	0.91	1.84	1.29	1.41
	Southbound	1.25	1.16	0.43	0.41	2.01	0.90	1.55	1.21	1.28
5	Northbound	1.00	1.00	0.17	0.54	1.28	0.97	1.07	0.95	1.04
	Southbound	1.00	1.03	0.10	0.83	1.20	0.88	1.08	0.97	1.04

TABLE 7 SH1N Descriptive Statistics for 5-m SCRIM SFC_{50} Measurements, Northbound

Site No.	SFC_{50} (x 100)								
	Wheelpath Averaged Statistics							Individual Wheelpath Mean Values	
	Mean	Median	Std Dev	Min	Max	Lower Quartile	Upper Quartile	Outer	Inner
1	70.6	71	3.4	44.0	81.5	69.0	72.5	69.7	71.4
2	78.1	78	3.7	61.5	88.5	76.0	80.5	77.0	79.4
3	69.1	70	4.9	45.5	78.5	66.5	72.5	64.0	74.0
4	70.0	70	6.1	34.5	89.0	67.0	72.5	67.0	73.0
5	70.1	70	3.0	57.5	78.0	68.0	72.0	70.0	70.0

in the mean RST fine macrotexture between outer and inner wheelpaths apart from site 3 in the southbound lane, which shows a significant loss of macrotexture in the outer wheelpath. This result typically indicates the presence of flushing (*8*) and is consistent with the RAMM pavement condition ratings for site 3. Similarly, the RST rough macrotexture data show significant differences in texture depth between outer and inner wheelpaths for sites 1 and 4, and the SCRIM skid resistance data for sites 3 and 4, indicating loss of surface seal either through scabbing, flushing, or patching. Again, these findings are generally consistent with the visual survey ratings. However, when considering mean values given in Tables 5 to 7, site 2 is shown to have the lowest macrotexture depth and site 3 the lowest microtexture. In comparison, the normalized RAMM pavement condition ratings given in Table 3 indicate that the greatest loss of surface seal has occurred on sites 1 and 2.

Many of the above anomalies between automatic and manual survey procedures could have been resolved if measurements of macrotexture and skid resistance were made near the center of the lane in addition to the wheelpaths, thereby enabling the degree of surface deterioration to be more readily identified.

Analysis of Continuously Sampled Pavement Distress Data

The following additional analyses were performed on the RST- and SCRIM-derived data for each of the road sections listed in Table 2:

1. Descriptive statistics (mean and standard deviation) based on systematic sampling of a 100-m interval at the start of every 0.5 km and continuous sampling were compared to assess the validity of existing sampling procedures used in walkover surveys;
2. SCRIM data based on 5-, 100-, and 500-m reporting lengths were compared to demonstrate the need to relate intervention levels to reporting levels; and
3. Regressions were performed between all the RST measured variables and RST macrotexture and the SCRIM-derived 50-km/hr SFC to establish the degree of correlation among the pavement defect measures.

Influence of Partial Sampling

Both t and F tests for a 5 percent level of significance were applied to the measures of rutting, RMS fine macrotexture, and 50-km/hr SFC in an attempt to establish whether there were differences between the means and variances derived from 20 percent systematic sampling and those from 100 percent sampling. Unfortunately the minimum reporting length for the RST was limited to 100 m, and so it was not possible to duplicate the 10 percent sampling used in walkover surveys.

With reference to Tables 8 to 10, values of the calculated t-statistic all lie well within the critical interval defined by $t_{0.975}$, so the hypothesis that there is essentially no difference between the means derived from 20 and 100 percent sampling is accepted. Similarly, the F-test shows that there is no significant difference (i.e., $\sigma_1^2/\sigma_2^2 \leq F_{0.025}$) between the two variance estimates, apart from only two cases. These results, when combined, indicate that we can be 95 percent confident that pavement distress data obtained from 20 percent systematic sampling using automatic means is sufficient to correctly infer the condition of the entire network.

Influence of Reporting Length

With 100 percent sampling, an immense amount of data is collected. This can take a considerable time to summarize and analyze. To overcome this problem, outputs from

TABLE 8 Comparison of Sample and Population Means and Standard Deviations—Rutting

Site No.	Direction	No. of 100 m Length Samples		Mean Rut Depth (mm)		Std Dev (mm)		"t-test"		"F-test"	
		20%	100%	20%	100%	20%	100%	$t_{calculated}$	$\pm t_{0.975}$	$(\sigma_1)^2/(\sigma_2)^2$	$F_{0.025}$
1	Northbound	14	68	6.6	7.1	2.8	3.1	-0.552	1.993	1.27	2.71
	Southbound	14	68	7.2	7.1	3.0	3.0	0.112	1.993	1.00	N/A
2	Northbound	6	24	6.0	6.4	1.0	2.2	-0.420	2.05	4.84	6.29
	Southbound	6	24	5.5	6.1	3.1	3.0	-0.420	2.05	1.07	3.18
3	Northbound	5	26	5.5	5.4	3.9	3.4	0.057	2.04	1.32	3.69
	Southbound	5	26	6.1	4.7	2.2	1.6	1.621	2.04	1.89	3.69
4	Northbound	12	60	4.4	4.2	2.7	2.5	0.246	1.997	1.17	2.20
	Southbound	12	60	6.0	5.3	2.9	3.3	0.674	1.997	1.30	3.00
5	Northbound	6	30	3.2	3.3	1.9	1.4	-0.145	2.03	1.84	3.04
	Southbound	6	30	4.7	4.7	4.9	4.9	0	2.03	1.00	N/A

TABLE 9 Comparison of Sample and Population Means and Standard Deviations—Average RST RMS Fine Macrotexture

Site No.	Direction	No. of 100 m Length Samples		Mean RMS Fine Macrotexture (mm)		Std Dev (mm)		"t-test"		"F-test"	
		20%	100%	20%	100%	20%	100%	$t_{calculated}$	$\pm t_{0.975}$	$(\sigma_1)^2/(\sigma_2)^2$	$F_{0.025}$
1	Northbound	14	68	0.85	0.85	0.11	0.10	0	1.993	1.21	2.13
	Southbound	14	68	0.77	0.77	0.09	0.09	0	1.993	1.00	N/A
2	Northbound	6	24	0.26	0.33	0.08	0.14	-1.14	2.05	3.06	6.29
	Southbound	6	24	0.25	0.34	0.06	0.14	-1.48	2.05	5.44	6.29
3	Northbound	5	26	0.63	0.52	0.09	0.14	1.64	2.04	2.42	8.52
	Southbound	5	26	0.44	0.49	0.15	0.13	-0.742	2.04	1.33	3.69
4	Northbound	12	60	1.03	0.94	0.73	0.67	-0.412	1.997	1.19	2.20
	Southbound	12	60	0.58	0.60	0.22	0.20	-0.306	1.997	1.21	2.20
5	Northbound	6	30	0.55	0.55	0.02	0.08	1.00	2.03	16.00	6.24[a]
	Southbound	6	30	0.58	0.56	0.06	0.06	0.724	2.03	1.00	6.24

[a]Sample and population standard deviations significantly different.

TABLE 10 Comparison of Sample and Population Means and Standard Deviations—$SFC_{50} \times 100$

Site No.	Direction	No. of 100 m Length Samples		Mean SFC_{50} x 100		Std Dev (mm)		"t-test"		"F-test"	
		20%	100%	20%	100%	20%	100%	$t_{calculated}$	$\pm t_{0.975}$	$(\sigma_1)^2/(\sigma_2)^2$	$F_{0.025}$
1	Northbound	14	68	69.9	70.5	2.0	2.1	-0.97	1.993	1.10	2.71
2	Northbound	6	23	79.1	78.1	2.7	2.2	0.91	2.05	1.51	3.25
3	Northbound	5	26	70.2	69.1	1.7	2.9	0.80	2.04	2.91	8.52
4	Northbound	12	60	70.1	70.0	2.1	4.8	0.07	1.997	5.22	3.00[a]
5	Northbound	6	30	69.0	70.1	2.3	2.0	1.16	2.03	1.32	3.04

[a]Sample and population standard deviations significantly different.

continuous devices such as RST and SCRIM are reported over length intervals that are typically several orders of magnitude longer than the sampling length interval. For example, the SCRIM machine measures the SFC in each wheelpath at 5-m intervals. However, in a survey of the New Zealand state highway network performed in 1990, the reporting interval was chosen to be 500 m. Such an averaging procedure can result in a significant smoothing of the raw data. Opportunity was therefore taken to compare descriptive SFC statistics calculated on the basis of 5-, 100-, and 500-m lengths for each of the road sections listed in Table 2, particularly in relation to the identification of road sections with less than a specific SFC level. The results of this analysis are given in Table 11.

As expected, mean values are not affected by the averaging process. However, as a consequence of the reduction in the degree of scatter in the data, the standard deviation reduces and the minimum and maximum values converge as the reporting length is increased from 5 to 500 m. More important, the loss of resolution associated with increasing the number of data points averaged results in an incorrect assessment of the true condition of the pavement in relation to the intervention criteria. For example, Table 11 shows that 25 percent of SHN1 between reference stations 915/6.10 and 915/8.71 (site 4) had a wheelpath-averaged SFC less than 0.55 when derived from the source 5 m measurements, yet if 100- or 500-m reporting lengths are used, this pavement section is shown to have skid resistance characteristics that are neither better nor worse than the others investigated.

Accordingly, it is essential that the reporting length and selected intervention levels be consistent with the minimum pavement length that justifies resurfacing and shape correction. Typically, such a length ranges between 20 and 50 m, the lower value applying to urban roads, whereas the higher to rural roads. Furthermore, the source measurements should never be discarded as they can be useful for ranking road sections with nominally the same mean value of pavement defect parameter that is being considered.

Correlations Between Various RST Measures of Pavement Defect

Tables 12 to 16 show how IRI roughness, rutting, and RMS fine and rough measures of macrotexture relate to each other for the five road sections presented in Table 3.

First, it can be seen that the degree of correlations between the various defect measures varies considerably

TABLE 12 Correlation Between RST Measures of Pavement Distress—Site 1, Northbound and Southbound (southbound in parentheses)

	IRI	Rutting	Fine Macro	Rough Macro
IRI	1.0	0.193 (0.059)	0.299 (0.095)	0.248 (0.084)
Rutting		1.0	0.402 (0.073)	0.361 (0.051)
Fine Macro			1.0	0.851 (0.860)
Rough Macro				1.0

TABLE 11 Averaging Effect on SFC Descriptive Statistics

Site No.	Averaging Length	Average SFC Statistics				Length of Section with SFC <0.55	
		Mean	Std Dev	Minimum	Maximum	Lane-Kilometres	% of Surveyed Length
1	5	0.71	0.03	0.44	0.82	0.25	3.7
	100	0.71	0.02	0.65	0.78	0	0
	500	0.71	0.01	0.68	0.72	0	0
2	5	0.78	0.04	0.62	0.89	0	0
	100	0.78	0.02	0.75	0.82	0	0
	500	0.78	0.01	0.76	0.80	0	0
3	5	0.69	0.05	0.46	0.79	0.65	25
	100	0.69	0.03	0.62	0.74	0	0
	500	0.69	0.007	0.68	0.70	0	0
4	5	0.70	0.06	0.35	0.89	1.15	19
	100	0.70	0.05	0.60	0.83	0	0
	500	0.70	0.04	0.61	0.78	0	0
5	5	0.70	0.03	0.58	0.78	0	0
	100	0.70	0.02	0.66	0.75	0	0
	500	0.70	0.01	0.69	0.73	0	0

TABLE 13 Correlation Between RST Measures of Pavement Distress—Site 2, Northbound and Southbound (southbound in parentheses)

	IRI	Rutting	Fine Macro	Rough Macro
IRI	1.0	0.063 (0.114)	0.050 (0.024)	0.080 (0.038)
Rutting		1.0	0.017 (0.015)	0.038 (0.018)
Fine Macro			1.0	0.931 (0.960)
Rough Macro				1.0

TABLE 14 Correlation Between RST Measures of Pavement Distress—Site 3, Northbound and Southbound (southbound in parentheses)

	IRI	Rutting	Fine Macro	Rough Macro
IRI	1.0	0.189 (0.041)	0.042 (0.006)	0.061 (0.008)
Rutting		1.0	0.019 (0.010)	0.032 (0.032)
Fine Macro			1.0	0.945 (0.782)
Rough Macro				1.0

TABLE 15 Correlation Between RST Measures of Pavement Distress—Site 4, Northbound and Southbound (southbound in parentheses)

	IRI	Rutting	Fine Macro	Rough Macro
IRI	1.0	0.562 (0.497)	0.057 (0.114)	0.135 (0.156)
Rutting		1.0	0.159 (0.050)	0.271 (0.081)
Fine Macro			1.0	0.682 (0.957)
Rough Macro				1.0

TABLE 16 Correlation Between RST Measures of Pavement Distress—Site 5, Northbound and Southbound (southbound in parentheses)

	IRI	Rutting	Fine Macro	Rough Macro
IRI	1.0	0.032 (0.482)	0.000 (0.103)	0.000 (0.025)
Rutting		1.0	0.113 (0.168)	0.096 (0.100)
Fine Macro			1.0	0.957 (0.917)
Rough Macro				1.0

between a northbound and southbound run for a particular section. This result suggests that the lane direction of the pavement condition survey should be recorded in RAMM.

Second, RMS fine and rough macrotexture measures are well correlated and so only one measure of macrotexture appears necessary.

Third, significant correlations sometimes occur between IRI roughness and rutting, and rutting and macrotexture. Such correlations should be investigated further to establish whether they can be used to distinguish between roughness effects caused by rutting and shoving, and macrotexture losses caused by scabbing and flushing.

Further Work

The timing of the RST and SCRIM surveys necessitated the use of the 1989 walkover visual survey data for the comparative study. Unfortunately this was far from ideal. First, the automatically and manually acquired pavement condition data were separated by more than 1 year. Second, and more important, 1989 coincided with the first year that RAMM condition rating surveys were conducted on New Zealand's state highway network, so the data were not as accurate as they should be because of unfamiliarity by some raters with correct measurement procedures. This problem has now been addressed by the introduction of formal training and implementation of QA procedures.

Accordingly, a contract has been let in September 1993 by Transit New Zealand for a more extensive 3-year trial by a vehicle equipped to determine longitudinal roughness, flushing, and rutting. This 3-year trial will enable the year-to-year variability of automatically collected condition rating data to be assessed and a more extensive investigation of the degree of correlation between the automatic and manual data collection methods.

Conclusions

The reported study, using RAMM pavement condition ratings and 100 percent sampling of various pavement condition parameters at highway speeds using continuous measuring devices such as the SCRIM and the RST, has led to the following conclusions:

1. Variability in manually acquired condition rating data can be minimized through appropriate attention to the training of raters and implementation of quality assurance procedures designed to ensure consistency in the measurement of pavement defects.

2. It was found that the RST's pavement condition indexes investigated (rutting and macrotexture) do not generally correlate well with traditional pavement condition ratings obtained using visual or manual survey procedures. Nevertheless, because of the measurement repeatability that can be achieved with the RST, it has value as a survey tool, particularly in regard to periodic monitoring of the network to detect pavement condition changes over 3- to 5-year intervals. The resulting data bases would be useful for assessing the effectiveness of existing design, construction and maintenance procedures, and also for deriving and validating pavement distress prediction models. Survey lengths corresponding to only 10 to 20 percent of the total sealed state highway network should be adequate for such a purpose.

3. The value of making continuous texture depth measurements could be considerably enhanced through relating these measurements to road geometry, in particular horizontal curvature, as scabbing (chip loss) commonly occurs on the outside of the curve because of vehicle cornering forces and by making an additional texture depth measurement in the center of the lane to supplement those in the wheelpaths so that the degree of texture loss can be established.

4. With 100 percent sampling, an immense amount of data are collected. These data can take a considerable time to summarize and analyze. To overcome this problem, outputs from continuous measuring devices are reported over length intervals that are typically several orders of magnitude larger than the sampling length interval. A limited study of the influence of reporting length was performed on SCRIM data. This showed that mean values were not affected by the averaging process. However, as a consequence of the reduction in the degree of scatter in the data, the standard deviation reduces and the minimum and maximum values converge as the reporting length is increased. More important, the loss of resolution associated with increasing the number of data points averaged results in an incorrect assessment of the true condition of the pavement in relation to intervention criteria. Accordingly, it is essential that the reporting length and intervention levels selected be consistent with the resolution of the measuring device and also the minimum pavement length that justifies resurfacing and shape correction.

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Repeatability and Reproducibility of Manual Pavement Distress Survey Methods

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Manual survey costs usually increase with the decrease in the subjectivity of the method chosen because of the inclusion of more details in the survey. Thus, it is important to find the trade-off between cost and subjectivity. As subjectivity is related to repeatability (i.e., the capability of producing identical results by several rounds of measurement done by the same raters) or to reproducibility (i.e., the capability of producing identical results by different raters), these values were measured for both the United States Air Force (Pavement Condition Index) [USAF (PCI)] and Washington State Department of Transportation (Distress Rating) [WSDOT (DR)] procedures, as well as for the Israeli one-score method. A walkover survey was employed for the USAF (PCI) procedure, as well as both walkover and windshield surveys for the WSDOT (DR) process and the two recent Israeli procedures [DR and Distress Number (DN)]. It was found that the repeatability and reproducibility of the Israeli quick windshield survey do not differ substantially from those of the USAF (PCI) walkover analysis. The standard deviations of score differences associated with these methods generally yield similar values in the range of 8 to 13 points, with some exceptions. Moreover, a highly significant correlation has been found between the detailed walkover PCI values and those of the DN in the quick Israeli windshield survey. Accordingly, the Israeli windshield DN method is highly recommended for use in any PMS network level. In addition, for rating distresses in greater detail, the walkover WSDOT (DR) survey is also endorsed to save time and money. As for the windshield WSDOT (DR) survey, some modifications are still called for to make it a reliable method.

It is well known that periodic and accurate assessment of pavement distress condition is of critical importance for any pavement management system (PMS). Accurate and timely information lead to better decisions regarding investment policy. Such resolutions are crucial for developing a program that will render the best service to the public per dollar invested.

With the aim of achieving that objective, for many years, manual distress surveys have been performed by raters who walk or drive along the road and classify the distress on the basis of their visual observations. Several procedures have been developed for these surveys, including some comprehensive pavement distress identification manuals (*1–5*).

The most subjective procedure is the windshield survey, in which the rater assigns the final numerical score on a predefined scale for the state of overall distress. Conversely, the least subjective procedure of the manual distress survey methods is the walkover survey where the individual distress items are rated by type, extent, and severity, whereupon the final score is calculated from deduct values. It is also commonly believed that the greater the number of details incorporated in this survey, the more extreme the objectivity of the survey method.

That relationship between objectivity (or subjectivity) and the number of details incorporated in various methods of manual distress surveys is dealt with in this paper through a comparison of these methods' repeatability and reproducibility levels, as specified in the following section.

ACCURACY, REPEATABILITY, AND REPRODUCIBILITY

Making any measurement always involves errors, and no measurement is ever exact. Generally, measurement errors originate from a number of sources, but can be attributed to one of the two following categories: systematic or random errors, as shown by Equation 1.

$$d_{ij} = d_i^* + a_j + \epsilon_{ij} \tag{1}$$

where

- d_{ij} = measured value for pavement section i in the surveyed network, by a rater j for one round of measurement or by one rater for round of measurement j;
- d_i^* = true value for pavement section i in the surveyed network;
- a_j = systematic measurement error (i.e., an additive bias) specific to rater j or to measurement round j; and
- ϵ_{ij} = the random error of measurement specific to pavement section i in the observed network, by rater j for one round of measurement or by one rater for round of measurement j, both with $E(\epsilon_{ij}) = 0$.

In Equation 1, the systematic measurement error, a_j, is related to the measurement's accuracy. Its value stems from the difference between the mean of a set of measured values for any pavement section i and the true value for that section. Also, in Equation 1, the random errors are categorized by the variance of the ϵ_{ij} values. For the instance of several rounds of measurement with one rater, this variance is termed repeatability (or sometimes precision), indicating the capability of producing identical results by one rater in several rounds of measurement. For the other case of one measurement cycle with several raters, the variance is named reproducibility, indicating the capability of producing identical conclusions by different raters, or in other words, the ability to achieve consistency among manual survey raters. A graphical illustration of accuracy, repeatability, and reproducibility is given in Figure 1.

The calculation of accuracy was outside the scope of this study. This estimate is only possible when the true values, d_i^*, are known. However, as consistency is generally considered to prevail over accuracy (*15*), no effort was made in this study to attain the true d_i^* values. Conversely, the calculation of repeatability or reproducibility is done with the aid of the following correlation (*9*):

$$\mathrm{Var}\,(d_{i1} - d_{i2}) = \mathrm{Var}\,(\epsilon_{i1}) + \mathrm{Var}\,(\epsilon_{i2}) - 2\mathrm{Cov}\,(\epsilon_{i1}; \epsilon_{i2}) \tag{2}$$

In this relationship $\mathrm{Var}\,(d_{i1} - d_{i2})$ denotes the discrepancy between readings of two rounds of measurement, 1 and 2, with one rater, or between readings of two different raters 1 and 2 for one round of measurement. In addition, in the equation, $\mathrm{Cov}(\epsilon_{ij}; \epsilon_{ij})$ denotes the covariance of the random errors and is thus equal to zero. Now, assuming that the variance of the random errors is independent of the rater or of the round of measurement, the following final expression may be obtained:

$$\mathrm{Var}\,(\epsilon_j) = 0.5\,[\mathrm{Var}\,(d_{i1} - d_{i2})] \tag{3}$$

where, $\mathrm{Var}\,(\epsilon_j)$ is the repeatability or the reproducibility of the measurements. It should be indicated that the objectivity or subjectivity described in the previous section is evaluated by the repeatability or reproducibility of any given manual means of survey.

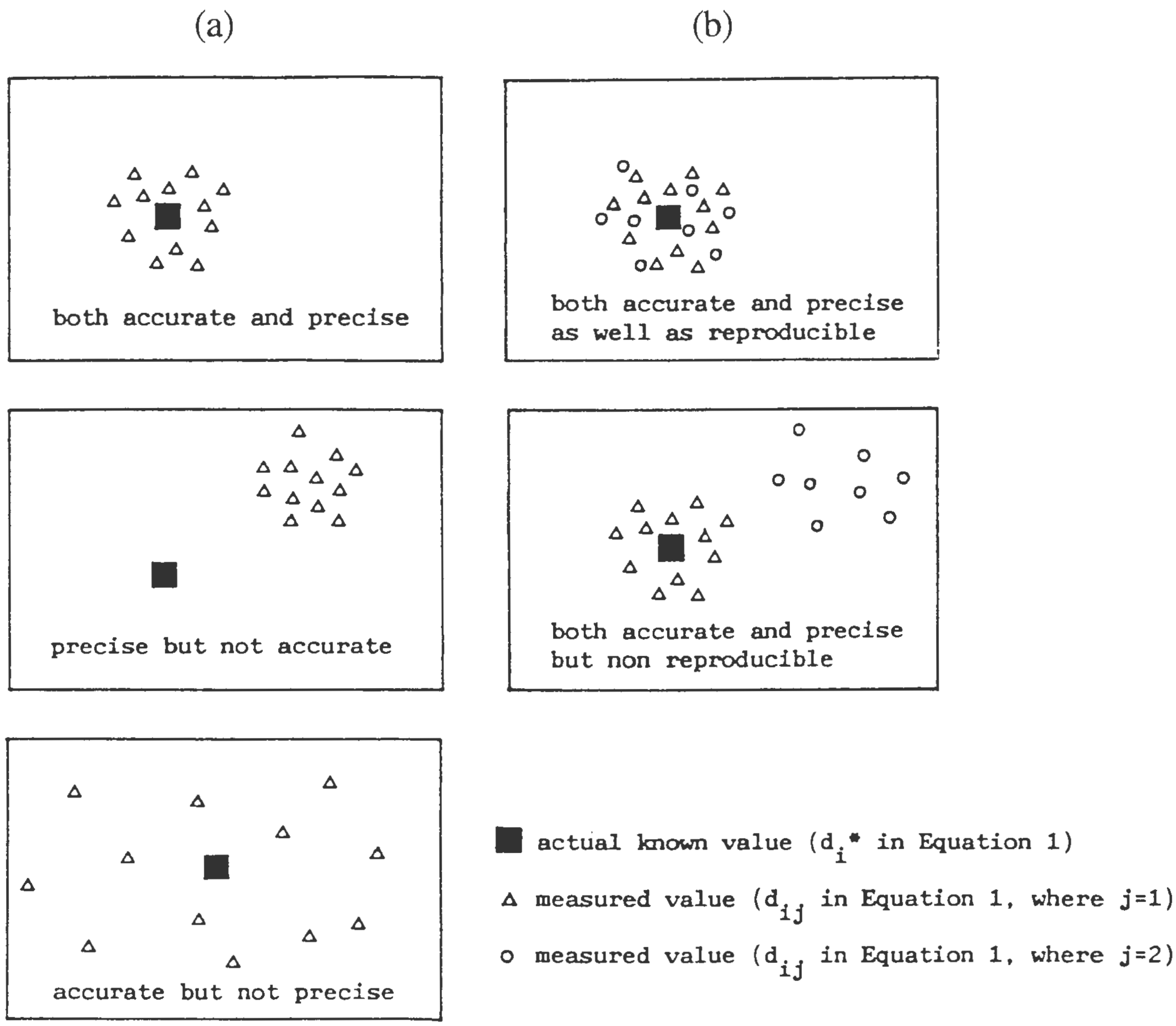
SHORT DESCRIPTION OF METHODS EMPLOYED

Four survey methods were fully or partially employed in the study. These were the United States Air Force (USAF) PCI method (*2*), the Washington State Department of Transportation (WSDOT) DR method (*5*), and the the modified DR and DN methods derived from recent Israeli practice. The PCI and DR modes use a procedure that associates deduct (penalty) points with specific distress type, severity, and extent combinations. These points are summed and then subtracted from some upper limit or maximum value, usually 100.

Following these two methods, the quick Israeli method is based on the ordinary WSDOT survey procedure. However, in the proposed Israeli method, the survey is conducted exclusively from a moving vehicle to make it very swift. Also, in this modified method, the length of each surveyed pavement section is its entire span (usually 1 km). The DR values are calculated in the same manner used in the WSDOT procedure, using its original deduct values. In addition, it should be mentioned that in this method, experienced highway engineers are usually employed, who also present the DN scores, where each rater assigns the final numerical score (on a predefined scale) for the overall distress conditions for each surveyed segment. The predefined scale of these DN scores ranges from 1 (an undamaged condition) to 5 (situation of general failure), as shown in Figure 2. More details are presented in a work by Livneh (*14*).

OBJECTIVES

Survey costs decrease proportionally with the decline in the objectivity of the survey method. Thus, it would be interesting to find the trade-off between cost and objectivity. This trade-off aims to originate from the following objectives:



Note: Other combinations of accuracy precision and reproducibility are possible

FIGURE 1 Illustration of (*a*) accuracy and precision (*8*) and (*b*) reproducibility.

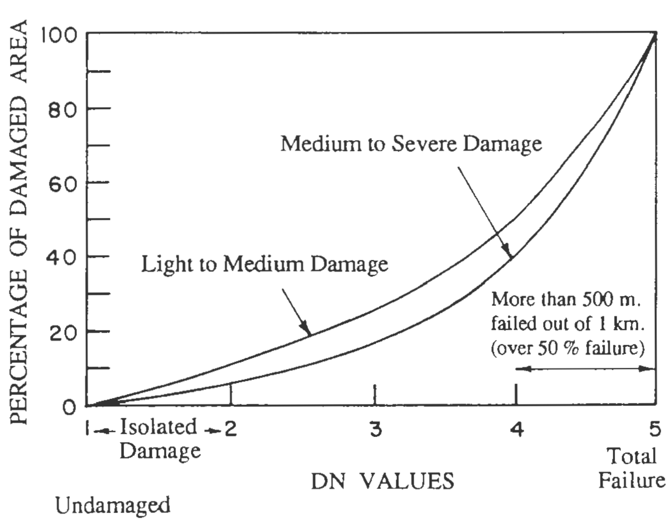


FIGURE 2 DN evaluation curve.

1. The evaluation of repeatability and reproducibility of the survey methods employed in this study, mainly the USAF (PCI) walkover procedure and the suggested Israeli (DN) quick windshield single-score method;
2. Determination of the statistical feasibility of the suggested Israeli (DN) quick windshield method in terms of its statistical comparison with the USAF (PCI) technique; and .
3. Measuring the survey time or speed of each method implemented in this study.

As previously suggested, to meet the above objectives, this paper presents statistical analyses of site studies carried out both in Israel and abroad. The Israeli analyses included site survey of the DN and PCI values on numerous road sections, in one round of measurement with various raters, and sometimes in two rounds with one rater. Some limited DR values were also surveyed. The various statistical analyses performed on the survey methods are presented in the following sections.

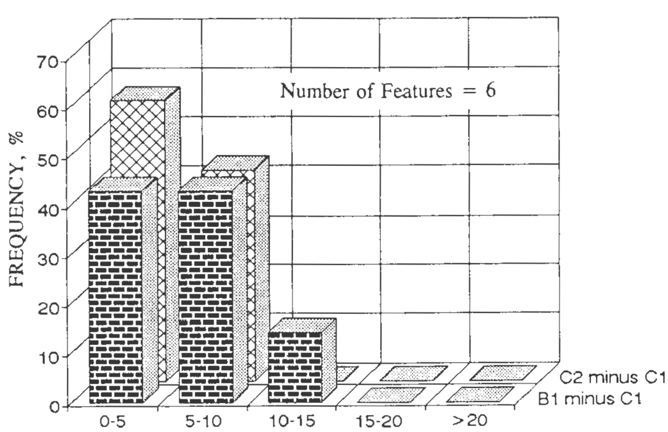
Statistical Analysis of PCI Method

The basic principle underlying the PCI method is that the PCI value calculated for any pavement section from the survey outputs would be almost identical to the PCR values assigned by a panel of experts as their final numerical score for the overall distress condition. Thus, to detect the identity, field surveys composed of various expert raters were conducted by the USAF at various locations. By these means, the distress definitions and their deduct curves were also verified. Some of the results yielded by these surveys are shown in Figures 3 and 4, and also in Table 1.

Figure 3 is based on the PCR values assigned by three expert raters (C1, B1, and C2) for six given features, each comprising 6 to 12 surveyed units. Figure 4 is based on the above values assigned by another team of four expert raters (C1, C2, C3, and C4) for three other given features, each comprising 9 to 22 surveyed units. These figures give the frequency distribution of the standard deviation of PCR differences by feature, as an indicator of the reproducibility of the procedure. In addition, Table 1 shows the overall mean values of the standard deviation of score differences (see line 6 in Table 1). Both figures indicate that the frequent state for the standard deviation of the above differences may be in the range of 5 to 10 points and occasionally in the range of 10 to 15 points. As for the mean values of the above standard deviations, these are dealt with in another section "Overall Comparison of Means."

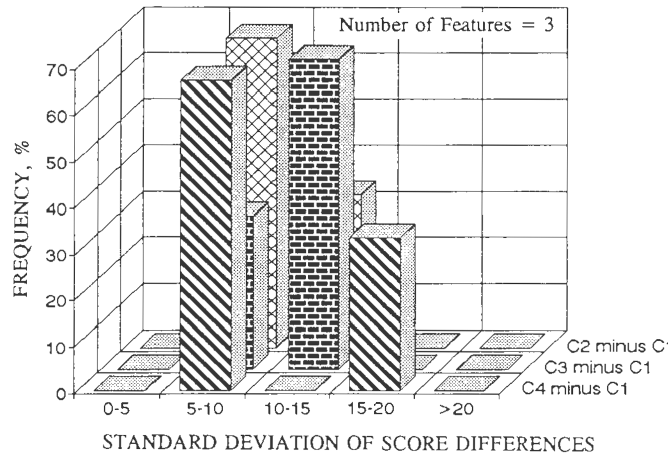
A comparative study was carried out, along the same lines, in Israel (in almost uniform clear weather conditions), to evaluate the statistical parameters of the PCI values, thus supplementing the PCR parameters. The frequency distribution results for the seven features recently observed (each feature comprising 6 to 15 surveyed units) are given in Figure 5; in addition, the overall mean results are shown in Table 1 (see line 6). Due to this figure, the frequent state for the standard deviation of the above PCI value differences may be in the range of 5 to 10 and occasionally, even in the range of 10 to 15 points. Standard deviation results were also recorded in the range of 20 to 25 points, indicating very poor reproducibility of the measured values in the PCI method. Perhaps these inferior results may be ascribed to the possibility that the raters lacked sufficient experience, but this probability cannot detract from the fact that the PCI procedure is not preferable to the PCR approach from an impartial view, as one might expect.

In addition to the above survey, another, aimed at detecting repeatability values, was recently carried out in Israel (6). A 4 800-meter road segment was observed on two different occasions, both in clear weather conditions (about 2 weeks apart), by the same two raters. The survey mode entailed the DR and the DN walkover methods for section lengths of approximately 50 to 60 m, the DR and DN windshield methods for section lengths of approximately 220 m, (by grouping four 50- to 60-m sections together), and the PCI method for the matching approximately 50- to 60-m segments. The standard deviations of rating differences obtained in the two surveys and the mean of these rating differences are given in Table 2. This table shows that the standard deviation of PCI differences measured for the 50- to 60-m pavement sections in two rounds of measurement was 13 points. This estimate is similar to the foregoing and hence strengthens the above prevalent conclusions regarding the procedure's subjectivity.



Note: C1, C2 and B1 are the respective scores of the 3 raters.

FIGURE 3 Frequency chart for standard deviations of PCR score differences (*11*) (asphalt pavements only).



Note: C1, C2, C3 and C4 are the respective scores of the 4 raters.

FIGURE 4 Frequency chart for standard deviations of PCR score differences (12) (asphalt pavements only).

TABLE 1 Overall Statistical Parameters of Rater Differences in Various Survey Methods

Line No.	Survey Method	Walkover PCR		Walkover PCR			Walkover PCI		DN	
1	Fig. No.	3		4			5		10	
2	Score Differences of Raters	B_1-C_1	C_2-C_1	C_2-C_1	C_3-C_1	C_4-C_1	A-B	A-C	A-C	B-C
3	Number of Sites or Features(s)	6	6	3	3	3	7	7	9	8
4	No. of Total Surveyed Units (N)	52	59	40	40	40	85	85	410	391
5	Mean of All Score Differences	-0.3	-0.8	-0.3	-1.2	-0.8	4.2	2.0	-0.7	-3.2
6	Mean SD of All Score Differences	8.3	5.5	9.0	10.2	10.8	16.2	15.7	8.8	13.2
7	Root of Eq.4 Numerator	7.9	5.9	11.9	15.8	20.1	33.8	30.5	18.4	45.7
8	Root of Eq.4 Denominator	7.8	5.3	8.3	9.4	9.3	14.2	12.7	8.6	12.0
9	Calculated F Statistic	1.02	1.26	2.04	2.67	4.67	5.68	5.75	4.67	14.6
10	Tabulated F Statistic	2.30	2.28	2.86	2.86	2.86	2.12	2.12	1.90	2.56
11	Null Hypothesis (μ=0)*	A	A	A	A	R	R	R	R	R

* R denotes reject and A denotes accept.

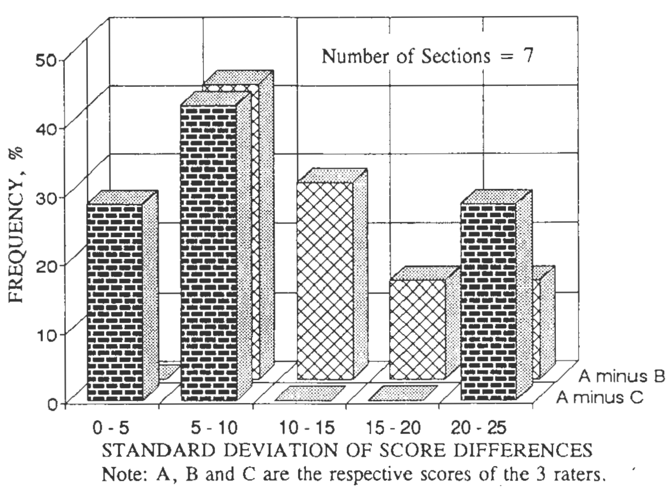


FIGURE 5 Frequency chart for standard deviations of PCI score differences (asphalt pavements only).

Statistical Analysis for DR Method

The DR method was recently applied by WSDOT (7) as one of the comparative means used to evaluate the consistency and compatibility of the Pavedex Pas 1 automated distress measuring device. In the above study, three sets of walkover measurements by three different raters were compared to determine the consistency among the raters, on a total sample size of 193 pavement sections, each 160 in length. As shown in Figure 6, less than 20 percent of the pavement sections were consistently evaluated by all three raters with respect to the condition of transverse and longitudinal cracking. Regarding the alligator cracking, about 35 percent of pavement sections were consistently rated by all three raters. Nevertheless, as one would expect, these data show that raters are much more consistent than random: at least 28 agreements were at-

TABLE 2 Comparison of Standard Deviation Values of Measurement Differences Obtained by One Rater in Two Measurement Rounds (Repeatability) (6)

Survey Method	PCI	DR		DN*	
	Walkover	Walkover	Windshield	Windshield	Rideover
No. of Surveyed Units	92	92	25	92	25
SD of Measurement Differences	12.6	12.2	22.0	10.8	11.4
Mean of Measurement Differences	-6.2	6.8	15.5	1.4	-4.5
Calculated t-Statistic	4.72	5.35	3.52	1.24	1.97
Tabulated t-Statistic for α=0.05	1.99	1.99	2.06	1.99	2.06
Null Hypothesis** (μ=0)	R	R	R	A	A

* Scores were translated into a 0-100 scale.
** R denotes reject and A denotes accept.

tained out of 193 evaluations, far more than the random expectation of only a maximum of 6 agreements out of these 193 evaluations. These six calculated agreements are derived from a binomial distribution for the above, as this distribution is appropriate for executing a randomness test for the problem under discussion (7).

This study did not include a statistical analysis for the overall DR values. However, their repeatability level can be estimated from the Israeli study carried out on 92 pavement sections, 50 to 60 m long, along with the PCI research. As shown in Table 2, this value is equal to 12 points and is analogous to that determined from the so-called "true" PCI values, thus indicating no inferiority to the PCI method.

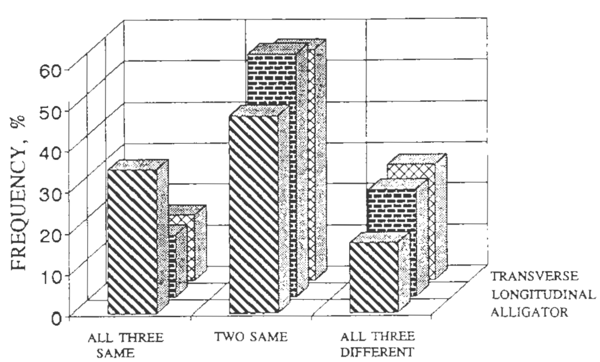


FIGURE 6 Frequency chart for consistency of distress measurements among three raters using the WSDOT method (7).

Table 2 also gives the results for the windshield DR study implemented with the above walkover DR study on twenty-five 200- to 220-m pavement sections along the same stretch of road. The repeatability of the windshield DR values was found to be very poor, indicating difficulties in classifying distress type and its correct category while riding a vehicle.

Statistical Analysis for DN Method

The high relative capability of the DN rating may be first indicated by the results recently yielded in Israel for 236 surveyed pavement sections, each 1 km or more long. The DN values for these sections were assigned by a two-rater team. Together with this evaluation, detailed parameters were also measured for calculating the PCI values for each sample unit in the pavement sections, according to the USAF procedure. The outcome is given in Figure 7. In this figure, PCI is the average PCI estimate for a pavement section, calculated from the sample units' PCI values, and DN is the average DN score assigned by the two raters for the pavement section's entire length. The statistical correlation shown in Figure 7 is very close to the equality line, thus manifesting the relatively high intensity of the DN method.

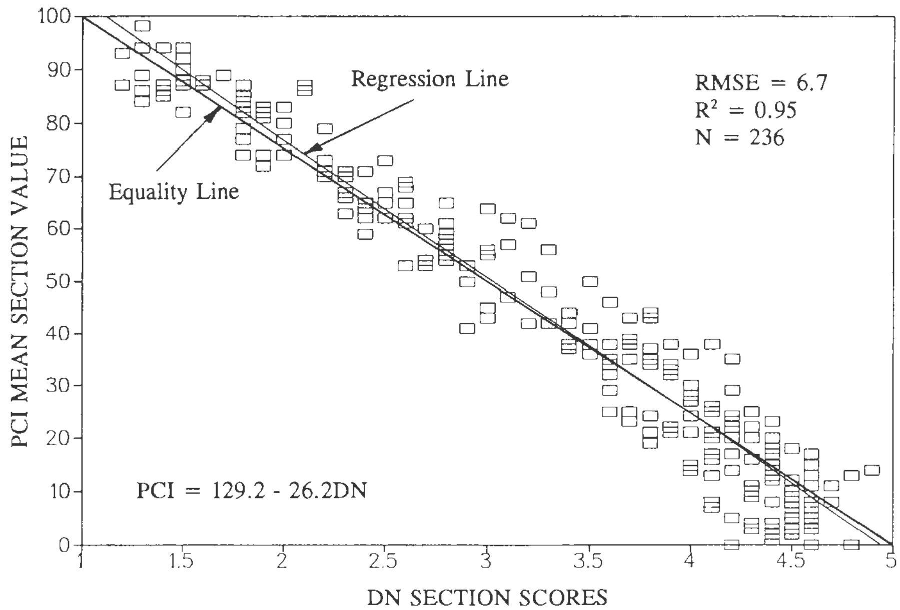


FIGURE 7 Relationship between average PCI scores and DN scores for surveyed sections.

It is also of interest to compare the PCI-DN correlation with that of the PCI-PCR, where the applied PCR values are the average of those assigned by the rater-team. This latter correlation is shown in Figure 8 for the data of Figure 3, and in Figure 9 for the conclusions of Figure 4, indicating that the statistical strength of the PCI-DR relationship is similar to that of the PCI-DN correlation, both in terms of R^2 and RMSE values and in their closeness to the respective equality lines.

In addition, a windshield DN study was carried out by three raters in clear weather conditions (A, B, and C), who surveyed a number of features at eight given sites, each comprising 9 to 92 surveyed units. The results are given in Figure 10 and Table 1, indicating that in the frequent state, the standard deviation of score differences is in the realm of 5 to 10 (following conversion of the DN scale to the 0 to 100 PCI scale). Again, these values are similar to those yielded for both the PCR, walkover, DR, and PCI

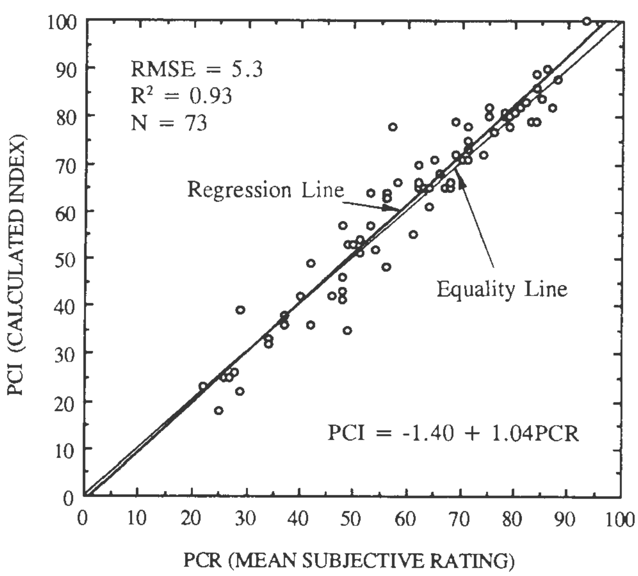


FIGURE 8 Correlation between PCI and PCR in Construction Engineering Research Laboratory's (CERL's) tests (*11*).

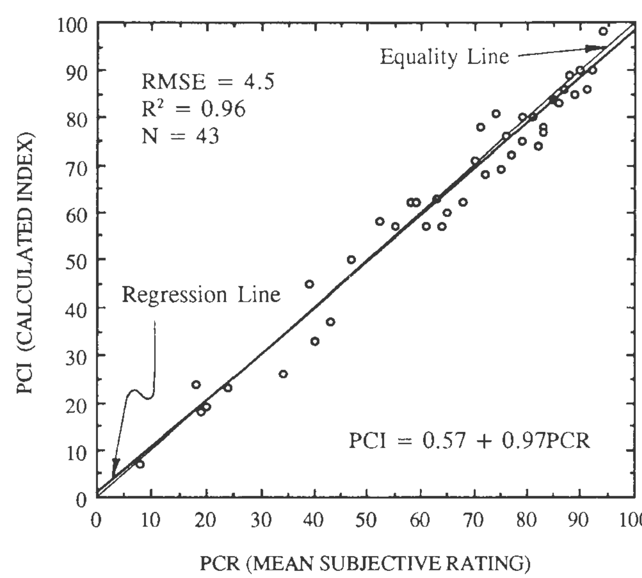
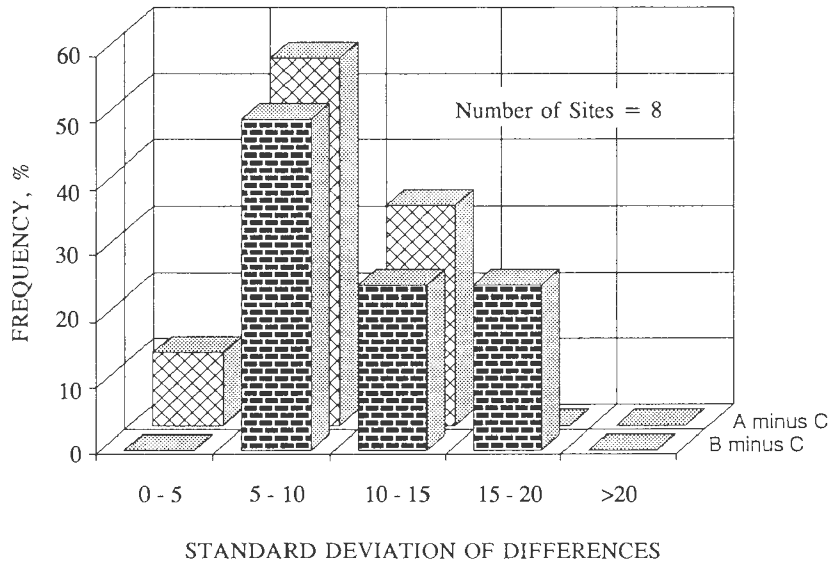


FIGURE 9 Correlation between PCI and PCR in CERL's tests (*12*).



Note: A, B and C are the respective scores of the 3 raters

FIGURE 10 Frequency chart for standard deviations of DN score differences following conversion to a scale from zero to 100 (asphalt pavements only).

values. Hence, it can be stated that the results of the windshield DN survey can be viewed as corresponding to about the same reliability level as more detailed walkover procedures, such as the walkover DR and the PCI methods. Regarding the latter, better results were obtained with the windshield DN method.

This conclusion is also confirmed by the repeatability values for the windshield and walkover DN survey methods shown in Table 2. Moreover, all the standard deviation values in scores of differences shown in Table 2 are identical, except the windshield DR method.

Overall Comparison of Means

In addition to the statistical comparison made in the previous sections, an overall comparison is made here, which includes the comparison of means. This enables one to determine whether the difference in accuracy (i.e., the contrast in the systematic additive error, a_j) for several rounds of measurement with one rater, or for several raters with one round of measurement, is statistically insignificant. For a zero value, one may reiterate that the consistency between raters or rounds of measurements is high, perhaps thus indicating high levels of accuracy.

The appropriate statistical analysis for the above comparison of means is the randomized paired comparison F-test, as depicted elsewhere (9). For reasons of clarity, one may assume that the standard deviation of the score variations for all given sites or features are identical (i.e., that σ_s = const for $s = 1 \ldots S$. This assumption leads to computed F_0 statistic, which is exactly distributed $F_{\alpha, s, N-s}$:

$$F_0 = \frac{\frac{1}{S}\sum_{s=1}^{S} N_s \hat{\mu}_s^2}{\frac{1}{N-S}\sum_{s=1}^{S}(N_s - 1)\sigma_s^2} \tag{4}$$

The above statistic is used to examine the zero joint hypothesis that $\sigma_s = 0$ for $s = 1 \ldots S$, that is,

$$H_0{:}\mu_s = 0, s = 1 \ldots S \tag{5}$$

where

- μ_s = true and $\hat{\mu}_s$ = calculated mean of the differences of scores for a given site or feature,
- σ_s^2 = true and $\hat{\sigma}_s^2$ = the calculated variance of the differences of scores for a given site or feature,
- N_s = number of sample units literally surveyed on a given site or feature s,
- N = total number of sample units surveyed on all given sites or features (i.e., $N = N_1 + N_2 + \ldots N_s$); and
- S = number of site or feature s.

Now if

$$F_{\alpha, S, N-S}(\text{tabulated}) < F_0 \text{ (calculated)} \tag{6}$$

the above null hypothesis (Equation 5) that μ_s is zero jointly for all the S surveyed sites or features is totally rejected (i.e., $\mu_s \neq 0$) with an α significance level.

Table 1 gives the results of the F-test. It may be concluded that the acceptance or rejection results of the null hypotheses of the various survey methods are inconsistent, and it can therefore be stated that one cannot favor any particular survey method over another as regards its accuracy, for which the μ_S values serve as a reliable indicator. Similar results were obtained by means of a *t*-test conducted on the survey results given in Table 2.

In addition to those conclusions, Table 1 also shows that, in general terms, the reproducibility of the employed survey methods (i.e., the DR, DN, and PCI) is essentially similar as their overall mean standard deviation of score differences (see line 6, Table 1) and does not vary considerably from one survey method to another. However, it is also evident that the mean standard deviation values for the PCI were the worst, and the mean standard deviation values for the PCR were usually superior. This outcome indicates that the reliability of the Israeli quick windshield DN method as measured by the standard deviation value of score differences (i.e., 11 points, see Table 2, or 9 to 13 points, see Table 1) is essentially similar to that of the walkover DN survey (i.e., 11 points, see Table 2), or even that of the walkover PCR survey performed with the detailed PCI procedure correlation (i.e., 8 to 11 points, see Table 1). Moreover, this conclusion is supported by the fact shown in Table 2 that the repeatability and reproducibility of the Israeli quick windshield DN survey do not differ substantially from those of the walkover PCI survey and are sometimes superior (i.e., 16 points, see Table 1).

Sampling Procedure and Measured Survey Time

To evaluate the work input essential for the various survey methods discussed in this paper, some deliberation should first be given to the statistical feasibility of the inspection by sample procedure. It is well known that in the PCI method, sample inspection of every unit in a pavement section may require considerable effort, especially if the area is large. The time and effort involved in frequent surveys of an entire section subjected to heavy traffic volume may be beyond available human resources, funds, and time. Therefore, a sampling plan is needed to allow adequate determination of the PCI by inspecting only a portion of the sample units in a pavement section.

The number and location of sample units to be inspected depends on the inspection's objective. If the purpose is to determine the overall condition of the pavement (in the network level), then a survey of one or two sample units per section may suffice. These should be selected to represent the overall condition of the section. If the aim is to ascertain the detailed distress conditions of the pavement (in the project level), then more sampling should be performed. The minimum number of sample units (n_s) to be inspected should provide a reasonable estimate of the true mean PCI of the pavement section. Customarily, one aims to attain an estimated PCI value within ±5 points of the true mean PCI, about 95 percent of the time. The relevant expression for calculating this is (*10*):

$$n_s = \frac{N_s\sigma_m^2}{\frac{e^2}{4}(N_s - 1) + \sigma_m^2} \tag{7}$$

where

N_s = total number of sample units in the pavement section equal to or greater than 3,
e = allowable error in the estimate of the section PCI (e is usually 5 points), and
σ_m = standard deviation of the measured PCI values of all N_s points therein.

Equation 7 is true only if the standard deviation of the random error is zero. As this is erroneous, the correct expression for the $\alpha_i = 0$ case is

$$n = \frac{N_s\sigma_p^2}{(N_s - 1)\left[\frac{e^2}{4} - \sigma_e^2\right] + \sigma_p^2} \tag{8}$$

$$\sigma_p^2 = \sigma_m^2 - \sigma_e^2 \tag{9}$$

where σ_p is the standard deviation of the inherited heterogeneity of the product process (i.e., product variability), or, in other words, the standard deviation of all "true" PCI values across the given section (i.e., without any random measurement errors); and σ_e is the standard deviation of the random measurement error ϵ_i. According to Equation 8, when $\sigma_e^2 \geq e^2/4$ all N_s sample units of a given section should be surveyed. In such circumstances, it may be concluded that the estimated mean PCI is within $\pm 2\sigma_e$ of the true mean PCI about 95 percent of the time. Consequently, from a practical point of view, all the N_s sample units should be examined, and the anticipated e will exceed the desired 5 points and is as high as $\pm 15 \times 2/\sqrt{2} = \pm 20$ points.

In light of the above, the comparison of the survey time consumed by raters in any survey method should be made by inspecting the entire samples unit of the section. It should be emphasized that such a comparison is needed also for the network level, as the recommendation of the PCI method of inspecting only two representative sample units only out of the entire sample units in the section (2) is also incompatible with the statistical findings. Table 3 shows the measured time and the speed of the survey on a 4 800-meter road segment. As mentioned, this segment was divided into ninety-two 50- to 60-m pavement section, or alternatively, into twenty-five 200- to 220-m pavement sections.

The values given in Table 3 are compatible with those reported in the technical literature. For instance, the sur-

TABLE 3 Survey Time and Survey Speed For Two-Lane, 4 800-m Road Segment in Israeli Study (6)

Survey Method	Mode of Manual Survey	No. of Sections Surveyed	Survey Time In First Survey Round - in Minutes	Survey Time In Second Survey Round - in Minutes	Average Survey Speed - in Km/h
DN	Walkover	92	80	90	4.4
	Windshield	25	25	25	11.5
DR	Walkover	92	205	200	3.1
	Windshield	25	35	45	7.2
PCI	Walkover	92	430	425	0.7

vey speed for the New York State Thruway Authority (NYSTA) PMS distress windshield survey is reported to be around 8 to 16 km/hr (*13*) and the WSDOT hand-mapping walkover survey is said to proceed at a speed of about 0.2 km/hr (*7*).

According to Table 3, the quickest survey method is, as expected, the windshield DN, and the slowest survey procedure is the walkover PCI method. The ratio of the time required by these is about 1 to 16. This ratio is reduced to 1 to 5 when the windshield DN method is replaced by the walkover DN. These survey time ratios should be appraised when adopting a method for practical application from among the manual survey methods discussed.

CONCLUSIONS

The reliability of the Israeli quick windshield DN method, as measured by the standard deviation value of score differences (i.e., 11 points, see Table 2; 9 to 13 points, see Table 1) is essentially similar to that of the walkover DN survey (i.e., 11 points, see Table 2) or even that of the walkover PCR survey carried out in connection with the calibration of the detailed PCI procedure (i.e., 8 to 11 points, see Table 1). Moreover, this conclusion is supported by the fact that the repeatability and reproducibility of the Israeli quick windshield DN survey do not differ substantially from those of the PCI walkover survey and are sometimes superior (i.e., 16 points, see Table 1).

It was determined in an Israeli comparative study that a highly significant correlation exists between the calculated PCI values and the surveyed DN values, similar to those of the PCI-PCR correlations. Thus, the Israeli windshield method is highly endorsed for use in any network level PMS survey if an overall rating alone is needed. Also the statistical analysis for the sampling procedure indicates that the DN method is preferable to the detailed walkover PCI method even when this PCI method initializes a limited sample of 2 units only of all units in the section, as suggested by PCI in its original procedure.

In addition, if it is necessary to rate distresses (say for the project level) in some detail, the walkover DR survey for all the sample units is also highly endorsed as a reasonable trade-off between the additional information gained by a more detailed method and its survey cost. It should be stressed that the ratio of the most detailed walkover PCI survey to the least detailed walkover DN survey is around 1:2. One should recall that because a distress survey is an intensive data collection activity, only a limited number of distress types can be recorded. Thus, for each type of pavement appraised, it is critical to monitor only those distresses that provide significant input to a particular agency's maintenance and rehabilitation decision making, and this is implemented in the WSDOT procedure.

As a consequence of this study, the windshield DR method cannot be a substitute to the walkover DR method as a more rapid alternative, because of its poor repeatability (i.e., standard deviation of score differences of 22 points, see Table 2). To increase this potential, it is perhaps worthwhile carrying out the windshield DR survey along the same basic guidelines identified with the windshield NYSTA PMS distress survey (*13*). In this survey method, three raters, traveling in a van, are assigned only specific distress types (out of all the surveyed types) to monitor and rate.

In addition to this variability introduced by individuals and their interpretations of the distress scales, many other factors in such windshield surveys may affect the survey repeatability or reproducibility. Such factors include seat position, rater fatigue, sun's angle of incidence, pavement dampness, light intensity, and so forth. These factors should be taken into consideration when applying the windshield DR or DN survey. This can be implemented by dictating only predefined constant conditions, such as the identical time of year, identical time of day, clear skies, dry pavements, and so forth.

Finally, it is worthwhile reiterating that the subjective rating methods are used primarily because they are inexpensive and can be performed quickly. Surprisingly however, the present study found these subjective rating methods to be much less subjective than was supposed.

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Investigation into Observational Variations in Pavement Condition Survey

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A workshop was conducted to test the raters in the evaluation of pavement surface distresses. Thirty-three raters, with varying experience in pavement evaluation, from five regional offices participated in the workshop. The raters subjectively recorded the severity and extent of 15 distresses pertaining to six flexible pavement sections. The data gathered were analyzed to study the variability of ratings, regional differences, experiential influence, and to identify the distresses that may be particularly difficult to assess. The selection of sites, methodology used in the study, and detailed analysis of data are described. Because the rating procedure was entirely subjective, the results were found to reflect wide variations among all regions. For instance, one of the regions underestimated the distresses, probably because the raters were trained by a senior rater who tended to underrate distresses and therefore passed on biases. No significant differences were found in the variability of results by experienced or inexperienced raters. Although centerline and transverse cracking emerged as the most consistently rated distresses by both groups, identification of alligator cracking apparently perplexed inexperienced raters. The study demonstrates that experience alone does not necessarily produce higher accuracy or greater consistency. It is important that raters be periodically trained and tested to keep biases from developing and perpetuating.

All pavement management systems include pavement evaluation as an essential component. Pavement evaluation, in turn, invariably includes pavement's ride quality or roughness and distresses as basic elements, although other elements such as structural adequacy and rut depth may also be incorporated. Pavement evaluation is used to assess the present condition of the pavement and plan the rehabilitation measures wherever required. Pavement distress manifestation is used to determine the causes of pavement deterioration and select the most appropriate remedial treatment to restore pavement serviceability.

In quantitative terms the pavement condition is generally expressed as a pavement condition index (PCI) or other similar indexes. These composite indexes are derived from their constituent elements. The contribution of individual elements to the overall index depends on their respective weightages assigned in the equation for calculating the composite index.

Although ride quality, structural strength, and rut depth can be determined accurately and objectively using automated or mechanical methods, the most common method of evaluating surface distresses, however, is through visual inspection of the pavement. Although systems are being developed to carry out distress surveys using imaging technique, they have not yet found a wide acceptance for various reasons.

The visual inspection method, being subjective, is prone to personal bias and lack of consistency and repeatability. However, the inaccuracy inherent in the method can be reduced by adopting standardized procedures and through training. If a number of raters are asked to evaluate a pavement, their ratings are likely to show variations due to many factors, such as the rater's own bias, experience, exposure to various types of distresses, and training received. Although these factors are well recognized, there is little information available about their impact on the variability in a visual pavement distress survey. The variations in distress evaluation will affect the overall PCI in proportion to the respective weightages assigned to the constituent elements of index.

Practice in Ontario

Subjective Procedure Before 1984

The Ministry of Transportation of Ontario has had a system in place since the mid-1960s to evaluate pavement condition. The overall subjective pavement condition rating (PCR) consisted of two physical parameters: the ride quality of the pavement and the severity and extent of surface distress manifestations. The ride quality was evaluated subjectively by driving over the pavement section at a given speed and assigning it a value, on a scale of 0 to 10, to reflect the ride comfort. Evaluation of the second parameter involved driving slowly over the section to identify the types of distresses present and their severity and extent (density) (*1*). To describe the magnitude of the severity and the extent, each was assigned five classes. The overall PCR was obtained by subjectively combining the two assessments (i.e., ride quality and the distress manifestations) and comparing it against a set of model descriptions. The PCR was expressed as a number on a scale of 0 to 100.

Procedure to Determine PCI

In 1984, when the Ministry's PMS was developed, it was decided to eliminate the subjectivity from the ride quality assessment by measuring it mechanically, because technology had become available to determine it reliably and objectively. Insofar as the assessment of pavement distresses was concerned, it was decided to continue with the practice of visual evaluation (2). The underlying reasons for the decision were

- A long-established procedure that had served well;
- Comprehensive data base on pavement performance in place;
- Detailed manuals existing since 1975 were widely accepted, regularly updated, and used ministry-wide since 1978;
- Availability of a large pool of knowledgeable and experienced engineering staff or raters in all regional offices;
- It was an economical method, because pavement inspection was part of the routine responsibilities of the engineering staff and the evaluation could be carried out with other duties; and
- Technology to automate pavement distress survey was in its early infancy.

On the basis of experience gained since 1978, the number of distress manifestation categories was reduced from 27 to 15, to simplify the procedure and data collection/ processing. The reduction was achieved by combining two or three similar distresses into one. For example, the two distress categories "rippling" and "shoving" were combined into a single category. Also, it was mandated that pavement condition survey (i.e., both roughness and distress manifestations) would be conducted on a 2-year cycle, with half the province covered each year. The pavement distress survey is carried out visually by geotechnical engineering staff in each of the five regional offices. The Ontario highway network under the provincial jurisdiction consists of 22 000 centerline km of highway, of which about 11 000 km are surveyed each year.

The ride quality or pavement roughness is measured by an accelerometer-based, trailer-mounted, portable universal roughness device (PURD). The root mean square vertical acceleration values (RMSVA) are correlated with the ride quality, or ride condition index (RCI), through the following transform function.

$$\text{RCI} = 26.64 - 7 \cdot 34 \log_{10} (\text{RMSVA}) \qquad (1)$$

where RCI is ride condition index, on a scale of 0 to 10, and RMSVA is root mean square vertical acceleration.

To quantify the distresses, each distress category was assigned a weighting value from 0.5 to 3.0, and each of the five classes of severity and extent was assigned values from 0.5 to 4.0, as shown in Table 1.

To express the cumulative influence of the distresses, a formula was developed on the basis of the utility theory, which puts all distresses on the same scale and considers their contribution in terms of the overall index (*3*). The index is referred to as distress manifestation index (DMI) and is calculated using the following equation:

$$\text{DMI} = \sum_{i=1}^{n} W_i (S_i + D_i) \qquad (2)$$

where

W_i = weighting value representing the relative weight of a distress type,
S_i = weighting value for severity of the distress, and
D_i = weighting value for extent (density) of the distress.

TABLE 1 Distress Manifestations and Weighting Values

TYPE	CODE	DESCRIPTION	WEIGHTING VALUE W_i
SURFACE DEFECTS	1	Ravelling and Coarse Aggregate Loss	3.0
	2	Flushing	0.5
	3	Rippling and Shoving	1.0
SURFACE DEFORMATION	4	Wheel Track Rutting	3.0
	5	Distortion	3.0
CRACKING	6	Longitudinal Wheel Track - Single - Multiple	1.0
	7	Longitudinal Wheel Track - Alligator	3.0
	8	Centreline - Single - Multiple	0.5
	9	Centreline - Alligator	2.0
	10	Pavement Edge - Single - Multiple	0.5
	11	Pavement Edge - Alligator	1.5
	12	Transverse - Half - Full - Multiple	1.0
	13	Transverse - Alligator	3.0
	14	Longitudinal Meander and Midlane	1.0
	15	Random	0.5

SEVERITY OF DISTRESS

Code	Description	Weighting Value S_i
1	Very Slight	0.5
2	Slight	1
3	Moderate	2
4	Severe	3
5	Very Severe	4

EXTENT (DENSITY) OF DISTRESS

Code	Description	Extent of Occurrence %	Weighting Value D_i
1	Few	<10	0.5
2	Intermittent	10-20	1
3	Frequent	20-50	2
4	Extensive	50-80	3
5	Throughout	>80	4

The weighting values were chosen using expert opinions and by calibration techniques to represent the perceived contribution of different distresses to the DMI, and ultimately to the overall PCI. For example, "single and multiple cracking in the longitudinal wheel track" has a W_i of 2.0, and along "centerline" or "pavement edge" has a W_i equal to 1.0. In other words, cracking in the wheel track is considered to contribute twice as much to the DMI as cracking along centerline or pavement edge. The weighting values, however, are not intended to capture the pavement roughness component, which is accounted for by the RCI. This is reflected, for example, in the relatively low W_i of 1.0 assigned to half, full, and multiple transverse cracking.

The PCI combines the influence of RCI and DMI using the following empirical equation:

$$\text{PCI} = 100\,(0.1\,\text{RCI})^{1/2}\,\frac{205 - \text{DMI}}{205} \tag{3}$$

where $0 < \text{PCI} \leq 100$.

Equation 3 shows that DMI has a linearly proportional direct effect on the PCI and that its magnitude depends on the RCI of the pavement. For a given value of RCI, the change in PCI due to a change in DMI can be calculated from

$$\Delta\text{PCI} = -0.154\sqrt{\text{RCI}} \cdot \Delta\text{DMI} \tag{4}$$

Thus, for example, for a smooth pavement with RCI = 8.0, an increase in DMI of 2.3 units results in a decrease in PCI of 1 unit; for a rough pavement with RCI = 4.0, it requires 3.2 units of change in DMI to cause a change in PCI of 1 unit, illustrating that an error in DMI has a significant impact on the PCI.

To improve the effectiveness of PCI as a reliable indicator of pavement condition and as a tool for planning pavement maintenance and rehabilitation strategies, it is imperative that errors resulting from subjective assessment of the DMI be minimized. To this end, the Ministry developed a program to test its raters on a circuit consisting of a number of pavement sections. The purpose of this workshop was to

- Investigate the variability in the identification and evaluation of distresses (DMI) and study the influence of the rater's experience; and
- Provide feedback to individual raters, identify their bias in rating, and use this information to minimize it and thus improve the consistency of provincewide rating system.

Correlation Program Workshop

Site Selection

The first task in the workshop was the selection of sites. A search of the Ministry's pavement management system data base revealed a number of potential sites in the vicinity of Brantford, about 100 km west of Toronto. After a visit to these sites, a total of six asphalt pavement sections were selected. In addition, two surface-treated sections on county roads were also selected as part of the circuit but are not included in this discussion and analysis, which is confined to asphaltic concrete pavement sections only.

Each section was about 2 km long, beginning and ending at clearly identifiable features such as side road junction (Figure 1). The sections ranged from a relatively new pavement with few distresses (PCI $\approx$ 85) to one in fairly advanced stages of deterioration (PCI $\approx$ 50). Poorer sections could not be included because the network has few sections that have PCI values lower than 50; they are generally rehabilitated by that time. There was a concentration of pavements in the PCI range of 60 to 70 because these pavements exhibit a variety of distresses with a full spectrum of magnitude and because it is in this range when the rehabilitation plans and measures are decided. All sections were evaluated in detail before the workshop.

Preparation

Geotechnical engineering staff from the five regional offices involved in pavement evaluation were invited to the workshop. In all, 33 raters participated in the program. The number of raters from each region ranged from five to nine. The raters had varying backgrounds: they had received on-the-job training from different senior regional staff, thus were likely to pick up individual biases; some had many years of experience, while others had little experience in rating the pavements; some were exposed to distresses prevalent in their regions, such as random or cracking caused by expansive aggregates, while others were not.

The raters were paired two to a car, with an experienced rater accompanied by a less experienced one, but each rater was required to rate independently. Starting at different sections and traveling by different routes to avoid crowding at any one site, the raters drove slowly over each section either on the pavement or on the shoulder stopping often for a closer inspection of distresses. Severity and density of distresses applicable to the section were checked off on the prescribed rating form (Figure 2).

Analysis of Data

On completion of the fieldwork, each rater was provided with a printout of his or her ratings, calculated DMI for each section, and a cumulative DMI (i.e., $W_i \cdot (S_i + D_i)$, for each distress type for all sections, as well as a similar printout for the average of the group. The raters could thus compare their own ratings for each section or their evaluation for each distress type with the average values for the entire group.

A statistical analysis was carried out using SAS software (*4*) to further study:

- Overall variations in ratings,
- Differences in ratings between the regions,
- Effect of rater's experience on the ratings, and
- To identify the distresses that were particularly difficult to evaluate.

The six sections exhibited a wide range of type and magnitude of distresses, and most of these were present on more than one section, which allowed for repetition. This, combined with a reasonably large and diversified group of raters, provided a good combination of factors conceivably influencing the variability of ratings. Because of the subjective nature of the rating procedure, one would expect a range of values in ratings. Ideally, the variation should be small, which would indicate an ideal rating system and consistently reliable raters. Many questions, however, arise if it is found that the variability is large: Is it confined to certain individuals who need more training? Is it the entire group or a subgroup such as one region that exhibits abnormal results indicating a lack of training? Are there certain distress types that are more confusing than others?

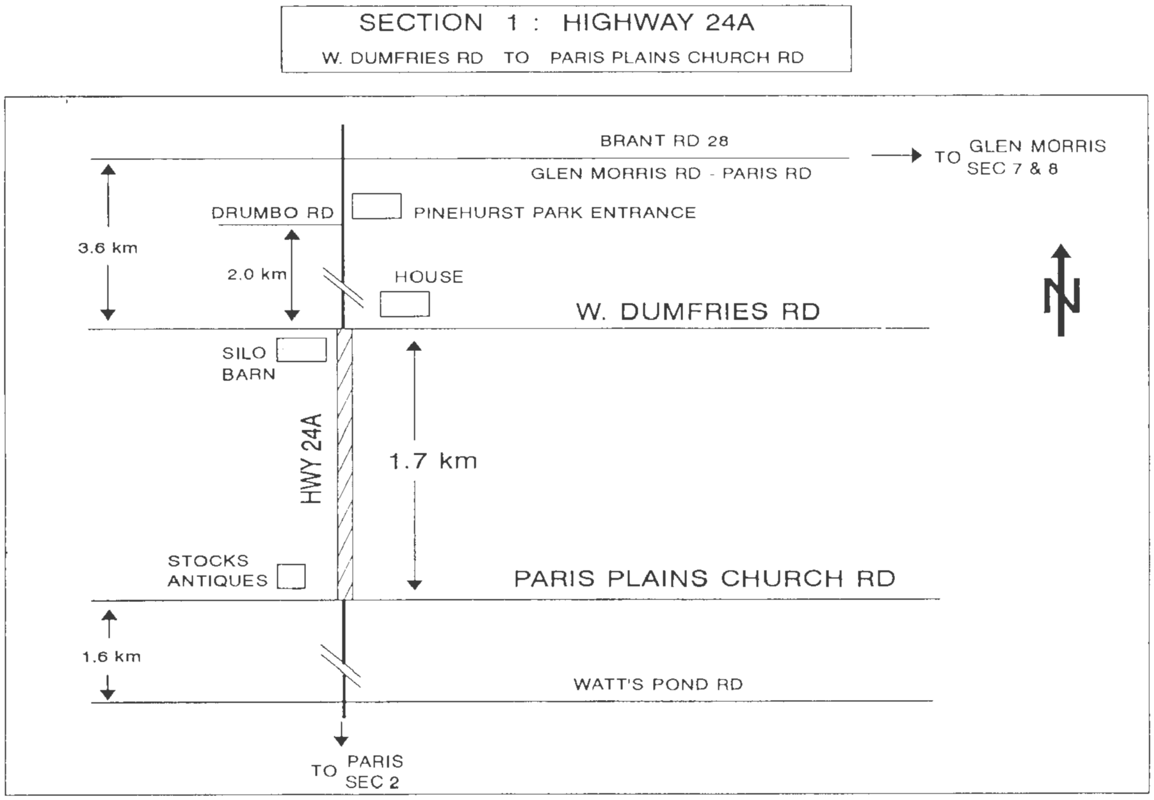

FIGURE 1 Site plan (example).

A fairly good idea of the variability can be obtained from the statistics on central tendencies and dispersion, particularly the mean, standard deviation (SD), and coefficient of variation (CV). Summary statistics of DMIs for each section (Table 2) show that for five of the six sections the mean DMI generally ranged between 30 and 70, SD between 10 and 20, and CV between 30 and 40. The raters exhibited a large variability in results on the five moderate to severely distressed pavements. In particular, section 5, a newer pavement with few distresses and consequently a low DMI, indicated a low standard deviation, but a high coefficient of variation, which was to be expected.

In the Ministry's equation for calculating PCI, the RCI has a dominant influence on it. For a new pavement with no distresses, the PCI is calculated entirely from its RCI. As the pavement deteriorates, the RCI decreases, but the DMI increases and so does the PCI. In practice, however, for most serviceable pavements, the contribution of DMI to the PCI equation seldom exceeds 30 percent.

Differences Between Regions

The previous discussion relates to the entire population of raters. However, these raters came from five regions, and it is probable that each region rates the pavement differently because of inherited bias during the training or because of rater's exposure or the lack of exposure to certain distresses.

The next step was to study the interregional differences. Three statistical parameters, mean, (SD), and CV related to the DMI of each section were used for comparison purposes. The values for each region are shown in Table 2 and Figure 3.

The values in Table 2 show that compared with other regions Northern Region produced lower mean DMIs for all sections. The total of average DMIs for all six sections in the case of Northern Region was 188.7; for the other four regions it ranged from 254.7 to 316.5. The remaining four regions had generally similar values of DMIs, but Central Region had slightly lower values than the rest. To compare the consistency of one region with another, the CV of DMI is presumably a better indicator, because the low DMIs reported by Northern Region render the comparison of the SD less appropriate. Eastern Region had, in general, the lowest CV, and Central Region had the highest. This is particularly evident for sections 1 to 4, where the CV for Eastern Region ranged from 19.5 to 22.8 and for Central Region from 32.9 to 42.7.

One explanation for the low DMIs from Northern Region could be its raters' constant exposure to severe frost and cold temperature-related distresses caused by the harsh climatic conditions of the region. This may have

SECTION 1: HIGHWAY 24A

RATER # _ _

FROM: W. DUMFRIES RD

TO: PARIS PLAINS CHURCH RD

PCR = _ _

RCR = _ . _

Riding Comfort Rating (At 80 km/h)

- 10 EXCELLENT Smooth and Pleasant
- 8 GOOD Comfortable
- 6 FAIR Uncomfortable
- 4 POOR Very Rough and Bumpy
- 2 VERY POOR Dangerous at 80 km/h
- 0

Pavement				SEVERITY OF DISTRESS					DENSITY OF DISTRESS EXTENT OF OCCURRENCE, %				
				Very Slight	Slight	Moderate	Severe	Very Severe	Few <10	Intermittent 10-20	Frequent 20-50	Extensive 50-80	Throughout 80-100
				1	2	3	4	5	1	2	3	4	5
SURFACE DEFECTS		Ravelling & C. Agg. Loss	1										
		Flushing	2										
SURFACE DEFORMATIONS		Rippling and Shoving	3										
		Wheel Track Rutting	4										
		Distortion	5										
CRACKING	Longitudinal Wheel Track	Single and Multiple	6										
		Alligator	7										
	Centreline	Single and Multiple	8										
		Alligator	9										
	Pavement Edge	Single and Multiple	10										
		Alligator	11										
	Transverse	Half, Full and Multiple	12										
		Alligator	13										
	Longitudinal Meander and Midlane		14										
	Random		15										

Distress Comments (Items not covered above) ______________________________

FIGURE 2 Flexible pavement condition evaluation form (example).

psychologically induced the raters to underestimate the distresses in milder climates of the south where the circuit was located. This hypothesis is, however, refuted by the high values of DMI reported by Northwestern Region, which has similar climatic conditions. The lack of rating experience could be another logical explanation, because Northern Region had only one participant with more than 5 years of experience. This explanation too is proven false, because Eastern Region, which has a similar lack of experienced raters, did not exhibit the same trend of underestimating the distresses. The only plausible explanation appears to be that raters in Northern Region were trained by the same senior person, who had a tendency to underscore the distresses and passed bias to the trainees. When the dispersion in the values of DMI is considered, Eastern Region, in general, showed the lowest dispersion. Central Region with the highest concentration of experience had the highest dispersion, indicating that experience alone may not be sufficient to narrow the differences. This issue, however, needs further exploration.

Experience as a Factor

It is obvious from a review of inter- and intraregional DMI data that there is a large spread in the evaluation of all sections as reflected in the values of DMI and its CV. The degree of deterioration of the pavement appears not to be a factor because newer and older pavements have equally large CVs. One region reported low DMI values, but it too had wide variation within the region, just as other regions did. Because large variability is evident within all regions, the region could not be a contributing factor. Another major factor could be the rater's experience. With more accuracy and consistency, the experienced raters should exhibit less variation among themselves

TABLE 2 DMI Statistics Compiled by Regions

DMI Statistics	South-western	Central	Eastern	Northern	North-western	All Regions
	Regions					
Section 1						
Mean	47.8	42.5	44.7	26.0	46.0	41.6
SD	15.7	17.1	10.1	8.7	16.8	15.7
CV	32.8	40.2	22.6	33.5	36.5	37.7
Section 2						
Mean	58.2	57.4	64.1	38.4	60.8	55.8
SD	20.7	23.7	12.5	5.6	18.3	19.3
CV	35.6	41.3	19.5	14.6	30.1	34.6
Section 4						
Mean	61.2	51.6	56.9	40.2	71.0	55.9
SD	26.1	17.0	11.9	5.9	19.8	19.6
CV	42.6	32.9	20.9	14.7	27.9	35.3
Section 4						
Mean	54.6	53.6	62.7	37.3	65.7	54.4
SD	16.2	21.2	14.3	9.9	19.2	18.7
CV	29.7	39.6	22.8	26.8	29.2	34.4
Section 5						
Mean	19.8	13.3	23.5	8.6	21.8	16.9
SD	10.0	5.9	8.2	5.4	11.1	9.5
CV	22.8	44.4	34.9	62.8	50.9	56.2
Section 6						
Mean	43.9	36.3	43.7	38.2	51.2	42.1
SD	12.0	11.6	12.1	16.7	9.5	12.8
CV	27.3	32.0	27.7	43.7	18.6	30.4
Total DMI	285.5	254.7	295.6	188.7	316.5	266.7

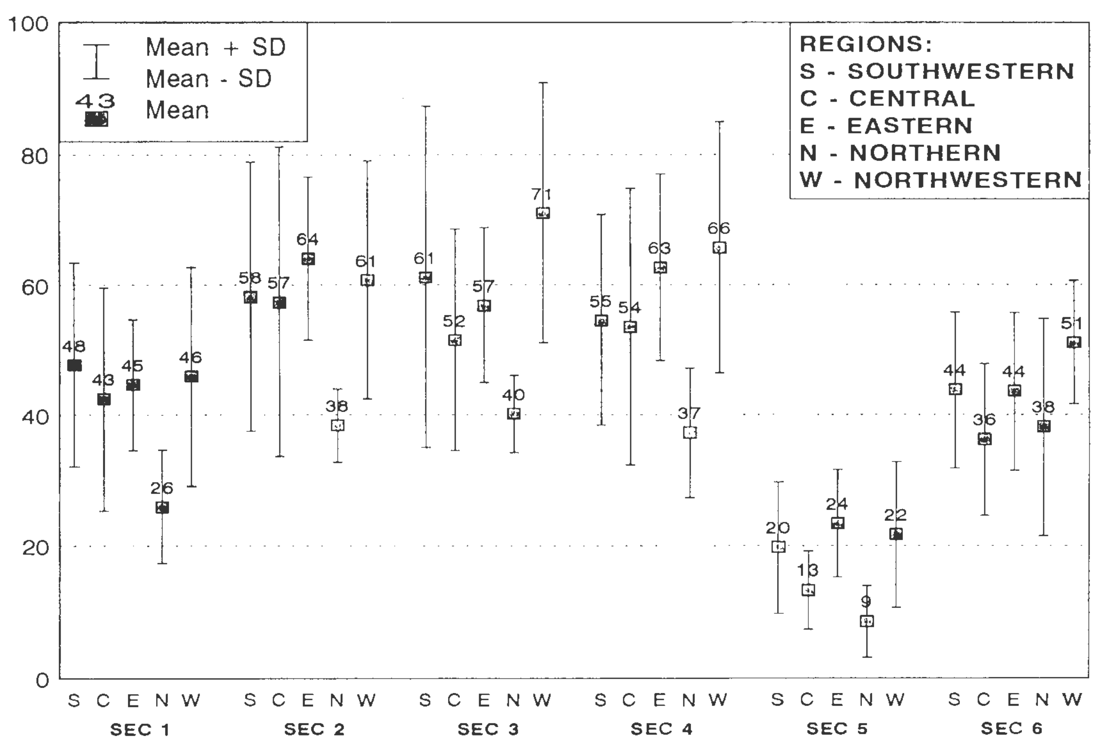

FIGURE 3 Mean and standard deviation of section DMI by regions.

compared with inexperienced raters. To investigate this hypothesis, the raters were divided into two groups: experienced and inexperienced. Only those with at least 5 years of experience in pavement evaluation were considered experienced raters. Thus, the experienced group comprised 12, whereas the inexperienced group 21 raters.

If experience is a factor, it should be evident in the analysis. The DMI statistics for each section were compiled separately for the experienced and the inexperienced raters and are shown in Table 3. Two general trends emerge.

- Mean DMIs of the inexperienced group were lower than those of the experienced group, except for Section 5, but were particularly low for Sections 1, 2, and 3; and
- Dispersion as reflected by SD, range, and CV of DMI for all sections was comparable for the two groups.

It can be inferred from the first generalization that either the inexperienced raters are likely to underestimate distresses or the experienced raters tend to overestimate distresses, or both statements are true.

To test the above hypotheses, it is necessary to estimate the probable magnitude of each distress type for each section. For this purpose, data for the severity and extent of each distress for each section are separated for the experienced and inexperienced groups. An analysis was carried out to produce the central tendencies, that is, mean, median and mode, and SD and CV for each severity and extent. The results, particularly the central tendencies, were used to estimate the most probable values. Severity and extent of each distress present on the section were assigned an integer value. These values were used to calculate the probable DMI for each section. This, along with DMI data for the experienced and inexperienced raters, is shown in Table 3. The probable values so derived matched closely with those obtained from the prior evaluation.

A comparison of the probable DMI values with the mean DMI values for the experienced and the inexperienced groups indicates that the inexperienced raters tended to underestimate distresses. It is likely that the inexperienced raters missed or overlooked distresses more often. Further analysis is required to ascertain whether this is the case.

On the other hand, the comparable values of dispersion parameters for the two groups lead to the conclusion that more experience on the part of raters does not necessarily result in less variability or greater uniformity among raters.

Difficult Distresses

The general tendency of the inexperienced raters to underestimate the magnitude of distresses leads to the next logical questions: Are there some specific distresses that are more difficult to assess? Can those be identified? To unravel this, a method had to be devised that would examine data based on individual distress type. The procedure used to analyze data was as follows: unweighted

TABLE 3 DMI Statistics for Sections

	SECTION					
	1	2	3	4	5	6
Experienced Raters						
Mean	47.9	64.8	62.2	57.0	16.5	44.6
SD	15.6	20.7	21.6	18.9	10.2	14.1
Min.	24.3	35.3	36.5	13.0	5.3	18.3
Max.	73.5	89.0	104.0	79.5	37.5	64.3
Range	49.3	53.8	67.5	66.5	32.3	46.0
CV	32.5	32.0	34.7	33.3	61.8	31.7
Inexperienced Raters						
Mean	38.0	50.7	52.3	53.0	17.1	40.7
SD	15.0	16.9	18.0	18.9	9.3	12.2
Min.	12.5	26.8	30.0	24.5	3.0	23.3
Max.	67.8	94.0	99.5	95.5	39.0	64.5
Range	55.3	67.3	69.5	71.0	36.0	41.3
CV	39.5	33.3	34.4	35.6	54.0	30.0
Probable DMI						
	38.3	57.3	52.0	55.0	11.8	43.8

values of severity, extent, and the weighted values of distress manifestation were ($DM = W_i \cdot (S_i + D_i)$ were aggregated for a distress type for all sections. The resulting data were separated for the experienced and the inexperienced groups and tabulated to provide the mean and dispersion indicators for the cumulated values of severity, extent, and DM of a distress type (Table 4). There is some simplification involved in the analysis, in that the random variations among raters may mask a trend. But, if there is a systematic or general tendency to over or underestimate a given distress, it should be evident from a comparison of the mean values of the two groups. To resolve the issue of what is over or under the estimate, and by how much, a benchmark value had to be established. The benchmark chosen for this purpose was the previously derived probable values for the distresses. The unweighted probable values of severity and extent and the weighted DM were each aggregated by each distress type for all sections and used as the standard against which to compare other values (Table 4).

An examination of the data in Table 4 reveals some general and specific trends. In general, the mean values for the inexperienced group were lower than those for the experienced group, except for rippling and shoving. This further confirms that inexperienced raters have a tendency to underestimate distresses compared with experienced raters. Some distresses were particularly underestimated and more difficult to assess for inexperienced raters. These were alligator cracking of almost all types, longitudinal wheel track, and longitudinal meander and midlane cracking. Of severity and density, the former was more difficult to describe.

Both groups of raters exhibited large variations in describing all distresses, except for non-alligator–type centerline and transverse cracking, which were the most consistently reported distresses. Even this apparent improvement in consistency for the two distresses should be viewed with caution, because these distresses were common to all sections and the severity and extent levels were also relatively high. Because of the large frequency of occurrence and higher magnitudes of severity and extent, the errors are likely to be balanced out in the process of aggregation.

The technique of aggregating the scores for the severity and extent of a distress type for all sections can be a useful tool for a rater to identify his or her biases by comparing their results with the average values or probable values.

TABLE 4 Aggregate Score for All Sections by Distress Type

	Pavement Surface Distresses														
	1 RAVELLING & CA LOSS			2 FLUSHING			3 RIPPLING AND SHOVING			4 WHEEL TRACK RUTTING			5 DISTORTION		
	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM
Experienced Group															
MEAN	11.8	14.8	53.0	2.6	3.9	2.2	0.5	0.3	0.4	8.9	16.1	50.4	10.0	8.2	32.3
SD	2.6	7.9	18.5	2.4	6.8	3.5	1.2	0.9	1.1	4.1	9.6	28.1	4.3	3.3	12.7
MIN.	6.0	6.0	36.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	5.0	13.5	5.0	3.0	13.5
MAX.	17.0	30.0	90.0	9.0	25.0	12.8	4.0	3.0	3.5	14.0	30.0	96.0	17.0	13.0	51.0
RANGE	11.0	24.0	54.0	9.0	25.0	12.8	4.0	3.0	3.5	13.0	25.0	82.5	12.0	10.0	37.5
CV	21.8	53.4	34.9	94.0	174.0	159.4	248.6	266.3	255.0	45.5	59.5	55.8	42.6	40.7	39.4
Inexperienced Group															
MEAN	10.9	15.2	52.1	2.5	3.7	2.1	0.5	0.7	0.7	8.3	16.0	48.4	9.1	7.8	29.8
SD	3.1	7.7	21.4	2.1	3.6	1.9	1.5	2.1	2.3	3.8	9.4	26.9	3.7	4.1	14.0
MIN.	5.0	4.0	19.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	2.0	9.0
MAX.	17.0	30.0	99.0	7.0	10.0	5.3	6.0	8.0	8.0	14.0	30.0	85.5	15.0	17.0	57.0
RANGE	12.0	26.0	79.5	7.0	10.0	5.3	6.0	8.0	8.0	14.0	30.0	85.5	11.0	15.0	48.0
CV	28.4	50.6	41.1	83.4	98.2	93.7	322.7	319.4	316.6	45.7	58.7	55.6	40.1	52.9	47.0
Probable Values															
	13.0	14.0	46.5	2.0	1.0	0.8	0.0	0.0	0.0	10.0	16.0	48.0	9.0	7.0	24.0

(continued on next page)

Implications for Pavement Management System

PCI plays a dominant role in PMS (5) by

- Assessing the health of the network,
- Deciding which sections need to be rehabilitated and when,
- Preparing a multiyear plan for rehabilitation program,
- Assessing the financial needs of the program, and
- Prioritizing the projects.

Because DMI affects PCI, any variations in DMI have an impact on the foregoing activities. For instance, if one region tends to underestimate the distresses, it will result in higher than real PCI values for its highways, making them appear to be in a relatively better condition. Therefore, fewer of them will qualify to be in need of rehabilitation, and more of them will be allowed to deteriorate further before any action is planned or taken. Considered over the network, this could introduce significant inequalities and inaccuracies. Conversely, the practice of overestimating distresses generates artificially low values of PCI, which might prompt action earlier than necessary, resulting in uneconomical use of resources and divertion of funds away from the areas of genuine need. The seriousness of the consequences, of course, depends on the magnitude of the inaccuracies in DMI and PCI.

To illustrate the point, let us consider Section 6 of the circuit. The results from the survey are as follows:

- RCI = 6.8,
- Probable DMI = 43.8,
- Mean DMI = 42.1,
- Calculated PCI = 69,
- Minimum DMI = 18.3,
- Maximum DMI = 64.3,
- Minimum PCI = 61, and
- Maximum PCI = 78.

These results show a spread of 46 points in DMI and 17 points in the calculated PCI. Both the minimum and maximum values of DMI were reported by the experienced raters. According to the Ministry's guidelines for planning, a section should be put on the 5-year plan if its PCI is less than 70. Therefore, section 6 represents a typical

TABLE 4 (*continued*)

	Pavement Surface Distresses														
	6 CRACKING LONG W.T. S&M			7 CRACKING LONG W.T. ALGTR			8 CRACKING C.L. S&M			9 CRACKING C.L. ALGTR			10 CRACKING P.E. S&M		
	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM
Experienced Group															
MEAN	12.5	10.3	14.2	5.3	3.8	15.6	16.7	17.3	11.7	7.0	5.4	15.8	13.6	17.3	10.6
SD	3.4	4.3	5.0	4.0	2.9	10.9	3.7	3.6	2.5	4.3	3.8	10.4	4.4	2.4	2.4
MIN.	4.0	2.0	3.0	0.0	0.0	0.0	10.0	10.0	6.3	0.0	0.0	0.0	8.0	13.0	6.5
MAX.	16.0	18.0	22.0	11.0	9.0	34.5	23.0	23.0	14.5	14.0	13.0	34.0	22.0	22.0	15.0
RANGE	12.0	16.0	19.0	11.0	9.0	34.5	13.0	13.0	8.3	14.0	13.0	34.0	14.0	9.0	8.5
CV	27.2	41.3	35.4	75.4	76.4	69.9	22.2	21.0	21.6	61.5	70.2	65.8	32.5	13.8	22.5
Inexperienced Group															
MEAN	9.6	9.0	11.3	3.3	3.0	10.8	16.0	17.1	11.2	3.7	2.9	7.8	12.5	15.7	9.4
SD	4.5	4.4	5.7	2.9	2.4	9.3	1.7	2.7	1.5	3.4	3.4	8.4	2.9	3.1	2.2
MIN.	0.0	0.0	0.0	0.0	0.0	0.0	12.0	10.0	8.0	0.0	0.0	0.0	8.0	11.0	6.0
MAX.	17.0	17.0	22.0	10.0	8.0	30.0	19.0	22.0	14.3	13.0	13.0	32.0	19.0	21.0	14.0
RANGE	17.0	17.0	22.0	10.0	8.0	30.0	7.0	12.0	6.3	13.0	13.0	32.0	11.0	10.0	8.0
CV	46.5	48.8	50.2	88.3	80.0	86.0	10.8	16.0	13.6	93.8	117.7	107.9	22.8	19.6	23.4
Probable Values															
	13.0	11.0	15.0	3.0	3.0	9.0	18.0	19.0	12.8	10.0	4.0	11.0	15.0	17.0	11.0

(*continued on next page*)

TABLE 4 *(continued)*

	Pavement Surface Distresses														
	11 CRACKING P.E. · ALGTR			12 CRACKING TRANS HFM			13 CRACKING TRANS ALGTR			14 CRACKING MR/ML			15 CRACKING RANDOM		
	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM	ΣS_i	ΣD_i	ΣDM
Experienced Group															
MEAN	8.6	6.8	14.7	18.4	22.6	29.5	7.0	5.7	23.3	11.8	9.6	13.5	8.7	9.7	6.0
SD	3.4	3.4	6.9	2.0	1.9	3.0	3.5	3.9	14.5	2.4	2.8	3.4	5.9	5.7	3.7
MIN.	3.0	3.0	5.3	16.0	19.0	25.0	2.0	1.0	6.0	8.0	6.0	8.5	0.0	0.0	0.0
MAX.	15.0	16.0	32.3	23.0	26.0	34.5	12.0	14.0	51.0	15.0	14.0	18.5	18.0	20.0	12.3
RANGE	12.0	13.0	27.0	7.0	7.0	9.5	10.0	13.0	45.0	7.0	8.0	10.0	18.0	20.0	12.3
CV	39.9	49.5	47.2	11.0	8.3	10.3	50.6	68.3	62.4	20.6	29.7	25.4	67.9	58.9	61.0
Inexperienced Group															
MEAN	6.0	5.8	11.1	16.6	20.2	25.8	4.3	4.1	15.4	9.6	7.3	10.3	8.7	8.6	5.6
SD	3.7	3.7	7.6	1.7	3.2	3.7	4.2	3.6	15.5	4.0	2.9	4.1	4.6	3.2	2.4
MIN.	2.0	2.0	3.0	13.0	13.0	18.5	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	1.5
MAX.	14.0	16.0	31.5	19.0	25.0	31.5	15.0	12.0	51.0	15.0	12.0	17.5	16.0	14.0	9.0
RANGE	12.0	14.0	28.5	6.0	12.0	13.0	15.0	12.0	51.0	15.0	12.0	17.5	14.0	12.0	7.5
CV	62.7	64.5	68.8	10.0	15.9	14.3	96.1	89.0	100.4	41.5	40.3	39.4	52.2	37.7	43.5
Probable Values															
	8.0	6.0	11.3	18.0	22.0	28.5	7.0	6.0	21.0	13.0	10.0	13.5	9.0	10.0	57.5

pavement section that would be a suitable candidate for consideration in the 5-year plan, because its PCI is 69. But according to one rater, its high PCI of 78 precludes it from any such consideration. On the other hand, in the opinion of another rater the section should be accorded a high priority because of its low PCI of 61. It is obvious that both decisions are erroneous and would have serious consequences for the rehabilitation of the section and would adversely affect other sections as well.

Summary and Conclusion

As part of training in pavement evaluation, 33 raters were tested in assessing the severity and extent of 15 flexible pavement distresses. Six flexible pavement sections were included in the circuit. The raters were drawn from five regional offices of the Ministry and had varied experience in pavement evaluation, ranging from very little to many years. For the purpose of the study, those with at least 5 years of experience were considered experienced raters and the remaining inexperienced. The results were to be used by the raters for self-evaluation of their biases. The method in conducting the workshop was described.

Statistical analysis of the data was carried out to study

- Magnitude of variations in rating,
- Inter- and intraregional differences,
- Influence of experience on accuracy and variability of ratings, and
- Distresses that may be rather difficult to rate.

The following conclusions can be drawn from the results:

- There was a large variation in ratings of most distresses among the raters;
- One region had a tendency to underestimate distresses, probably because of the training given by a senior rater who may have passed on bias to the new raters;
- All regions exhibited high intraregional differences;
- Experienced raters did not show more accuracy or consistency in rating than did the inexperienced raters. This means that individual bias rather than the experience plays a dominant role;

- Inexperienced raters had greater difficulty in identifying alligator cracking, longitudinal wheel track cracking, and longitudinal meandering and midlane cracking, and the assessment of severity was relatively more difficult; and
- Centerline cracking and transverse cracking were rated more consistently than the other distresses by all raters.

To improve the accuracy and consistency in rating, raters should be trained and tested in an environment in which exchange of ideas in distress evaluation can take place and individual biases can be identified and minimized. To this end, the Ministry is establishing training circuits in each of its five regions. Using these circuits, the staff will be periodically trained and tested to ensure the integrity of provincewide distress data. In the absence of such a program, individual biases can develop and may even be reinforced with time and eventually transferred to other trainee raters.

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Quality Standards for Reliable Pavement Roughness Evaluation

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A pavement management system (PMS) requires reliable data to project maintenance needs and evaluate the success or failure of various maintenance options. Assessments of ride quality, based on either response-type roughness measurements or longitudinal profile measurements, are often used to characterize pavement conditions and predict future needs in a PMS. To successfully determine changes in pavement roughness, the measurement equipment must provide accurate repeatable results and be stable over time. Records of pavement profile taken at intervals form a basis on which changes in roughness can be deduced, whether by calculation of International Roughness Index (IRI) or some other roughness characteristic or statistic. For this reason, measurements of longitudinal profile are a key component of the long-term monitoring effort conducted by the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) studies. For the SHRP/LTPP program the K. J. Law profilometer was selected because of its well-tested record and ability to provide rapid measurements of longitudinal profile on highway pavements. The backup device for the SHRP program is the Face Technologies "dipstick", which can also be used as a reference for the dynamic calibration check on the profilometer. A description is given of PROQUAL, a suite of computer programs developed by SHRP for field quality assurance and subsectioning of profile data, inputting, checking, and analyzing profile data before uploading to the Regional Information Management System and then finally the National Information Management Systems (RIMS/NIMS). The software also provides procedures for the dynamic calibration of the profilometer and processing longitudinal and transverse data collected with the dipstick. Statistical criteria are used in the field data collection process to determine adequacy of the data with respect to repeatability. Data that do not fit the requirements are discarded, and a minimum data set is declared accepted. IRI, root-mean-square vertical acceleration, Mays output, and slope variance values are calculated; profiles are stored. Examples of data of the SHRP program collected over 4 years are used to demonstrate with confidence the reliability of the data collected as part of the LTPP program. There is also a discussion of how the procedures and software developed for the SHRP program may be transferred to other agencies.

The pavement serviceability index (PSI) is a pavement performance measure used by agencies in their pavement management systems (PMSs) to evaluate the condition of pavements as a guide to trigger planning and design of maintenance or rehabilitation interventions. Over the years since its introduction in the late 1950s, a number of vehicle-mounted devices designed to measure riding quality were used to support an agency's PMS, with varying degrees of success. One of the problems encountered is a question of stability of the device over a period of years, which in combination with actual fluctuations in pavement roughness casts doubt on the reliability of the evaluation and on the validity of using riding quality to trigger maintenance interventions.

The Long-Term Pavement Performance (LTPP) program is a major component of the Strategic Highway Research Program (SHRP). Continued under the FHWA-LTPP Division, its goal is to improve the ability to design and construct long-lived, cost effective pavements. This program monitors pavement performance parameters, such as changes in profile, surface condition, and structural integrity on 152.5-m (500-ft) sections of existing, rehabilitated, and newly constructed pavements with different structural compositions and in different environmental conditions selected or constructed within a series of experiments. Throughout the life of the project, the FHWA-LTPP Division through its four regional offices, will collect pavement profile data at perhaps up to 3,000 sections throughout the United States and Canada.

The primary devices used to obtain LTPP profile data are four (one per each of four regions) K. J. Law Model 690 digital noncontact profilometers (Figure 1), three of which are in identical recreational vehicle (RV) bodies, with the fourth mounted in a standard cargo van. From a data collection standpoint, the fourth profilometer differs from the others only in the spacing of the wheelpath sensors, 1.37 m (54 in.) center to center, as opposed to 1.65 m (65 in.) for the RV bodies. These devices sample the relative profile elevation in each wheelpath every 25.4 mm (1 in.), average the 25.4-mm samples over 300 mm (1 ft), and store an average profile data point every 150 mm (6 in.). A 91.5-m (300-ft) filter is used to remove the longer wavelength features from the profile data as it is collected, and before storage.

FIGURE 1 Profile data collection using the K.J. Law 690 DNC profilometer.

FIGURE 2 Profile data collection using the Face Technologies Dipstick.

In addition, the dipstick (Figure 2) is used for longitudinal profile measurement at sites that are relatively inaccessible to the profilometers because of physical/geographical or scheduling constraints, and for transverse profile measurements. The relative elevation measurements obtained with the dipstick are at 300 mm (1-foot) intervals, with no averaging or filters applied.

For profile data to be useful, automated tools are needed to ensure accuracy and uniformity and reduce the raw profile data to indexes that can be used for pavement evaluation purposes. SHRP has developed a suite of computer programs to fill the needs for the data collected as part of the LTPP monitoring. Although developed primarily for use with the SHRP profilometers and dipstick, the software could easily be adapted to accept data from other profile measurement devices. Details of SHRP's profile measurement procedures are provided in SHRP-LTPP *Manual for Profile Measurements* (1).

In this paper, the results of over 4 years of monitoring pavement profiles of specific sections of existing highways are used to demonstrate that the quality assurance procedures developed for the LTPP programs provide reliable answers to the stability of profile measurement equipment over time, illustrate that profiles can change seasonally, and demonstrate that in the short term pavements can get smoother as well as rougher over time. These results were all obtained subject to the quality assurance procedures, which are described in the paper.

Quality Assurance Program

Data Collection

Field data collection guidelines have been developed for the profile data collection at the SHRP-LTPP sites to ensure consistency in calibration of equipment, collection of profile data, and verification of the quality of field data collected. A single software program, PROQUAL (Profile Quality Assurance and Analysis Software) (2), is used to ensure that a thorough and consistent (in a nationwide sense) quality assurance program is undertaken by the four contractors collecting profile data for the LTPP experiment. In addition, the four regional profilometers assemble regularly and do comparative studies over different pavement types, with different levels of roughness to ensure the compatibility of data from each profilometer.

Obvious sources of errors or variation in profile measurements at highway speeds of a segment of highway obtained at different times are the differences caused by operator identification of wheelpaths, vehicle tracking at different speeds, and difficulties encountered in repeating the measurements with identical start/stop segment locations.

The 152.5-m (500-ft) test sections in the LTPP program have each been laid out with painted stripes across the mid-lane area at the beginning and end of the test sections. The reflective stripes are used to trigger start/stop responses of the profile measuring equipment. The profilometers use a photo-cell to trigger the start location from the painted stripes and either a defined distance or event mark, established from the photocell activation on the stripes, to identify the limits of the test site.

At present, the goal for the LTPP profile measurement program is to measure the longitudinal profile of each LTPP test section, approximately once per year, as a minimum. In addition, selected test sections will be profiled four or five times per year, because they are included in a special study addressing seasonal variations in pavements. Last, a "final" set of profile data is obtained on sections scheduled for construction or major maintenance (e.g., reconstruction, overlay, etc.) shortly before construction activities begin.

The intent of the procedures established for profilometer measurements at the LTPP test sites is to provide five error-free sets of profile data per observation. Five runs, rather than just one, are needed to provide some measure of the run-to-run variability in the measured profile, so that year-to-year comparisons are not confounded by differences in vehicle tracking. Wheelpaths followed by the profilometer operator are based on continuous observations of signs of pavement wear and judgment of line of most apparent tightness or polishing. Usually, the first run over the section will serve mainly as a trial/observation pass. Checks on the level of between-run variability for a given section are also used as quality assurance measures, because excessive run-to-run variability may come about as a result of equipment malfunctions.

Where a high level of run-to-run variability is identified, the data for the five runs and the test section itself are reviewed by the profilometer operator for potential explanations.

Where the variability appears to be due to pavement related features (e.g., isolated cracks or a high level of transverse variability in profile), four additional runs are made to confirm the original data. Where no pavement-related explanation is evident, potential sources of equipment malfunction are investigated, and the data collection process is repeated until five acceptable runs are obtained. In some instances, erroneous data can be due to saturation of the profilometers' light sensors, caused by unfavorable ambient lighting conditions (low sun angle or vehicle headlights). In these cases, it may be necessary to terminate profiling operations for the day and begin again the next morning.

When the dipstick is used, no measure of transverse variability in the pavement profile is obtained, because of time constraints on the data collection imposed by the need for traffic control. Instead, a closed-loop survey (one run up, and one run back) is used to provide a quality check on the data. Because the closed loop begins and ends at the same point, the running sum of the relative elevation differences should "close" (i.e., be zero).

Profile Quality Assurance and Analysis Program

Four computer programs (PROFSCAN, PROFCHK, PROFCAL, and DIP) were developed to support the analysis of road profile measurements made as part of the LTPP monitoring effort. These programs were then interfaced and coupled into a single module called PROQUAL in a user-friendly microcomputer environment.

PROQUAL software was initially developed as a field quality assurance and subsectioning program for data collected with the profilometer. The initial software was called PROFSCAN. Subsequently, other modules were added to provide a complete package for entering, checking, and analyzing profile data for transfer to the Regional Information Management System and then finally to the National Information Management Systems (RIMS/NIMS).

PROFSCAN was written to be used by the Profilometer operator at the time of surveying SHRP-LTPP monitoring and weigh-in-motion (WIM) sites. The objective is to have the profilometer operator review the data while on site to avoid costly repeat trips. The profile data collection results from the first five passes over the test sites are analyzed to determine whether additional runs are required for that site. The decision depends on a set of statistical summaries such as the mean International Roughness Index (IRI) value, standard deviation, and coefficient of variance. The criteria evaluated by PROFSCAN and documented in the PROFSCAN output report are that at least three of the first five runs must have IRI values within ±1 percent of the mean IRI (of 5) and have a standard deviation of the 5 runs less than 2 percent of the mean IRI. Otherwise, nine runs are taken. Figure 3 gives an example of a typical output from the analysis of profile data through the PROFSCAN software. If the IRI value does not meet the statistical requirements, additional runs may be required to determine whether variances in IRI are the result of technical problems or run-to-run variability due to pavement condition. A spike report is also produced that identifies locations of significant change in profile elevation that could either be due to pavement features, such as a pothole or severely faulted

PROFSCAN SUMMARY REPORT

Monday, May 17, 1993 **08:45:55**

SETUP:
Spatial Filter Wavelength...... **Speed.....48:20 (mph)**
Start Method.......................... **PHOTOCELL**
Stop Method...........................
Wavelength Initialization....... **DISABLED**

SURVEY:		LOCATION:	
GPS..................	545007	Begin...........	
Oper/Driver.....	Basel/Scott	End..............	
Date..................	30/04/1992	Lane.............	LN 1
Time.................	14:13:20	Direction.......	WEST BD
Station..............	0 - 500	Horizontal Offset............	

CONDITIONS:
Pavement
Road............... **US 50**
Surface Mat'l... **P-CC**
Surface Cond.. **POOR**
Weather
Temperature.... **60 F**
Cloud................ **OVERCAST**
Other................. **PRE OVERLAY TESTING**

RUN #	IRI (in/mi) LEFT	RIGHT	BOTH	DISPLACEMENT (in)	INCLUDE IN STAT	POSSIBLE SPIKES
1	140.10	189.16	164.63	15.59	Yes	No
2	139.76	185.56 (L)	162.66	15.40	Yes	Yes (*)
3	140.09	186.06	163.07	15.44	Yes	No
4	140.50 (H)	190.25 (H)	165.37 (H)	15.66	Yes	Yes (*)
5	139.35 (L)	185.95	162.65 (L)	15.40	Yes	Yes (*)

Minimum	139.35		162.65
Maximum		190.25	165.37
Mean +1%	141.35	189.26	165.31
Mean	139.96	187.40	163.68
Mean -1%	138.56	185.52	162.03
Std. Deviation	0.38	1.92	1.12
2% of Mean	2.79	3.74	3.27
Coef. of Vari.	0.2	1.0	0.6

YOU HAVE SUFFICIENT RUNS

(*) - See file 545007.SPI for details
(L) - Lowest value.
(H) - Highest value.

FIGURE 3 Typical output from PROFSCAN.

joints on rigid pavements, or technical difficulties with the profilometer equipment (i.e., signal saturation or loss of signal reference).

In addition, the PROFSCAN software is used to subdivide continuously collected profile data into individual sections. This is particularly helpful when collecting profile data on special pavement study sites for where a number of sections are placed adjacent to each other, allowing all the data to be collected in one pass with the profilometer.

The second road profile, Quality Assurance Software, for use by the SHRP-Regional Coordination Office (RCO) is the PROFCHK program. PROFCHK is an extension of the PROFSCAN software and is intended to check the profilometer survey data for completeness and readability and then to generate an output file summarizing the results of the checking process. In addition, PROFCHK calculates the following road profile numerics:

- International Roughness Index (IRI) and displacement,
- Root-mean-square vertical acceleration (RMSVA),
- Slope variance, (SV), and
- Mays output (MO).

Before any profile summary numerics can be forwarded for inclusion in the regional and then national pavement data base, the analyst must check all profile data files to assess whether

1. The elevation data collected is out of range (e.g., occurrence of spikes, data outliers);
2. The results are reasonable from a statistical viewpoint on the basis of stipulated tolerance and criteria; and
3. Data are reasonable from a practical judgment standpoint (i.e., index values make sense based on historical comparisons, maintenance, or changes in local conditions).

The quality assurance portion of the program (which is run in the office) has several useful features. It allows the analyst to select different summary intervals for the IRI analysis, view plots of the data at different scales, and flag data that are anomalous as being (*a*) due to an actual pavement feature, (*b*) the result of an equipment malfunction, or (*c*) unexplained but does not alter the raw data.

The software provides a comment feature for each step in the data collection and analysis of the profile data. The proflometer operator can provide an end-of-run comment for each pass over the test section and specific comments based on the site review and analysis of data through PROFSCAN. The RCO engineer may also comment on the analysis and final review of the data.

On the basis of the aforementioned conditions, the RCO analyst can remove individual runs or logically delete invalid data points (elevations) from the analysis, as evidenced by signal saturation spikes or lost lock due to light leaks under the shrouds.

The historical data for each site are provided in a history file that is updated with each analysis occurrence. Figure 4 gives an example of the historical summary of numerics (IRI, RMSVA, MO, SV) for a GPS site in West Virginia, for data collected over 4 years.

An output file consisting of the original profile data, a summary of the analysis results (IRI, RMSVA, etc.), and a summary of the checking process is generated by the program for transfer to RIMS/NIMS.

The third profile quality assurance software for use by LTPP contractor is the PROFCAL program. The PROFCAL software is a utility program to assist in determining whether the profilometer equipment is operating correctly or needs routine calibration adjustments.

The PROFCAL program requires the profilometer to collect data over the site at four different speeds of 40, 60, 72, and 80 km/hr (25, 35, 45 and 50 mph). A variance of ±3 km (2 mph) is allowed. Five runs are required for each speed category. The software then calculates the IRI values for each wheelpath including the average value and the location of minimum/maximum elevations along with statistical summaries for each speed and the overall data set. Figure 5 gives an example of the summary results from the analysis of the IRI data collected at 60 km/hr (35 mph). An analysis of variance (ANOVA) is performed to determine whether there is a difference between the data sets collected at different speeds—Figure 6 provides an example of the comparison of four sets of IRI data collected at different speeds over a calibration test site. The results are then compared to the dipstick survey data for the same site. The profilometer is said to meet Class 2 requirements if the mean IRI results at each speed are within 5 percent of the dipstick results (i.e., Class 1 requirements). If the results at any speed do not satisfy this 5 percent tolerance, the program lists suggested trouble shooting scenarios for the operator to follow.

The DIP software was developed to provide input and processing capabilities for the Dipstick or "Digital Incremental Profiler" data. The software has two major submodules: longitudinal and transverse profiles. The first submodule allows manual entry of the longitudinal profile measurements made with the dipstick in both the left and right wheelpaths at 300-mm (1-ft) sample intervals. The data can also be uploaded from American Standard Code for Information Interchange (ASCII) text files using an interface program. Roughness indexes and displacement are calculated from the longitudinal profile data using the same coding developed for the profilometer.

The second module accepts manual entry of the transverse dipstick data and determines the rut depths for both

DATE SURVEYED	RUN NO.	IRI (in/mi)	RMSVA 4'	RMSVA 16'	MO	SLOPE VARIANCE
14/11/1989	1	142.57	2.89000	0.61000	81.45	8.37078
	2	145.86	2.91000	0.61000	81.91	7.57612
	3	145.13	2.92000	0.61000	82.14	7.61998
	4	142.36	2.86000	0.60000	80.58	7.22167
	5	143.00	2.89000	0.61000	81.45	7.91892
Section mean:		143.78	2.89000	0.60400	81.50	7.74149
20/09/1990	1	152.52	3.17000	0.64000	89.74	8.27728
	5	156.11	3.27000	0.64000	92.04	11.06149
	6	157.31	3.36000	0.64000	94.29	11.92499
	7	154.34	3.34000	0.64000	93.65	12.92510
	8	155.86	3.28000	0.64000	92.45	12.64078
Section mean:		155.22	3.28200	0.63700	92.43	11.36593
25/06/1991	2	158.62	3.44000	0.66000	97.11	9.86607
	3	160.03	3.43000	0.66000	97.06	8.94668
	4	158.87	3.46000	0.66000	97.86	9.34306
	5	161.58	3.48000	0.66000	98.03	10.62972
	6	160.94	3.46000	0.67000	98.15	9.21840
Section mean:		160.00	3.45300	0.65900	97.64	9.60079
15/11/1991	1	150.42	3.26000	0.64000	92.10	10.18547
	2	151.62	3.29000	0.65000	93.08	10.13311
	3	149.33	3.26000	0.64000	92.10	10.99880
	4	145.77	3.23000	0.64000	91.30	10.16561
	5	149.17	3.21000	0.64000	90.95	10.08302
Section mean:		149.26	3.24900	0.64100	91.90	10.31320
30/04/1992	1	164.63	3.50000	0.67000	99.25	11.14851
	2	162.66	3.46000	0.67000	98.15	10.12618
	3	163.07	3.47000	0.67000	98.56	9.79674
	4	165.37	3.48000	0.67000	98.50	10.27155
	5	162.65	3.50000	0.66000	98.67	9.89389
Section mean:		163.67	3.47800	0.66600	98.62	10.24738

FIGURE 4 Example of historical summary numerics for GPS 545007, West Virginia.

the left and right wheelpaths using the wire method for rut depth interpretations.

Example Results—GPS

Profiles of GPS sites gathered over the years since the start of the LTPP program are used here to illustrate the variety of observed behavior of pavement surfaces.

Table 1 is a summary of IRI values calculated from measured profiles of GPS sites in New Jersey over a 4-year period from 1989 to 1992. The table shows the IRI value for each of the five runs or passes at 80 km/hr (50 mph), which was accepted to represent the test section. It is seen that only one in three of the test sections is accepted from the first five runs, and one in eight needs nine runs for acceptance (criterion based on variance in IRI).

In 3 of the 10 test sections there is a decrease in IRI over the 4-year period. In section 341003, for example, the IRI values for 1989, 1990, 1991, and 1992 are 127, 117, 103, and 96, respectively. It is known, however, that IRI increases over the long term as is demonstrated in section 341030 where IRI values over the 4 years from 1989 to 1992 are 225, 253, 302, and 285.

Section 372819 shows a more consistent increase over the 4 years. Figure 7 shows the profile in early 1990 and late in 1990, in 1991 and in 1992 with the IRI progressing from 60 to 62 to 69 and to 74. The similarities (espe-

PROFCAL SUMMARY REPORT

Monday, May 17, 1993 10:01:46

SETUP:

Spatial Filter Wavelength.. 300.0
Start method........................ PHOTOCELL
Stop Method........................
Wavelength Initialization... DISABLED

SURVEY:

GPS.................... 361234
Oper/Driver....... Scott/Randy
Date.................... 18/05/1992
Time.................... 13:41:55
Station................ 0 - 500

LOCATION:

Begin......................
End.........................
Lane....................... LN 1
Direction.............. EAST
Horizontal
Offset..................

CONDITIONS:

Pavement
Road................. LAWRENCE BELL
Surface Mat'l.. ACC
Surface Cond... FAIR
Weather
Temperature.. 70 F
Cloud............... P CLOUDY
Other...............

Speed: 35 mph														
Interval	Run 1		Run 2		Run 3		Run 4		Run 5		Average		Std. Dev.	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
0 100	47.36	101.63	49.60	97.68	50.24	101.50	44.94	100.89	51.34	100.15	48.70	100.37	2.55	1.61
100 200	74.71	76.91	76.21	77.67	75.33	73.92	75.04	78.44	76.16	78.73	75.49	77.13	0.67	1.93
200 300	100.19	96.05	101.79	95.62	101.55	95.38	99.23	94.38	98.23	99.21	100.20	96.13	1.51	1.83
300 400	116.39	141.77	116.15	144.61	116.00	143.31	117.29	144.73	116.86	146.01	116.54	144.09	0.53	1.61
400 500	181.98	222.81	179.33	218.45	182.53	214.61	176.84	211.75	178.30	214.85	179.80	216.49	2.42	4.26
Average	104.12	127.83	104.61	126.80	105.13	125.74	102.66	126.03	104.17	127.79				
Std. Dev.	50.78	58.11	48.88	56.90	50.05	55.68	49.56	53.84	48.13	54.54				
Minimum IRI	47.36	76.91	49.60	77.67	50.24	73.92	44.94	78.44	51.34	78.73				
Maximum IRI	181.98	222.81	179.33	218.45	182.53	214.61	176.84	211.75	178.30	214.85				
Minimum Ele.	-0.968	-0.968	-0.978	-0.993	-0.974	-1.002	-0.967	-0.993	-0.980	-0.978				
Maximum Ele.	1.454	1.957	1.428	1.971	1.480	1.908	1.482	1.918	1.476	1.909				
0 - 500	104.85	127.52	105.16	126.58	105.79	125.44	103.14	125.80	104.76	127.41	104.74	126.55		
	116.18		115.87		115.62		114.47		116.09		115.65		0.69	

FIGURE 5 Example summary results from analysis of profile data collected at 60 km/hr (35 mph).

SOURCE OF VARIATION	SUM OF SQUARES	DEGREES OF FREEDOM	MEAN SQUARE MS	F-TEST CALC.	F-TEST TABLE @ 5% LOS
BETWEEN SPEEDS	44.77	3	14.9	22.8	3.24
WITHIN SPEEDS	10.46	16	0.65		
TOTALS	55.23	19			

LSD value= 1.08

MEAN IRI (in/mi)	SPEED (mph)	DIFFERENCE	COMMENTS
113.50	25		
		2.15	IRI's @ 35 mph are different from IRI's @ 25 mph
115.65	35		
		0.41	IRI's @ 45 mph are similar to IRI's @ 35 mph
116.06	45		
		1.64	IRI's @ 50 mph are different from IRI's @ 45 mph
117.69	50		

There is significant difference between the mean IRI values for the different speeds.
NOTIFY THE RCO ENGINEER then:
a) Check for driver behaviour (reaction time).
b) Check accelerometer calibration (left and right wheel paths).
c) Check distance measuring instrument and calibrate.
d) Check electrical components.
e) Check light source referencing system.
f) Contact K.J. Law for assistance in trouble shooting.

FIGURE 6 Example of comparison of four sets of data collected at different speeds.

cially for the longer wavelengths) in each of the four profiles are unmistakable.

The effect of diamond grinding on concrete pavement is shown in Figure 8, test section 245807. The IRI value in December 1989 was 169, which increased to 175 in October 1990. Diamond grinding was done in November 1990 but the profile was not measured again until April 1991. The IRI value was 79. The IRI value in June 1992 was 81. Again, the similarities among the four profiles are unmistakable, even though the IRI value after grinding is half what it was before.

The effect of an asphalt overlay of section 541640 is shown in Figure 9. The IRI value in November 1989 was 94, and this increased by September 1990 to 112.

The pavement was overlaid in summer 1991 and the IRI in November 1991 was 52. The April 1992 IRI value was 48. Again, the four profiles have distinct similarities in spite of the overlay.

In these examples the distinctive similarity of profiles taken of the same segment of roadway over 4 successive years is considered very strong evidence of the stability and reliability of the profiling system over time. It also lends credibility to the IRI values calculated from these profiles and support for the procedures adopted.

A dynamic calibration test site was established on a new section of roadway adjacent to the North Atlantic Regional Office in Amherst, New York. The roughness in the section was mainly due to inherent distortions with little initial surface distress manifestations. Aside from using this site for the dynamic calibration of the profilometer, it has also been monitored at regular intervals to assess potential seasonal changes in roughness as shown in Figure 10. Each of the IRI values shown in Figure 10 is an average of five times the number of runs usually taken to represent a site, and they all must satisfy the variance criteria for acceptance. Although the intent was to depict changes related to environmental conditions at the time of the test, many of the changes are due to distress formation at the test location, or minor maintenance intervention.

TABLE 1 Example Profilometer Data Collection and Processing Summary for GPS Sites in New Jersey

SHRP ID NUMBER	EXP. NO.	SURVEY DATE mm/dd/yy	IRI DATA SUMMARY										REHAB/ MAINT TYPE	REHAB/ MAINT DATE	
			Run Number									AVG			
			1	2	3	4	5	6	7	8	9	IRI			
341003	1	11/24/89	128.65	131.81	128.14	122.98	123.06					126.93			
		11/28/90	116.71	122.65		119.52	112.05	113.96				116.98			
		09/06/91				106.44	97.19	100.91	108.89		101.67	103.02			
		06/17/92			96.17		95.98	96.20	95.13	97.72		96.24			
341011	1	11/30/89	104.43	98.39	96.32	107.19	103.60					101.99			
		11/30/90	102.85	101.73	101.27	101.92	105.01					102.56			
		09/07/91	110.83		109.12	108.04		107.27	107.57			108.57			
		06/22/92	101.85	102.67	101.55		103.46		103.13			102.53			
341030	1	11/27/89	217.20	229.88	230.48	218.41	229.21					225.04			
		11/29/90	255.49	259.91	252.88		243.45	252.78				252.90	CS	02/25/91	
		09/06/91	306.96				305.66	299.36	299.35	300.16		302.30			
		06/17/92	283.34	284.61		287.73	282.62	286.30				284.92			
341031	1	12/01/89	109.46	110.49	112.01	109.02	115.35					111.27			
		11/15/90		112.50	116.56		115.78	116.84			113.38	115.01			
		09/08/91	119.49	123.92	120.00		123.82	121.79				121.80			
		06/21/92	116.17		114.10	113.31		115.60	116.48			115.13			
341033	2	11/28/89	202.17	201.93	202.37	197.87	204.59					201.79	CS ON SHDR	?	
		11/30/90		177.06	178.44	176.87	168.70	168.08				173.83			
		09/06/91	178.42	175.67	176.23	176.53	176.35					176.64			
		06/18/92			184.43			186.31	183.19	185.87	184.68	184.90			
341034	2	11/30/89	84.83	85.30	85.21	85.73	85.19					85.25			
		11/18/90	85.76	85.91	84.97	85.77	84.90					85.46			
		09/07/91			88.72	87.90			88.28	88.53	87.44	88.17			
		06/20/92		89.46	86.88	86.87	88.01	87.22				87.69			
341638	2	11/30/89	55.96	56.11	58.38	57.11	57.82					57.08			
		11/16/90	60.64	59.24	59.21	59.66	59.76					59.70			
		09/07/91	60.73	66.04	68.59				59.56	62.02		63.39			
		06/20/92	56.27	57.33	58.47	57.80	57.84					57.54			
340559	Aux.	01/25/92		153.84			152.53	153.07	153.89	152.85		153.24	OVERLAY	?	
(341995)		10/30/92		54.58	54.48	54.02	55.47	54.45				54.60			
344042	4	11/29/89	115.28	115.86	117.04	116.96	118.07					116.64	CS	?	
		11/16/90			158.57	153.33	159.81	166.52	166.04			160.85			*
		09/08/91	121.77	123.18	117.38	121.83	119.82					120.80			
		06/20/92					108.07	108.53	109.37	108.36	110.51	108.97			
346057	6A	11/28/89	123.63	122.90	121.55	121.49	117.09					121.33			
		11/29/90		94.60	95.13	97.61	96.80	96.48				96.12			!
		09/06/91	93.43	94.45	95.19	95.51	97.19					95.15			
		06/18/92	94.61	95.47		95.76	94.93		96.80			95.51			

* Pothole in RWP at station 162.5.

! Construction activities present during survey.

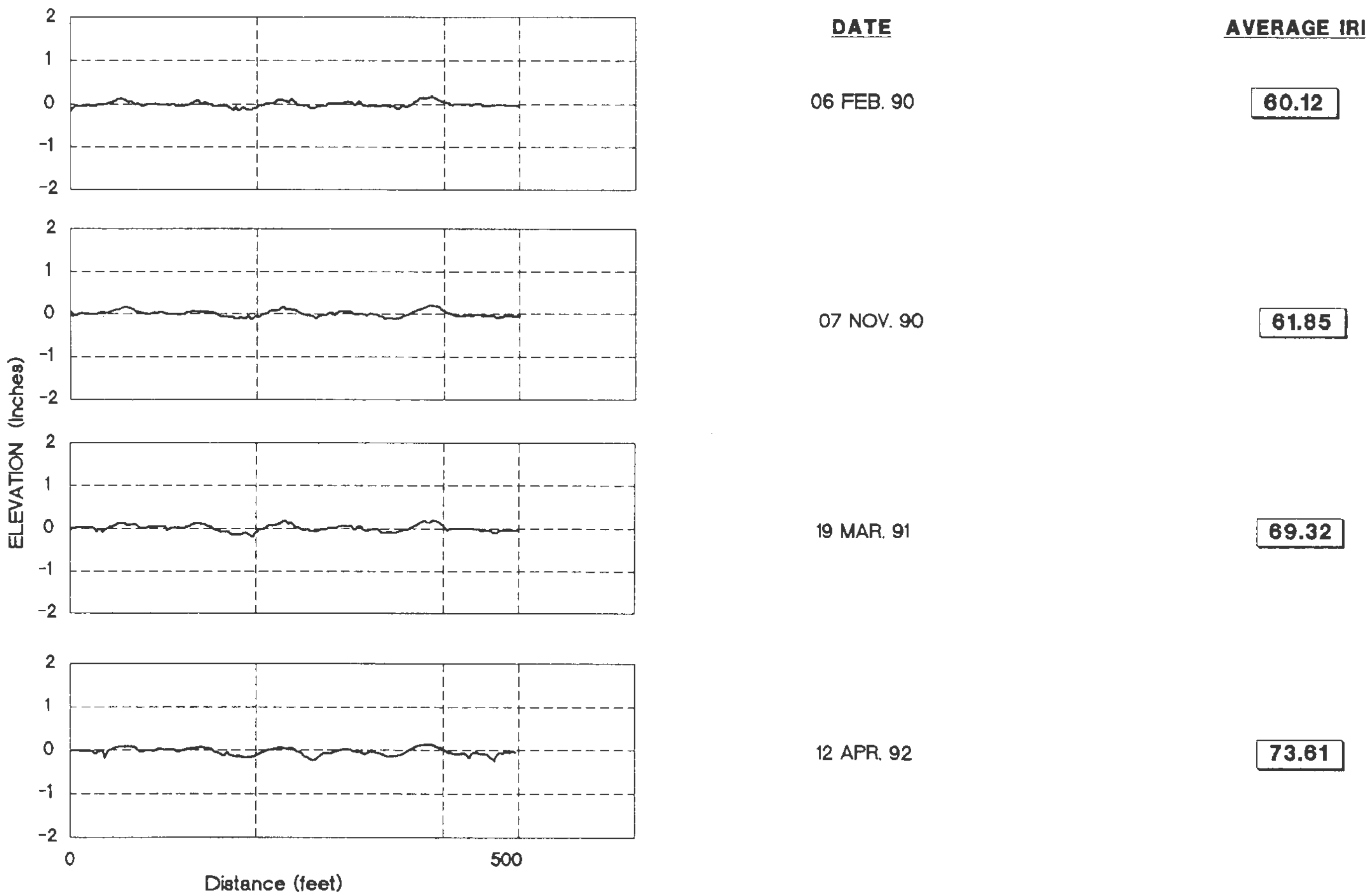

FIGURE 7 Increasing IRI with no maintenance—GPS 372819 (SHRP).

Adapting Procedures to Other Agencies

The procedures and software developed for the LTPP program could help agencies that want to monitor pavement sections for comparing various maintenance treatments or development of localized performance models. To accomplish this the PROQUAL suite of programs would have to be enhanced to accept data from other profile measuring devices that an agency might operate. This may entail modifying the software to accept a different file format and different sampling rate for the calculation of the various performance indexes.

Transfer of these specialized procedures from the LTPP program to an agency research or maintenance evaluation department can be effected with some additional effort. A technique is needed for characterizing a segment of highway, perhaps an inventoried segment, so that it can be monitored in a similar manner to the LTPP sections to determine change over the years. Although there are no restrictions on the number or length of pavement sections that can be input or analyzed and reported on through the PROQUAL software, for practical considerations it is probably best to limit the number of continuously collected pavement sections to be evaluated to the range of 20 with lengths of 400 m (1312 ft) or less. The PROFCAL portion of the software may also be useful to those agencies that want to perform dynamic calibration checks on their equipment. The comparison of profile data collected at various speeds over a section of pavement, when analyzed, will enable an agency to determine whether there is a speed-related tendency in their equipment or profiling operation and that the profiling device is acceptable from a repeatability/accuracy standpoint.

Planning for the Future

Although a great deal of progress has been made in the area of pavement roughness evaluation since the days when response-type roughness devices were used virtually exclusively, this field continues to evolve. When the SHRP-LTPP data collecting activities were getting underway just 5 years ago, only a few profiling devices were commercially available. Today, a number of manufacturers offer devices that show a great deal of promise. Improved sensor technology and the ever-increasing ca-

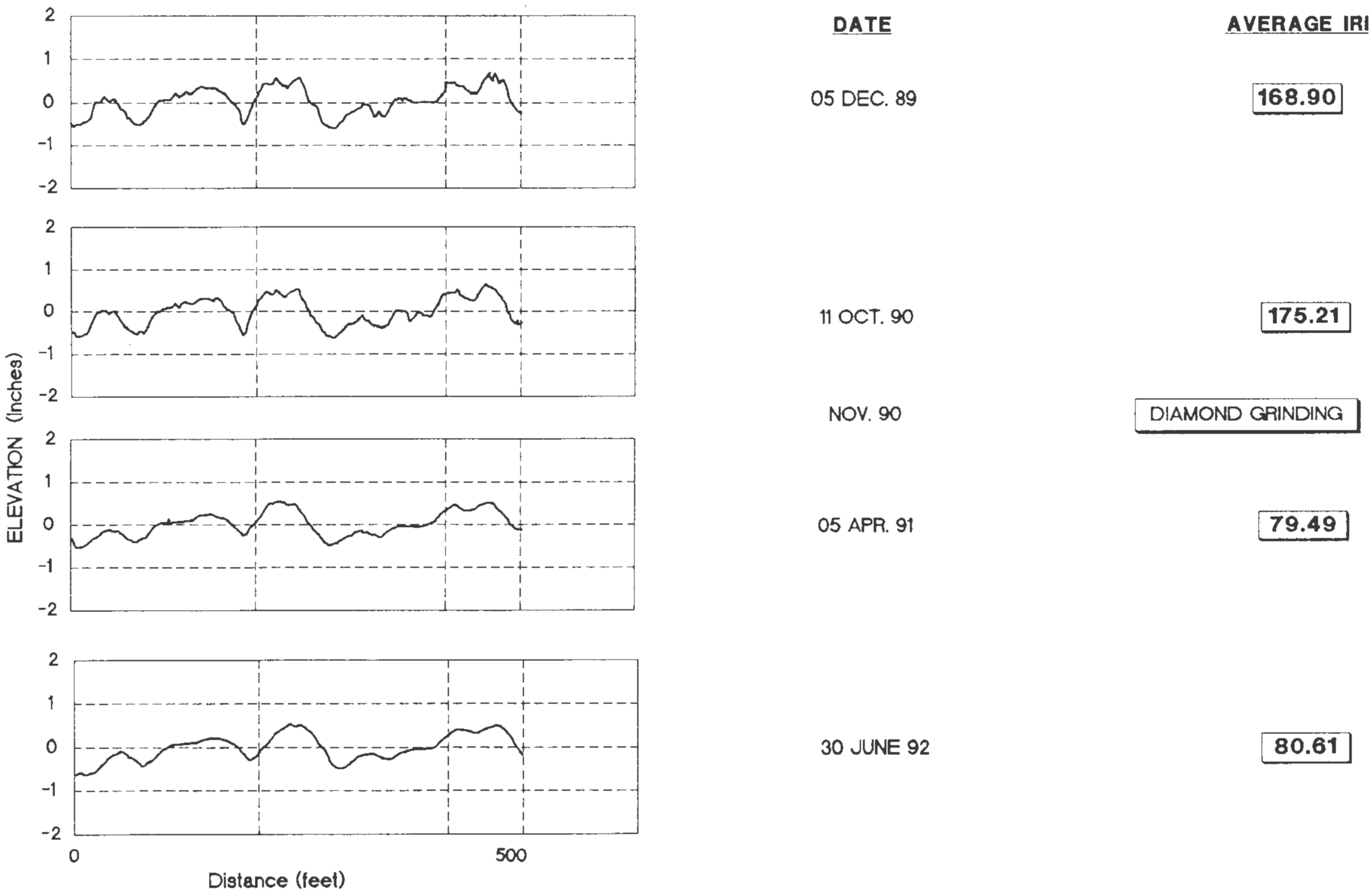

FIGURE 8 Effect of diamond grinding—GPS 245807 (SHRP).

pabilities of personal computers have brought about significant advances in profile data collection technology. These devices have the potential to be less costly to purchase and less costly to maintain—largely because of improved computer technology. The newer sensor systems have the potential to be more reliable, from a standpoint of ruggedness and sensitivity to ambient conditions (like sunlight).

Faster computer systems mean that data acquisition and storage algorithms are no longer limited by computer speed, but are instead constrained by technical requirements for the data. The LTPP program will take advantage of these advances in the near future, when replacements for the profilometers are acquired.

There has been somewhat less progress in the processing of pavement profile data, but advances in this area appear to be just over the horizon. The strengths and limitations of existing profile statistics, such as IRI, have been recognized, and efforts are underway to develop better schemes for comparing the output from different profiling devices, as well as more meaningful profile-based methods for evaluating pavement condition. The LTPP program will both foster and take advantage of these developments.

However, new developments, whether in profile measurement technology or in data processing technology, should not and will not be adopted without regard for compatibility with past data. A link between the old and the new must be maintained, if the data are to serve the intended purpose. The groundwork for maintaining this link has already been laid, in that the data collected to date have been stored in the "least-processed" form possible with the available technology.

Summary and Conclusions

As part of the SHRP-LTPP program, profile data are currently collected on nearly 3,000 pavement test sections in the United States and Canada. To ensure accuracy and uniformity in data collection and to reduce the raw profile data to performance indexes that can be used for pavement evaluation purposes, SHRP has developed a

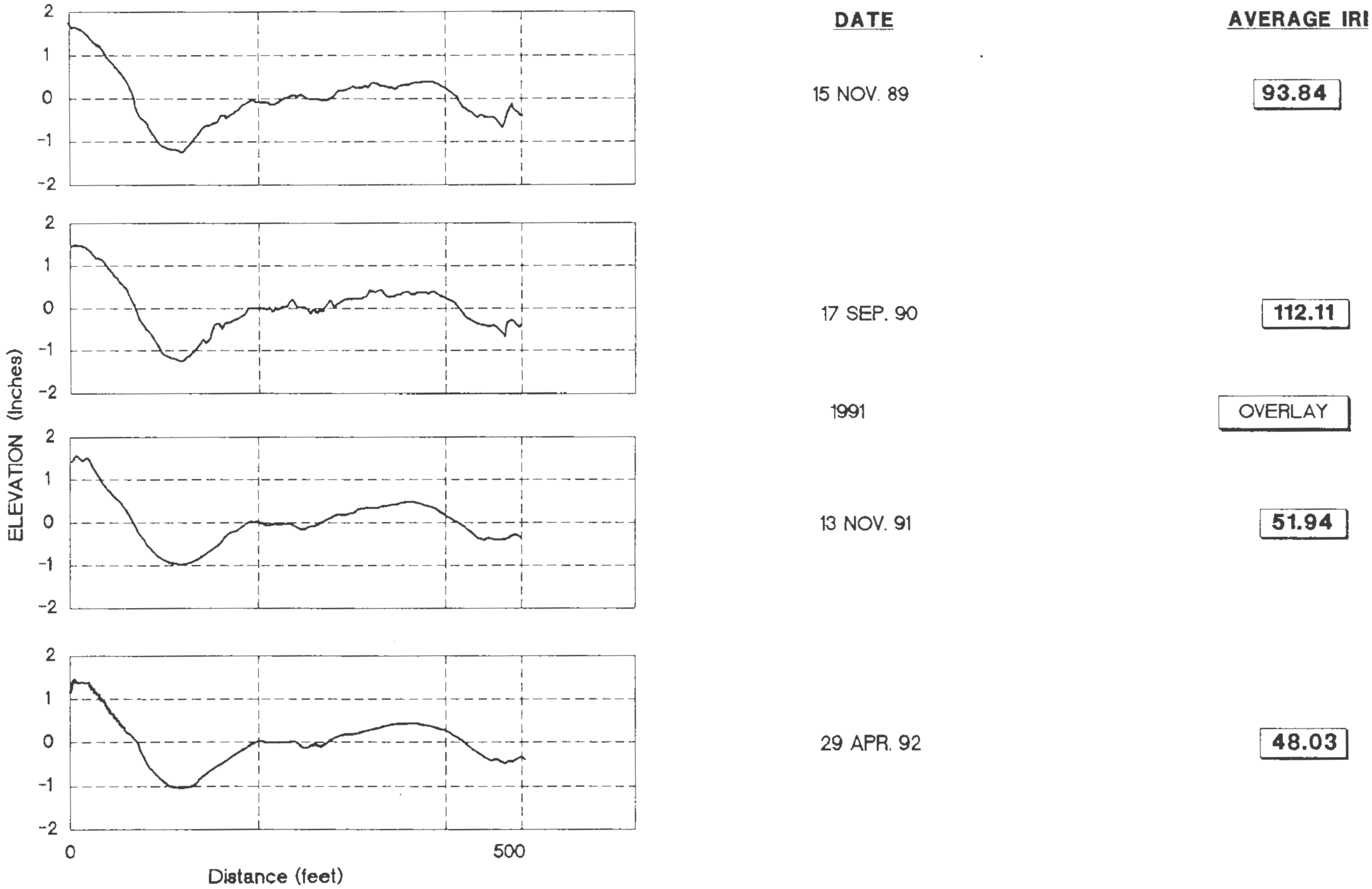

FIGURE 9 Effect of overlay—GPS 541640 (SHRP).

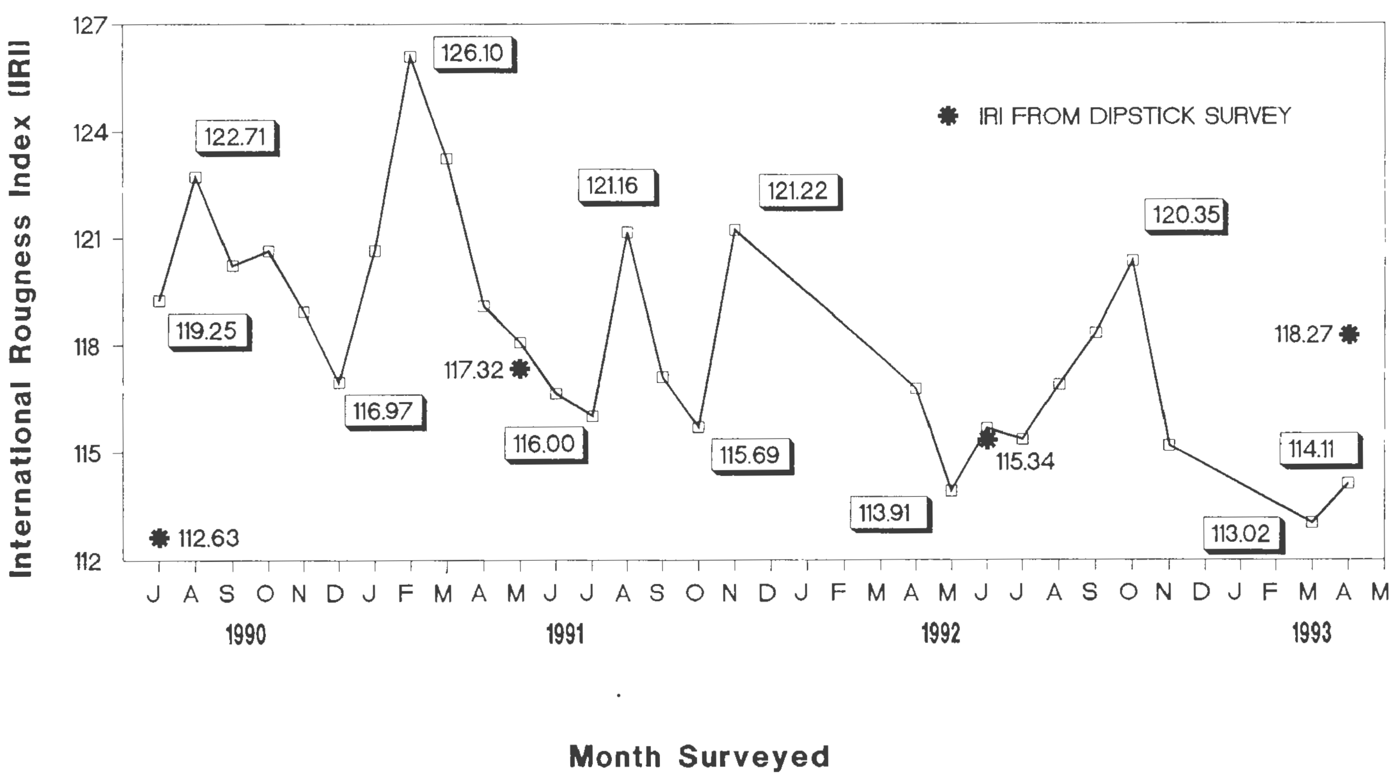

FIGURE 10 Profilometer dynamic calibration test site—North Atlantic Region.

suite of computer programs to support this data collection program.

Four computer programs were developed, interfaced, and coupled into a single module called PROQUAL. The individual software packages are:

1. PROFSCAN—developed as a field quality assurance and subsectioning tool to be used by the profilometer operator on or near the test site,
2. PROFCHIK—developed to implement a final series of quality checks for the SHRP profile data and compute a number of summary numerics or indexes for use in subsequent data analysis,
3. PROFCAL—developed for dynamic calibration of the proflimeter to ensure that repeatable and accurate data can be collected by the device, and
4. DIP—developed to input and analyze longitudinal and transverse profile data collected with the dipstick.

Although originally developed for use with the SHRP profile data, the software could be adapted if needed to other profiling devices to make an exceptionally useful pavement evaluation tool.

Examples of results obtained over the past 4 years of the SHRP-LTPP study are used to illustrate the stability of the measurements and the effects on roughness of seasonality and maintenance interventions. The experience with the profilometer when used in the manner described and with the PROQUAL software programs indicates that there need be no further doubts about the reliability, and stability over time, of evaluations made with these tools for use in pavement performance evaluations.

As advances are made in the profile data collection and processing technologies, the plans for the LTPP program are to update and keep current the technologies as new equipment is required over the life of the program. The improvements and updates will be undertaken with the knowledge that the data and resulting performance indexes must maintain consistency with past procedures.

REFERENCES

1. *SHRP-LTPP Manual for Profile Measurements, Operations Field Guidelines, Version 2.0, P-001.* Technical Assistance Staff, March 1993.
2. *PROQUAL, Version 1.4, User Documentation.* Prepared for SHRP by Pavement Management Systems Limited, June 1992.

Implementation of a Calibration Procedure for Falling Weight Deflectometers

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Gaylord Cumberledge, *Pennsylvania Department of Transportation*
Brandt Henderson, *Pavement Management Systems, Inc.*

A procedure for calibration of falling weight deflectometers (FWDs) has been developed by the Strategic Highway Research Program (SHRP). This procedure was developed to reduce the systematic error, typically up to ±2 percent of the load and deflection readings, by calibrating FWDs to a reliable reference standard. The procedure was developed for use with all types of FWDs. To date it has mainly been used with Dynatest FWDs; however, it has also been used with the KUAB and the JILS FWDs. The development of the calibration procedures, the equipment associated with the reference calibration systems, the facility requirements and operational aspects, and the calibration protocols necessary to perform reference and relative calibration of FWDs are described. Four regional calibration stations have been established by SHRP in cooperation with the state highway agencies in Minnesota, Nevada, Pennsylvania, and Texas to calibrate SHRP FWDs and those of other highway agencies, institutions, and private concerns. The Long-Term Pavement Performance Division of FHWA is now maintaining the liaison with the state departments of transportation (DoTs). The results from a series of round robin tests with the four regional SHRP FWDs indicated that there was no significant difference in the calibration factors attributable to the locations where the FWDs were calibrated. For owners and operators of FWDs there is an advantage to having deflection results from calibrated FWDs, because the results from back-calculation are more accurate.

The falling weight deflectometer (FWD) was selected by the Strategic Highway Research Program (SHRP) for the nondestructive deflection testing of a broad range of pavements within the SHRP program. The data collected by four regional contractors will be used for the structural evaluation of the pavement test sections and the development of analytic models.

SHRP's experience with the Dynatest FWD has shown that there is a small variation in deflection at a given drop height (*1*). This is both an advantage and a liability, because due to the high degree of repeatability, small differences between two FWDs can possibly be statistically significant. Typical specifications for FWDs allow up to ±2 percent error in the load and deflection readings. If one FWD is at one end of the allowable range, and another is at the other end of the range, the differences would be significant. It has been shown that small errors in the deflection readings can result in large variability of the back-calculated layer moduli (*2*).

It was recognized by SHRP that to obtain consistent and comparable deflection responses between four regional FWDs, the load cell and deflection sensors would have to be calibrated using independently calibrated reference devices (*1*). In this way the user of the FWD data could be sure that a uniform and standardized field measurement was being obtained, and data obtained by different FWDs would be comparable.

This paper presents a summary of the development of calibration procedures, selection of equipment, design and fabrication of the test pad in Pennsylvania, calibration protocols, experience gained from the implementation of the calibration procedures, and concluding remarks.

Initial Development of FWD Calibration Procedure

The original intent of the SHRP project was to develop a calibration procedure that could be applied to the four FWDs owned by SHRP and also to other state department of transportation (DoT) FWDs that might be used to assist SHRP. Although the four SHRP FWDs and those of many states are made by Dynatest, the states and FHWA own many FWDs that were made by other manufacturers, including KUAB, Pavement Mechanics, Inc. (the JILS FWD), and Phøenix. Thus it was intended from the beginning that it would be possible to use the equipment and the methodology to calibrate FWDs from all manufacturers.

To date the procedure has been used successfully with many different Dynatest FWDs and with several KUAB FWDs. It has been tried experimentally with a JILS FWDs built by Pavement Mechanics, Inc. It has not yet been tried with the Phøenix FWD, but the equipment is available to do so. Neither the equipment nor the procedure is suitable for use with cyclic-loading deflectometers such as the Dynaflect and the Road Rater.

The earliest SHRP efforts to develop a calibration procedure for FWDs were carried out at the research laboratory of the Indiana DoT in fall 1988. Purdue University advised and assisted the effort. A prototype instrumentation system was developed, involving a computer-based data acquisition system, a reference load measurement system, and a reference deflection measurement system. The four SHRP Dynatest FWDs were run through reference calibration of the load cell and each of the seven deflection sensors. From this pilot study several things were learned.

- It is feasible to do reference calibration of FWDs, but improvements in the equipment, particularly the reference load and deflection measurement systems, were necessary.
- It is necessary to conduct the calibration indoors so that the equipment and the operators are protected from the weather.
- The reference deflection measurement system must be isolated from transient vibrations generated by the FWD.
- A special test pavement must be constructed for conducting the calibration tests to ensure that the deflections are large enough.
- A standardized procedure for calibration of the FWDs must be developed so that calibration could be carried out regionally.
- After calibration the four FWDs yielded data from specified test points that were highly comparable. Before calibration the results were within the specification tolerances, but the deflection data were statistically significantly different.

The latter finding is a result of the fact that the measurements from any one FWD are highly repeatable. Therefore a small difference in the means of the measurements from two different FWDs can be statistically significant.

On the basis of these findings it was determined by SHRP that it would be desirable to develop an FWD calibration protocol and establish four regional FWD calibration centers (*1*). Various state DoTs were contacted to see whether they would be willing to host and operate the calibration centers. As a result, regional calibration centers are now operating under the management of the Minnesota, Nevada, Pennsylvania, and Texas DoTs. The calibration equipment is in St. Paul, Minn., Reno, Nev., Harrisburg, Pa. and Bryan, Tex.

Need for Accuracy in FWD Measurements

The need for calibration is best understood by examining the implications of FWD accuracy on the data and the interpretations that are made from the data (e.g., back-calculation of layer moduli). Typical specifications for FWDs require an accuracy within ±2 percent for the indicated load and deflections. This allows a systematic error that does not vary from time to time, but its magnitude varies from one transducer to another, depending on the accuracy of calibration of the transducer.

A second source of error comes from the analog-to-digital (a/d) conversion in the data acquisition system, typically with a range that is not more than ± 2 bits. This is a random error that continuously varies from one reading to the next, but the range is equal for all transducers.

The consequence of the systematic error in the indicated load is relatively small. If the load is registered 2 percent higher than it really is, the back-calculated moduli come out 2 percent high. The percentage effect on the modulus is the same for each layer. The random error is of even less concern. One bit typically corresponds to 45 N (10 lb) or so; thus the accuracy of a load measured as 27 kN (6,000 lb) is ordinarily limited by the systematic error, not the random error.

The consequence of errors in the indicated deflections is of greater concern. For a deflection sensor, 1 bit usually corresponds to 1 μm (0.04 mils). (Note: 1 μm = 10^{-6} m = 10^{-3} mm.) Therefore the random error of an indicated deflection is ±2 μm. The center deflection on a deflection basin, which might be 500 μm (20 mils) in amplitude for a medium-strength asphalt pavement, could potentially have an error as large as ±10 μm (because of the systematic error). The accuracy of an outer deflection, which at a distance of 2 m or so from the load might have an amplitude of 50 μm or less, would be limited by the random error. If the systematic error is ±2 percent, then any deflection that is measured to be less than 100 μm would have its accuracy controlled by the ±2 μm random error.

The effect of the random deflection error on back-calculated moduli was investigated by Irwin et al. (2). Using elastic layer theory, they calculated the deflection basin for a medium-strength pavement, simulating the data that might be obtained with a FWD. The computer program MODCOMP, Version 2.44, was used to perform the back-calculations.

They used a normally distributed random number generator to modify the deflection data, simulating the random error, assuming a standard deviation of ±2 μm, and rounding the result to the nearest whole unit. Thirty deflection basins were produced in this fashion, and the data sets were processed using the back-calculation program to determine the layer moduli. Because the moduli that were used to generate the original deflection basin were known, they could be compared with the 30 sets of back-calculated moduli. The results are given in Table 1.

The data in Table 1 show that the influence of the random deflection error is greatest for layer 1 and least for layer 4. The effect on the back-calculated modulus of the subgrade was essentially nil, and the error in the modulus of the surface layer ranged from −35 to +45 percent. These results were based solely on the ±2 μm random error. If a ±2 percent systematic error had been incorporated also, the effect would have been even more dramatic.

On the basis of studies such as these, SHRP decided to develop a procedure for the calibration of their FWDs that would reduce the systematic error of the load and deflection data to as close to zero as possible.

It was recognized that it would not be possible to reduce the random measurement error by means of calibration. However, by averaging replicate results of four drops at each drop height, the standard error of the mean would be diminished by the reciprocal of the square root of the number of drops. The net result would be to reduce the standard error from ±2 μm to less than ±1 μm.

Development of Calibration Equipment

An IBM-compatible, microcomputer-based data acquisition system was selected. The Metrabyte model DAS-16G 12-bit board was chosen for use, primarily because it came in two versions, one that could be used in an AT-style computer and a similar unit that could be used in a PS/2 computer. This allowed a maximum amount of flexibility because the two boards are software compatible.

For load cell calibration a reference load cell was custom designed. It has a load capacity of 180 kN (40,000 lb). Because SHRP has standardized the FWD load levels at 27, 40, 53, and 71 kN (6,000, 9,000, 12,000, and 16,000

TABLE 1 Effect of ±2 μm Random Measurement Error on Back-Calculated Pavement Layer Moduli (2)

Layer	Layer Thickness, in	Actual Modulus, psi	Range of Back-Calculated Moduli, psi	Standard Deviation of 30 Results
1	3	300,000	196,000 to 426,000	50,000
2	6	45,000	32,000 to 59,900	5,900
3	12	21,000	18,700 to 25,500	1,400
4	∞	7,500	7,390 to 7,670	90

Note: 1 in = 25.4 mm; 1 psi = 6.89 kPa

lb respectively), the reference load cell is calibrated to give a full-scale output (10 V) at 90 kN (20,000 lb). The reference load cell is calibrated annually using special equipment and software developed specifically for this purpose. To achieve a load measurement accuracy of 0.1 percent or better, a nonlinear model is used. The reference load cell is 300 mm (11.9 in.) in diameter and 83 mm (3¼ in.) high. It is designed to be placed directly under the load plate of the FWD, as shown in Figures 1 and 2.

For deflection sensor calibration a reference system incorporating a linear variable differential transducer (LVDT) was selected. A Schaevitz model GCD-121-125 gauge head is used. The stem of the LVDT is spring-loaded. It has a stroke of ±3.18 mm (±0.125 in.). Because the stroke on the Dynatest FWD deflection sensors is limited to 2 mm, the LVDT is calibrated to give full-scale output at ±2 mm. Calibration of the LVDT is accomplished using a micrometer, as shown in Figure 3. Special software is used for the calibration and data analysis, and a calibration accuracy of 0.1 percent or better is achieved.

FIGURE 1 FWD load cell calibration equipment.

The LVDT is positioned in tandem with the geophone under test (Figure 4). The Dynatest geophone has a magnetic base, which firmly attaches it to the deflection sensor holder that is, in turn, bolted to the floor. The body of the LVDT is mounted on the end of a cantilever beam, and is magnetically linked to the sensor holder. A second design of the deflection sensor holder was made to accommodate the taller seismometers in use on the KUAB and the other brands of FWDs. The horizontal I-beam is attached to an 1800-kg (4,000 lb) inertial block, which rests on low-frequency vibration damping pads at the four corners (Figure 5). The I-beam and the LVDT holder are made of aluminum to minimize their mass.

During deflection sensor calibration the FWD is positioned on a specially designed test pavement, about 500-600 mm (20-24 in.) away from the deflection sensor holder (Figure 6). When the FWD is used to produce a pulse load on the test pad, the sensor holder and the stem of the LVDT move an identical amount.

The body of the LVDT must not move for the peak deflection to be registered accurately. It is important for the inertial block and the aluminum beam to remain absolutely unmoved until a few milliseconds after the deflection sensor under test has experienced the peak deflection. To establish that the LVDT body did not move, a second FWD deflection sensor is mounted on the end of the beam, near the LVDT. It is visible in the right-center in Figure 4. Time history data acquired by the FWD then report the peak deflection of the deflection sensor under test and a complete record of the movement of the beam, if any. Beam movement less than ±2 μm (0.08 mils) is allowable.

FIGURE 2 Reference load cell beneath the FWD load plate; small wire descending from upper center of picture leads to FWD load cell.

FIGURE 3 Reference LVDT in micrometer calibrator; 2310 signal conditioner to the right of computer monitor.

FIGURE 4 Geophone in holder (on test pad) with LVDT mounted on end of aluminum I-beam; second geophone (right of LVDT) used to monitor beam movement.

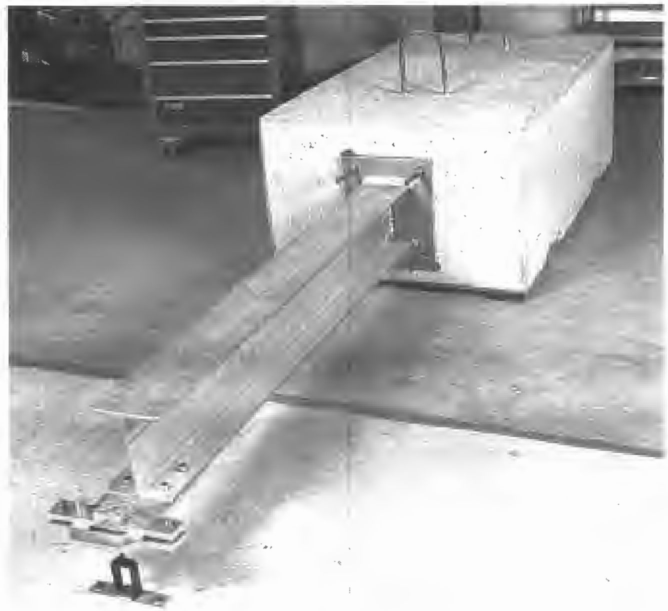

FIGURE 5 Aluminum I-beam mounted on concrete inertial block; deflection sensor holder bolted to test pad beneath end of beam. To calibrate KUAB seismometers, LVDT holder is moved to top of I-beam.

FIGURE 6 FWD deflection sensor calibration equipment.

A Measurements Group, Inc., model 2310 signal conditioner was selected. It is used to power the transducer and amplify the return signal for both the reference load cell and the reference LVDT. To provide the required +15 V and −15 V excitation for the LVDT, a special modification of the unit is required. The signal conditioner has features that make it particularly useful in this application, including an automatic zero balance and two levels of shunt calibration.

The cost of each calibration equipment set, including the concrete inertial block and all fabricated parts, the reference load cell, the LVDT and micrometer calibrator, the signal conditioner and the data acquisition board, but excluding the computer, was about $8,100 (in 1992 dollars).

Design and Construction of Test Pad

Probably the single feature that is most important for the success of the deflection sensor calibration is the design of the test pad. The deflection sensor holder is typically located on the centerline of the test pad, about 1.2 m (4 ft) from the edge of the slab and about 0.5 m (20 in.) from the center of the load. It is vital that the peak deflection at this location be at least 400 μm (16 mils) at the 71 kN (16,000 lb) load level. This assures that the ±2 μm random error is a small percentage of the peak deflection.

The linear range of the FWD deflection sensors differs with each FWD manufacturer. For the KUAB FWD it is 5 mm (200 mils). For the Dynatest FWD it is either 2 mm (80 mils) or 2.5 mm (100 mils), depending on which model is purchased. In most routine field uses of the FWD it is seldom that any deflection sensor except the one or two in the center of the deflection basin registers deflections anywhere close to the full range of the sensor.

The calibration range of 400 μm (16 mils) represents a practical compromise because it is difficult to construct a test pad that will reliably and repeatedly yield much larger deflections without engendering rapid fatigue failure in the concrete surface. The test pad must be designed to last for 5 years or more. Careful attention is given to the statistical evaluation of the calibration data to be sure that it is linear and that the calibration factors are valid, because the sensors are calibrated over only the lower portion of their range.

The calibration protocol requires five drops to be made at each drop height, which reduces the standard deviation of the mean to less than ±1 μm. Thus, the random error is less than 1 part in 400, or less than ±0.25 percent. This makes it possible to calibrate out the systematic error, without it being masked by the random error.

The calibration location at the Pennsylvania DoT facility posed a particularly difficult problem because the entire building was underlain by shale bedrock at a shallow depth. One corner of the building actually rests on the bedrock. Thus the floor slab was too stiff, and it yielded deflections that were less than half of what was desired.

To overcome this problem a 5-m (15-ft) square portion of the floor slab was removed and a 1.6-m (5-ft) hole excavated. The hole was lined with a heavy polyethylene membrane and then filled with a saturated clayey silt. The silt was placed in lifts and lightly compacted. The object was to create a foundation that had a modulus of elasticity around 50 MPa (7,500 psi).

When the surface of the silt was about 240 mm (9½ in.) from the floor level the plastic membrane was folded over the top, and a 130-mm (5-in.) layer of coarse crushed stone was placed and compacted. A steel and fiber-reinforced concrete slab, approximately 115 mm (4½ in.) thick, completed the test pad. A 40-mm (1½-in.) block-out was left around the perimeter of the test pad, which was later filled with a latex bridge expansion joint compound.

After the slab had cured for 21 days it was tested to determine the deflection. Amazingly, it yielded 407 μm (16.05 mils) of deflection at the desired location, which is just what was sought.

All traffic is prohibited on the test pad except for calibration testing. After nearly 2 years of operations, the physical characteristics had changed slightly. The deflection at the highest load level had decreased by 75-100 μm (3-4 mils). To adjust for this, the position of the deflection sensor holder (and hence of the concrete inertial block) has been moved about 0.5 m (18 in.) closer to the edge of the test pad, where the deflections are larger. A small amount of slab settlement and curling has also been observed. It is thought that the reduced deflections and the settlement may both be caused by a minor amount of consolidation and loss of moisture that is taking place in the clayey silt subgrade.

Variable site conditions make it difficult to come up with a single design specification for the test pad that would work in all locations. Keeping in mind that the goal is a 400-μm deflection at the sensor holder, the FWD calibration protocol can be achieved successfully anywhere that this criterion can be met. Thus to transfer the calibration method to other sites, in the United States or elsewhere, is primarily a matter of test pad design. Because the deflection of the test pad varies across its width and length, with the largest deflections at the four corners, it should be possible to develop additional FWD calibration test centers wherever they are needed.

Development of Calibration Protocol

Much of the initial development of the calibration protocol and the accompanying FWDREFCL data acquisition software was done at the Indiana DoT facility in 1988. Many refinements have been added subsequently by developers at Cornell University and PCS/Law, Inc.

The protocol calls for five drops at each of the four SHRP standard load levels, for a total of 20 peak readings. One transducer, either the FWD load cell or a deflection sensor, is calibrated at a time. A typical deflection-time trace is shown in Figure 7. Data are collected by the reference system at a rate of 10 readings/msec for a period of 500 msec. The release of the FWD mass triggers the start of the data acquisition period. A set of 250 readings are averaged, as shown in Figure 7, to define the base level, or "zero," from which the peak is determined.

The 20 data pairs (FWD system reading as abscissa, reference system reading as ordinate) are subjected to a linear regression that is forced through zero. The resulting slope is the reference calibration factor. It is a multiplier that, when applied to the FWD reading, yields a reading that is corrected to agree with the reference system. Figures 8 and 9 give examples of the reference calibration results for a load cell and a deflection sensor, respectively.

Each FWD transducer (typically the load cell plus seven or nine deflection sensors) gets an individual reference calibration factor. These numbers must be entered into the FWD software, and thus it is necessary that there be a place to put the calibration factors. It is the responsibility of the FWD manufacturer to provide a method of entering and properly using the calibration factors.

After the reference calibration factors have been entered into the FWD software, the FWD deflection sensors

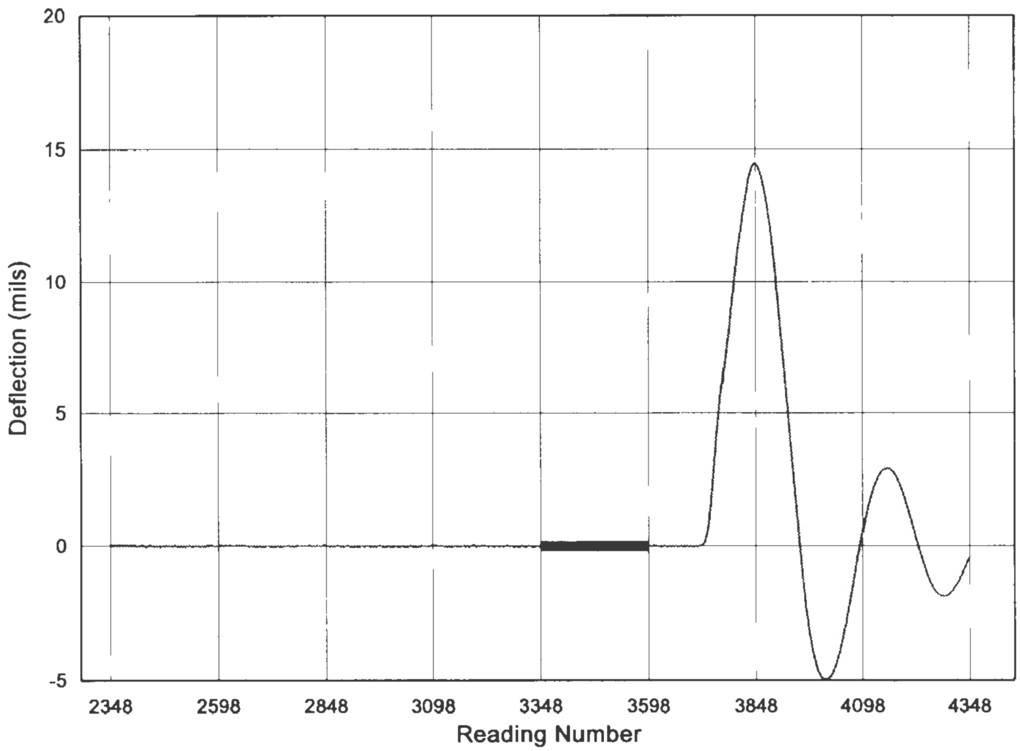

FIGURE 7 Typical time history plot for geophone calibration (only 2000 of 5000 data points collected are displayed). The 250 readings beginning 500 readings before peak are averaged to define zero level.

are subjected to as many as three relative calibrations. Relative calibration involves stacking the geophones in a stand, as shown in Figure 10, and subjecting them to a series of five drops, rotating the sensors through each position in the stand. Thus for a seven-sensor system there would be 35 drops. The drop height used and the position of the stand with respect to the center of load are adjusted to achieve a peak deflection near 400 μm. As was explained, this deflection level is chosen so that the random error will be small with respect to the peak amplitude.

The ratio of the average deflection for all sensors to the average deflection for an individual sensor is the relative calibration factor. An analysis of variance program, FWDCAL2, is used to evaluate the data. The relative calibration factor for each sensor is multiplied by the corresponding reference calibration factor to arrive at the final calibration factor. These final values are then entered into the FWD software. The results of a series of three relative calibrations are shown in Table 2.

Because the systematic error for both load and deflection is specified to be less than ±2 percent, it can be expected that the final calibration factors will be between 0.98 and 1.02. With relatively new equipment this has generally been found to be the case. It is important to keep a record of the calibration factors for the individual transducers over time. The factors should not change much, and if one does it is an indication that the transducer is nearing the end of its useful life and should be replaced.

It usually takes about 1 day to complete the testing, perform the calculations, and enter the results. This includes the time it takes to remove the deflection sensors from their holders on the FWD and return them to position. This time requirement may vary, of course, depending on the preparedness of the FWD and experience of the operator.

Precision and Frequency of Calibration

Various repeatability studies have been made using the SHRP calibration protocol. It has been established that if the procedure was repeated twice on the same sensor (load or deflection), the two calibration factors could be expected to be within 0.003 units of each other (i.e., within 0.3 percent). Three or more results typically have a standard deviation of less than ±0.003.

After the four regional calibration centers were established, a series of round robin tests was conducted using the four SHRP FWDs. It was not possible to have every FWD visit all four centers, and some equipment problems were experienced. Nevertheless, it was found that no significant difference was attributable to the location where

```
                     Filename: 8002048B.L01
           Date: 11-18-1993; Time: 13:09
            Air Temperature: 70

           System Under Test: 8002048
                FWD Operator: CJ SWANK
Calibration Equipment Operator: DAVE WASSEL
          Calibration Center: PennDOT Calibration Center
   Data Acquisition Board Type: MetraByte DAS16-G2
          FWDREFCL Software: Vers. 3.71; Release Date: 07/22/93

Reference Load Cell Data -
    Ref. Load Cell Serial Number: SHRP058
      Load Cell Calibration Date: 11-08-1993
    Load Cell Excitation Voltage:  10  volts
         Signal Conditioner Gain: 5.40 X100
           Load Cell Sensitivity:  25  bits
 Reference + Calibration Reading:  1.807 volts
  Measured + Calibration Reading:  1.802 volts
       Reference Unbalanced Zero: -0.098 volts
        Measured Unbalanced Zero:  0.000 volts
   Load Cell Regression Coef. A1: -9.7881        A2:  8.0776E-05
                              A3:  0             A4:  0
                              A5:  0

               All loads are in POUNDS

                             Ht 1      Ht 2      Ht 3      Ht 4
           Repeat Drop #1    6396*     9316      12044     15979
                       #2    6388*     9337      12040     15858
                       #3    6389*     9293      12038     15878
                       #4    6460*     9296      12010     15849
                       #5    6452*     9305      12039     15830
                             -----     -----     -----     -----
                     Mean    6417      9309      12034     15879
       Standard Deviation      36        18         14        59
       Excessive noise detected in Avg Zero for tests marked '*'

FWD Load Cell Data -
     FWD Load Cell Serial Number:     089
OLD Load Cell Calibration Factor:   0.998

                             Ht 1      Ht 2      Ht 3      Ht 4
           Repeat Drop #1    6456      9400      12200     16024
                       #2    6456      9408      12200     15904
                       #3    6472      9400      12184     15936
                       #4    6488      9392      12144     15880
                       #5    6496      9424      12184     15872
                             -----     -----     -----     -----
                     Mean    6474      9405      12182     15923
       Standard Deviation      18        12         23        62

Calculation Results -
               Adjustment Factor:   0.993
   Std.Error of Adjustment Factor:  0.0010
NEW Load Cell Calibration Factor:   0.991
```

FIGURE 8 Example report for load cell calibration.

the FWDs were tested. The four calibration centers were able to get the same calibration factors for a given FWD within the 0.003 criterion.

SHRP has established a policy for the relative calibration to be repeated monthly. This makes it possible to determine whether an individual geophone has failed, in which case it can be replaced with a spare. Thereafter the reference calibration must be repeated.

According to the SHRP protocol, reference calibration must be performed annually. Several studies have been conducted in which a SHRP FWD was given a complete reference calibration more frequently, and the results indicate that once a year is sufficient. The procedure has not been in place long enough to verify this fully, however.

One benefit of more frequent reference calibration became evident during the development and validation of the procedure. The SHRP North Atlantic Region FWD was found to have an internal electronic problem that caused the seven geophones to shift their calibration factors slowly over a period of weeks. These shifts were typically in the range of 1 percent (i.e., the calibration factors varied from 1.007 to 1.017) or less between reference cal-

```
                    Filename: 8002048B.G01
           Date: 11-19-1993; Time: 11:04
            Air Temperature: 70

          System Under Test: 8002048
               FWD Operator: CJ SWANK
Calibration Equipment Operator: DAVE WASSEL
         Calibration Center: PennDOT Calibration Center
   Data Acquisition Board Type: MetraByte DAS16-G2
          FWDREFCL Software: Vers. 3.71; Release Date: 07/22/93

Reference LVDT Data -
          LVDT Serial Number: 8021
       LVDT Calibration Date: 11-19-1993
       LVDT Calibration Time: 09:26
     LVDT Excitation Voltage:  15  volts
     Signal Conditioner Gain: 1.50 X1
            LVDT Sensitivity:  25  bits
       LVDT Reference Slope: -1.0000 microns/bit
     LVDT Calibration Slope: -1.0287 microns/bit

              All deflections are in MILS
```

	Ht 1	Ht 2	Ht 3	Ht 4
Repeat Drop #1	6.90	10.67	14.24	18.85
#2	6.85	10.66	14.26	18.92
#3	6.92	10.74	14.22	18.95
#4	6.92	10.65	14.25	18.95
#5	6.91	10.73	14.21	18.97
	-----	-----	-----	-----
Mean	6.90	10.69	14.24	18.93
Standard Deviation	0.03	0.04	0.02	0.04

```
FWD Deflection Sensor Data -
            Deflection Sensor Number:  1
     Deflection Sensor Serial Number: 661
OLD Deflection Sensor Calibration Factor:  1.002
```

	Ht 1	Ht 2	Ht 3	Ht 4
Repeat Drop #1	6.84	10.63	14.17	18.74
#2	6.84	10.67	14.21	18.82
#3	6.84	10.67	14.17	18.86
#4	6.84	10.67	14.21	18.86
#5	6.84	10.67	14.21	18.90
	-----	-----	-----	-----
Mean	6.84	10.66	14.19	18.84
Standard Deviation	0.00	0.02	0.02	0.06

```
Calibration Results -
                   Adjustment Factor:  1.004
       Std.Error of Adjustment Factor:  0.0006
NEW Deflection Sensor Calibration Factor:  1.006
```

FIGURE 9 Example report for deflection sensor calibration.

ibrations. Because all of the geophones shifted together, the monthly relative calibration did not disclose this problem. Thus if a given FWD is suspected of having problems, it might be worthwhile to perform reference calibration more often than once a year.

Scheduling Calibration

The Pennsylvania calibration center is indoors, in a large, heated facility. Thus, it is helpful to the host state to schedule calibration during winter when the personnel are not too occupied with field testing and operations. In the Pennsylvania calibration center, as at most of the calibration centers, the personnel do FWD calibration as a corollary duty, and they have pavement testing or other responsibilities as a primary duty.

An information sheet explaining the preparations that must be made before visiting the calibration center, as well as what will go on there, is available from any of the calibration centers or from the Long-Term Pavement Performance (LTPP) Division at FHWA. The FWD must be in good operating condition on arrival at the calibration center. The centers do not provide repair services and cannot provide advice in debugging a faulty FWD.

FIGURE 10 **Relative calibration of FWD deflection sensors.**

Certain aspects of the FWD software are essential to accomplish a successful calibration. The software must be capable of programming at least 56 steps into the drop sequence. The reference calibration requires 52 drops in the sequence, and the relative calibration requires 56 steps. For Dynatest FWDs it is necessary to have Version 10 or higher of the system software. For KUABs and the JILS FWDs, the manufacturer must be contacted to obtain the proper version.

To perform the relative calibration it is necessary for the FWD to have a stand that holds all of the deflection sensors. Some early Dynatest FWDs have stands that hold only four sensors, and those stands must be modified to properly execute the procedure. Most KUABs do not have a stand. Again, the manufacturer has to supply the proper hardware.

Having a copy of the SHRP protocol is an important part of achieving a successful calibration. If the FWD operator has read the protocol beforehand, he or she knows what to expect, and the entire process goes more smoothly.

Summary and Conclusions

A procedure for calibrating FWDs has been developed by SHRP. This procedure was developed for use with all types of FWDs. It has been used successfully with Dynatest, KUAB, and JILS FWDs, and it is adaptable to the Phøenix FWD.

To ensure that measurements are accurate and that different FWDs provide comparable results, it is necessary to calibrate the FWDs to a reliable reference standard. Equipment and software for reference calibration have been designed and proven. The calibration procedure offers excellent accuracy and repeatability. It is presently recommended that an FWD be reference calibrated annually. Four regional calibration centers have been established by SHRP in Minnesota, Nevada, Pennsylvania, and Texas to carry out the procedure.

The calibration of the deflection sensors is further refined by use of relative calibration. Relative calibration

TABLE 2 **Example Report for Three Relative Calibrations of Seven Deflection Sensors**

Sensor Number	Sensor Serial Number	Existing Calibration Factors	New Calibration Factors			
			Trial 1	Trial 2	Trial 3	Average
1	661	1.006	1.008	1.008	1.010	1.009
2	662	1.013	1.010	1.010	1.010	1.010
3	663	1.013	1.012	1.012	1.013	1.012
4	664	1.008	1.009	1.009	1.008	1.009
5	665	1.012	1.011	1.011	1.011	1.011
6	666	1.007	1.008	1.008	1.008	1.008
7	667	1.015	1.015	1.015	1.015	1.015

should be performed monthly to ensure that any change in an individual deflection sensor will be detected. If a deflection sensor must be replaced, reference calibration should be performed as soon as possible.

The FWD calibration center in Pennsylvania has been in operation since April 1992. It has been performing an average of about one calibration a month. It is helpful if the calibrations can be scheduled in winter. A checklist is available to help FWD operators prepare for a calibration.

The equipment and procedures for FWD calibration have been described. To transfer the calibration method to other locations it is necessary to design a test pad that provides the proper amount of deflection and that is specific to the site. This should be a relatively easy task for pavement engineers since the test pad produces a variety of deflections across its breadth.

Further Information

Responsibility for continuance of the LTPP project, begun by SHRP, has been transferred to the FHWA. On request to the LTPP Division, FHWA, 6300 Georgetown Pike, McLean, Va. 22102, the following materials are available:

- The FWD Calibration Protocol, which defines the procedures for reference calibration and relative calibration of an FWD, the procedure for calibration of the reference load cell, data analysis procedures, and equipment specifications for each procedure.
- The current version of the FWDREFCL computer program that is used in reference calibration for data collection and data processing.
- The current version of the FWDCAL2 computer program that is used in relative calibration for data processing.
- The current version of the LDCELCAL computer program that is used in calibration of the reference load cell for data collection and data processing.
- Drawings of the various parts that must be fabricated to build a FWD calibration equipment set.

ACKNOWLEDGMENTS

Many people helped to make a project of this magnitude successful. The authors particularly want to acknowledge the contributions made by Tom Leitzel and Dave Wassel at PennDoT, Doug Marshall at PMS, Inc., Carl Berryman and Rebecca McDaniel at Indiana DoT, Scott Rabinow at PCS/Law, Inc., Tom White at Purdue University, and Tom Szebenyi and Peter Messmer at Cornell University. Each of the operators at the four SHRP FWD calibration centers contributed greatly to the project. Cheryl Richter in the LTPP Division at FHWA (formerly at SHRP) provided overall project leadership and coordination.

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Role and Development of a Pavement Construction History Data Base Within a Pavement Management System

John Statton, *Department of Road Transport, South Australia*

The systematic historical recording of pavement configurations across a road network as affected by construction, rehabilitation, and maintenance treatments forms a crucial component of a pavement management system (PMS). The Department of Road Transport, South Australia is progressively implementing a comprehensive pavement construction history system (PCH) that will play a variety of roles within its PMS, including calibration of general pavement performance curves, monitoring the effect of specific pavement attributes on measured performance, and upkeep of the pavement condition information data base to reflect the effect of treatment works being undertaken. To achieve these requirements the design of the PCH data base has included a hierarchy of descriptors and standard codes to assist a wide variety of future retrievals. Commitment and support of field staff to data collation and data entry are critical to the credibility of the system. The involvement of a wide range of stakeholders in the system design and field staff in the refining and documentation of data collation and entry procedures has contributed to a sense of joint ownership of the system. The introduction of the simple personal computer (PC) map-based program ROADMAP for providing effective feedback of a wide variety of road-related data to users has been instrumental in securing support of field staff for data integrity and timely entry.

Generally within Australian State Road Authorities, the engineering history of road pavements has tended to be one of the best-kept secrets. The systematic recording of road pavement configurations, their component materials, the subsequent maintenance treatments applied, and their unit costs has to date not been widely practiced. Much of this valuable information is either buried in individuals' paper records, partly retained in people's memory, or lost for all time. Pavement condition is now generally regularly monitored, but in the absence of historical data on the types and costs of pavement and maintenance treatments it has not been possible to systematically monitor the effectiveness of road asset construction and maintenance practices. The ongoing development and implementation of pavement management systems (PMS) have required this issue to be addressed.

The Department of Road Transport, South Australia (DRTSA) is developing and implementing a comprehensive pavement construction history system (PCH) as an integral component of its pavement management system (PMS.) The PCH system will ultimately provide a historical physical record of construction and maintenance treatments on a computer data base that will serve a variety of roles in road management. Key factors considered in the basic design of the system and its links with other components of the PMS are discussed. The ultimate success of the system is dependent on the commitment of relevant staff to the timely collation and entry of data. Factors that are considered to have assisted in securing this support are described.

Impetus to Capture Pavement Descriptions

DRTSA has been progressively developing and implementing a PMS since 1990 for the 11 800 km of sealed road network that it maintains. The department's field operations are split into four geographic regions, which together cover the state's 984 000 km^2. The Financial Planning Network Optimisation System (FNOS), developed by the Roads and Traffic Authority of New South Wales (*1*), has been adopted as the network level optimization tool for its PMS. Among its inputs the FNOS program requires unit costs and pavement performance models for each of the treatment options considered by the program. These models are generally being developed by combining the engineering judgment of road managers within DRTSA with the intention of calibrating these models with actual data in the long term. This need provided the initial impetus for capturing and storing information on pavement works in a more systematic manner.

Historically, some attempts had been made to capture some very basic construction data. However, the integrity of these data was often poor or was out-of-date because it relied on construction personnel filling in the appropriate hard copy completion report at the end of the project. This task was generally not done because the staff responsible were primarily concerned with the field operations, expenditure control, and preconstruction for the next project. The corporate value of this information for long-term asset management was not recognized or adequately communicated. For construction staff there was no immediate obvious benefit in providing this information. The data that did make it into the system were difficult to retrieve through the mainframe computer network and were therefore not widely accessed or used.

Role of the PCH System

Objectives

The PCH system is being developed as a corporate system that will satisfy a range of stakeholder requirements. The following long-term primary objectives have been established:

- To provide an up-to-date corporate record of the physical engineering structure and unit costs of the pavement network for a range of stakeholders,
- To provide a mechanism to calibrate pavement performance models for input into PMS,
- To assist the systematic monitoring and improvement of pavement technology at a more detailed level,
- To modify as appropriate the pavement condition data base to reflect the anticipated effect of new treatments,
- To reduce, over time, the amount of pavement excavations when undertaking pavement investigations,
- To provide a link with the detailed recording of laboratory quality control test data;
- To assist in automatically updating basic inventory data such as road width, etc., and
- To provide part of a formal mechanism for handing over completed road projects from the centralized Road Construction Directorate to the Road Management Directorate (Regional Operations) in the department.

Integrating Road Related Data

The broad relationships between the PCH data base and other departmental road-related data bases are shown schematically in Figure 1. All these road-related data bases, as depicted by the shaded boxes, are maintained on the head office mainframe computer (VAX cluster). These data bases are related by a Departmental Common Road Reference system consisting of road number, road running distance, carriageway, and lane identification that are related to permanent geographic reference points. The reference system is complemented with physical markers in the field at nominal kilometer intervals.

The treatment selection component of PMS (FNOS program) and a general map-based data inquiry program (ROADMAP) both operate as standalone PC-based systems that are located on PCs throughout the head office and regional offices. These programs use the same data file, which is automatically created every month on the mainframe by accessing the latest relevant data from the corporate road related data bases and is made available for users to update their PC through the computer network. The decision to operate these programs as standalone PC systems has greatly enhanced the user interface, access speed, and consequent use of the data, which in turn have had a significant effect on maintaining user support for the systems.

Monitoring Pavement Performance

The PCH data base has been designed to enable the monitoring of pavement performance at two levels of detail: at a broad level to calibrate the pavement performance curves for input into the PMS FNOS program and at a more detailed pavement technology level to monitor the effect on performance of specific pavement attributes.

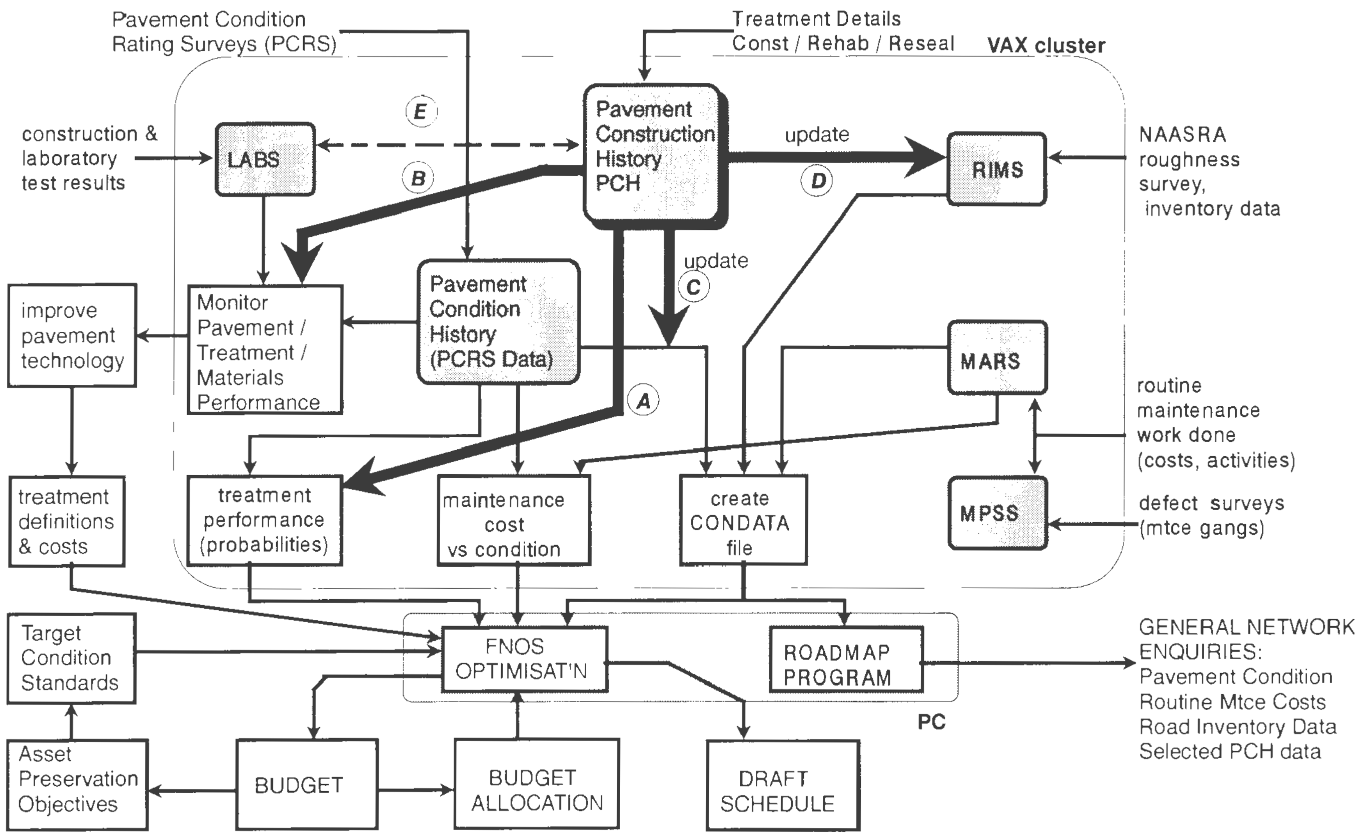

FIGURE 1 Links between PCH data base and other related data bases.

The FNOS program considers various treatment options in a generic or broad sense only (e.g., reseals, asphalt overlay, heavy patching, stabilization, reconstruction, etc.). The PCH system in conjunction with the pavement condition data base will be used to derive general pavement performance models for these generic treatment types for input into FNOS (link A, Figure 1). The generic treatment types therefore need to be contained as a hierarchy of description in the PCH system for these retrievals to be made effectively.

At a more detailed level the PCH system will also be used to monitor the relative effect on performance of differing pavement configurations, material types, layer thicknesses, special treatments, additives, or differing standards. Over time this will influence what type of generic treatment options will be considered within the PMS (e.g., for a reseal, what type of modified binder is performing the best, what polymer concentration is suitable, etc.). This link is denoted as B in Figure 1.

Maintaining the Pavement Condition Data Base

In DRTSA the pavement condition rating process is conducted annually each spring (October to November). However, network pavement condition is continually being altered by roadworks. When a new treatment is recorded into PCH, the pavement condition data base is automatically updated according to a set of standard rules. For example, where a new surfacing is applied to a segment of road, distress items of cracking, patching, defects, texture, and binder condition are defaulted to "good" condition. These defaulted values remain valid until the next pavement rating survey. This link is shown as C in Figure 1. This continual updating of the pavement condition data base is critical to the credibility of subsequent PMS processes to ensure that decisions are made on the best estimate of current pavement condition. These flow-on processes naturally only occur if the treatment data are entered into the system by the responsible officers. That the entry of these data has immediate impact on other types of information that operations personnel regularly access has provided additional impetus for PCH data to get entered in a timely manner.

Reducing Pavement Excavations

It is estimated that the department undertakes around 1,500 pavement excavations each year at a cost of approximately A $400,000 in the process of preparing pavement reports for rehabilitation or maintenance works. In many instances the work is undertaken primarily to determine the pavement configuration to assist with the analysis of falling weight deflectometer results. The systematic recording of pavement details over time will reduce the need for this work and its associated safety risks and traffic delays. Pavement excavations that are undertaken form a valuable source of information for the PCH system for existing pavements and it is intended to establish procedures to capture this information.

Historical Pavement Data

Although the PCH system was initially conceived to capture pavement details on current and future road construction and maintenance projects, its long-term value is dependent on the proportion of the network that is recorded into the system. Historical information is more difficult to capture depending on the quality of paper records contained in regional offices. All regions have participated in bringing the basic road surfacing details for the state network up to date and into the system. Individual regions are currently reviewing records of recent construction and rehabilitation works with a view to entering available details of underlying pavement configurations wherever possible.

Design of PCH System

Types of Data

The format and types of data to be stored in the PCH system were determined by consolidating a wide range of potential stakeholder requirements across the department. This was an iterative process that required up-front support from upper management, ongoing promotion of the potential benefits of such a system, and due cognizance given to the following factors:

- The relative ease of collating and storing a data item, and
- How the data are likely to be accessed in the long term; what format of inquiries would be undertaken.

The active involvement of a wide range of staff in this planning process was considered critical to ensure a shared sense of ownership of the system and sufficient and appropriate descriptors were included to satisfy future retrieval requirements.

As a result of this process the following hierarchies of data evolved:

- General project-level details: contractor, gang, specification number, type of work, funding program, location, plan numbers, date completed, project cost, etc.;
- Pavement/treatment type information: treatment classification (pavement type/rehabilitation type/resurfacing type), unit costs, location, etc.; and
- Pavement layer details: material descriptions (type, source, layer title, specifications), thickness, design compaction, special treatments, nonconformances, etc.

The PCH data base is essentially a layered system of information where each pavement layer is a layer of data in the data base. As rehabilitation works are undertaken other layers of information are added to the system. Each layer of information has a date reference as well as a location reference. The date reference is used to determine the level of the layer in the pavement. The information is recorded to lane level only on the data base. An example of the types of layer level information stored for surfacing treatments is shown in Table 1.

Wherever appropriate, standard codes have been developed to describe possible alternatives for each field in the data base. User input in the derivation of these codes to ensure compatibility with existing codes already in use was essential. The use of standard codes is considered a key element of the design of the system to assist with the subsequent retrieval of data through relational inquiries and to assist with validation at time of data entry.

Data Entry, Validation, and Accountability

The process of entering the data into the system (i.e., the user interface) has been made as simple as possible. Online computer terminals in regional offices are provided with an interactive computer screen process that takes the user through a hierarchical series of screens to describe the project. Data are validated as much as possible during the entry process in terms of valid locations (i.e., checked against the road reference system for valid road number, location, and lane ID) and valid descriptions. Users are provided with online, context-sensitive selection menus for the standard codes that have been established for the various fields. Once data for a project have been entered (initially into a temporary file), a hard copy listing is produced, which has to be certified as correct by the project engineer before the actual mainframe data base is updated. Where possible, supporting computer applications to assist the collation of data during the progress of the project are being developed. The timely storing of PCH data against the road reference system will require a revision of the processes used to maintain and update the road reference system itself as it is affected by new roadworks.

In DRTSA the ultimate accountability for the collation and entry of the PCH information rests with the personnel who are directly supervising the construction, rehabilitation or resealing activities (i.e., the project managers).

TABLE 1 Data Recorded in PCH for Surfacing Treatments

Location *Road No *Carriageway No (for divided roads) *lane Start MM (field marker) Start Distance End MM (field marker) End Distance Width Date (mth/yr) *Surfacing Code	
Primes application rate (binder) l/m^2 AE number (specification sheet) *binder type *contractor	***Slurry Surfacings*** *contractor AE number (specification sheet) no of layers (deep slurry) *mix size (each layer) *binder type *spread rate *mix no.
Spray Seals / Primer Seals / SAMIs application rate (binder) l/m^2 spread rate m^3/m^2 *screening source AE number (specification sheet) *binder type *contractor pre-coat (Y/N) binder additive (Y/N) flux (parts)	***Asphalt*** *layer title *mix size *mix design no. *Binder type thickness *manufacturing contractor *manufacturing plant *laying contractor tack coat (Y/N)

* denotes that standard codes have been developed

Only these staff have direct access and ultimate control over the final pavement details. The simultaneous development within the Department of Quality Management procedures for day labor construction, contract construction, and maintenance works has provided a valuable opportunity for PCH data collation and entry tasks to be embodied in quality management procedures for project management. Involvement of operations personnel in the development of these procedures has been important in contributing to their sense of part ownership of the overall PCH system.

Securing Commitment to PCH System

Overview

Regardless of how well the PCH data base has been designed and how user-friendly the computer input routine has been made, its ultimate success depends on the commitment of relevant staff to the tasks required to support the system. Commitment only comes with understanding and a shared sense of ownership. A number of factors are considered to have contributed to help securing this.

- The gradual change in departmental culture and focus from that of being a construction authority to one of road asset management;
- Having the need for a PCH system incorporated as an integral component of the corporate objectives established for PMS, securing a clear understanding of the role of a pavement construction history system in road management among the executives of the department, and ensuring that support for the system continues to be promulgated from upper management;
- Changes in organizational structure that have provided clearer accountability between the road management and road construction tasks;

- Clarification of the potential benefits of the system to a wide range of stakeholders and their involvement in the system development;
- Simultaneous introduction of a total project management approach and quality management principles to roadworks. This provided a unique opportunity for processes required to support the PCH system to be included as integral tasks for field operations staff, embodied in new quality management procedures;
- Direct involvement of field staff in the system development, in particular with the fine-tuning processes for data collation and in pilot testing, which has contributed to a shared sense of ownership of the system. The opportunity was exploited to create the awareness in these field staff that much of the information that historically only they had previously carried around (as paper records or in their memory) has significant corporate value;
- Staged implementation of the system. The first stage of the system that captured the details of surfacing information only was implemented in 1992 (*2*). This provided the simplest level of information to obtain and provided tangible early benefits when fed back to operations staff in a manageable form; and
- Giving high priority to feeding back relevant treatment information to road managers in a form that encouraged its effective application in management decisions.

Effective Data Feedback

A key factor in securing support for the PCH system and PMS in general has been the work undertaken to provide road managers across DRTSA with quick and easy access to a range of road-related data, including selected construction history data in a form that encourages effective application of these data in day-to-day road management decisions. This work culminated with the introduction of the ROADMAP computer program (*3*). This is a an easy-to-operate, completely user-definable, Windows-based PC program that provides a simple method of adding a geographical interface to a data base or spreadsheet. The program was developed by the department to provide operational road managers with a simple means of undertaking relational inquiries between road condition data, road maintenance cost information, and basic road inventory data using a simplified geographical map interface on the computer screen.

Access to data is provided in three basic ways, as follows:

1. Data for each road segment can be displayed in text form by pointing to the desired segment on the screen map,
2. Distribution of any data item across the network can be viewed by color-coding of the screen map with statistics calculated, and
3. Users can undertake a relational inquiry by establishing a combination of user-defined limits across a number of data types. The road segments that fulfill the user-defined criteria are highlighted on the screen road map or produced as a listing.

Using these procedures, users can quickly determine the characteristics of their local network, highlight trouble spots, and derive relationships between road condition data, maintenance costs, road inventory data, and basic pavement information (see Figure 2). The ease of program operation and map interface has helped bridge the computer gap for many new users and played a significant role in helping to develop a road network management culture in the newly established Road Management Directorate in DRTSA.

When early versions of the program were first released (before the beginning of the PCH system), operational staff were quick to point out the deficiencies in some of the inventory data that they could now access. They quickly came to appreciate, for example, that they could put information on resealing, if kept up-to-date, to good use by being able to simply relate it to pavement condition information within the program. This renewed interest in basic treatment information and its accuracy by the local regional staff established the ideal environment to introduce procedures to support the new PCH system. The benefits of effective feedback of road-related information to operational staff in a form that is of direct value to them were clearly demonstrated (*4*).

Conclusions

A comprehensive pavement construction history system is being progressively developed and implemented by DRTSA as an integral component of its PMS. The system is being designed to play a variety of roles in road management, including the calibration of pavement performance models for PMS, to systematically monitor the effect on pavement performance of specific pavement attributes and to help maintain an up-to-date pavement condition data base.

Key factors in the successful design and implementation of the system included:

- A developed understanding and support for the system at executive level, which is promulgated down through management structure;
- The careful identification and integration of realistic stakeholders' requirements;
- A hierarchical level of descriptors and standard codes, developed in conjunction with users, that will assist a wide variety subsequent retrievals;
- Data collation and computer input processes, developed in cooperation with field staff, that are incorporated

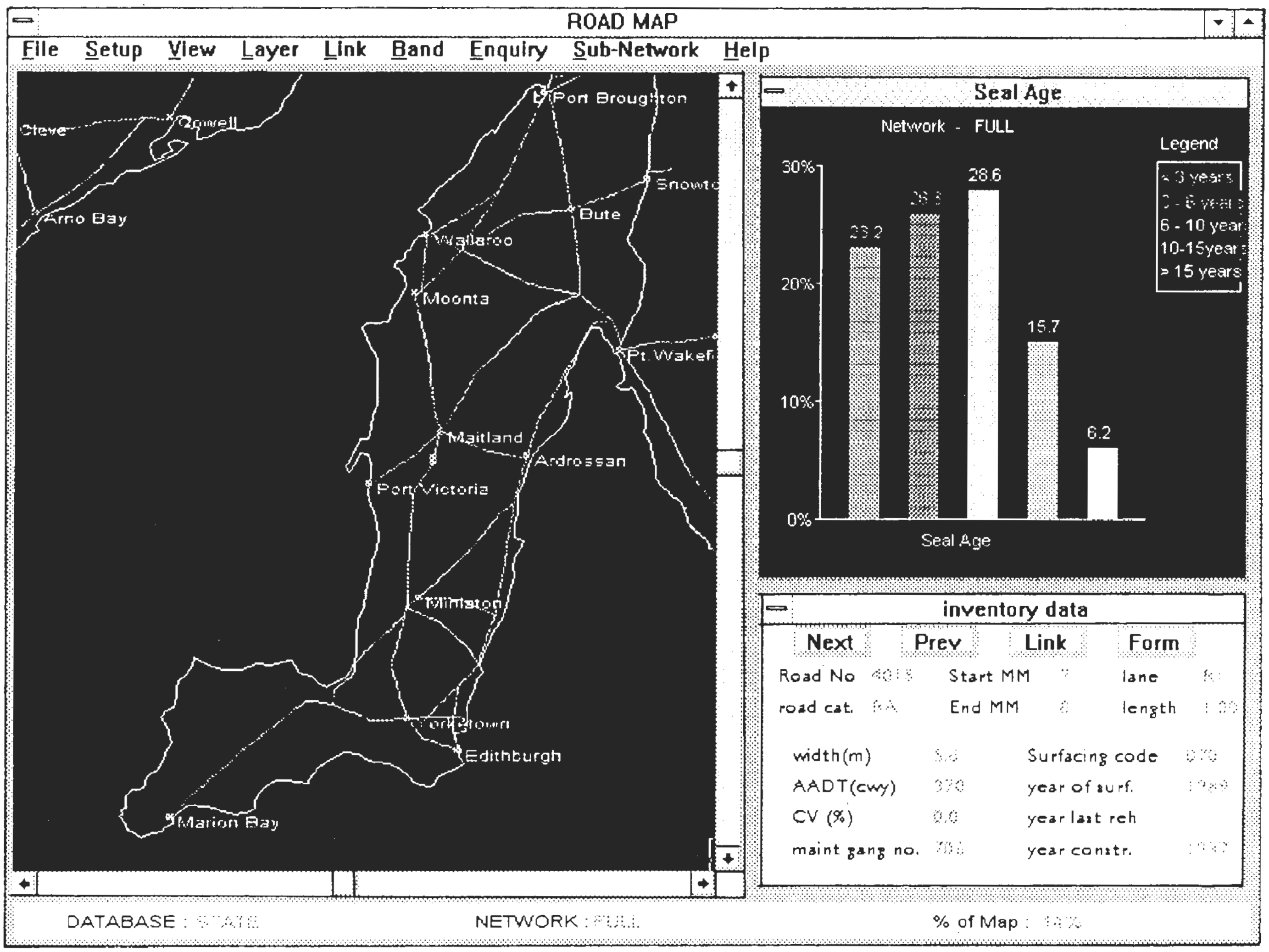

FIGURE 2 Example screen from the ROADMAP program.

in quality management procedures for road construction and maintenance activities;

- The continued departmental focus toward a road asset management role and clarification of accountabilities through organizational structure that supports this focus; and
- Wide application of a simple PC map-based data retrieval program that has allowed field staff to effectively use basic treatment history information in conjunction with other road related data. Efforts invested in providing improved access to data have been instrumental in securing field cooperation in further development and helped raise concern for data integrity for which they are now taking increased responsibility.

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Case Study of Benefits Achieved from Improved Management of Pavement Facilities

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Benefits to both the highway agency and the traveling public are significant when an effective pavement management system is used. Benefits to highway users related to improved long-term rehabilitation programming decision making are presented as a case study for the Chicago metropolitan freeway network. The vehicle kilometers traveled on pavements in good condition increased 20 percent over an ad hoc rehabilitation selection method when a simple ranking method was used and 260 percent when the incremental benefit cost method was used to select rehabilitation projects over a 10-year period for the same annual level of funding. The direct consideration of benefits in the management of a highway network will provide an opportunity for improved communication between engineers, policy makers, and funding authorities concerning the most appropriate method to develop a multiyear rehabilitation program.

A structured management system for pavements is strongly encouraged and even mandated in some cases today. Reasons provided range from improved decision making to better justification for rehabilitation programs. However, it is difficult to find documentation of actual benefits of implementing a pavement management system. This paper focuses on benefits achieved through improved management procedures associated with the development of multiyear programs for a given highway network case study.

This work is based on the development and implementation of a pavement feedback system by the Illinois Department of Transportation (IDOT). Complete details of the analysis procedures and results are given in a work by Mohseni et al. (*1*). All the analyses were conducted using the ILLINET pavement management software developed for IDOT.

Network Benefits

Quantifying benefits for pavement rehabilitation is essential to any comprehensive network-level pavement management system. Pavement benefit is used as the measure of effectiveness of rehabilitation alternatives applied to the pavement sections in a network over a time period. Quantifying benefits makes possible the selection of sections and rehabilitation alternatives that ensure the best use of limited funds.

There are two perspectives to pavement rehabilitation—that of the highway agency and that of the highway user. This analysis looks primarily at user benefits. The major benefit of pavement rehabilitation realized by improved pavement condition really goes to the user in the form of reduced vehicle operation costs, reduced lane closures, delays, and reduction in accident potential. User cost accounts for approximately 80 percent of the total transportation costs. The main concern of the public is adequate safety (friction, hydroplaning from rutting, etc.), reduced lane closures that cause congestion, and good ride quality. The main concern of transportation agencies in addition to these items is the costs associated with the short- and long-term maintenance and rehabilitation strategies.

There are several key aspects of pavement rehabilitation benefit (*1*). These include pavement condition level over time after rehabilitation (defined as performance), pavement use (traffic volume and mix, length of project), and pavement-related user costs resulting from different levels of pavement condition. Estimated pavement benefits should directly or indirectly include all of these aspects.

The following ways have been used to estimate pavement rehabilitation benefit; however, they do not all directly include the above key benefit aspects.

- Area under the performance curve resulting from rehabilitation (considers performance directly and user costs indirectly, but not pavement use);
- Extent of added life after the rehabilitation (considers performance and user costs indirectly, but not pavement use);
- Reduced user's costs (such as vehicle operating costs and reduced traffic delays from congestion caused by maintenance lane closures) resulting from rehabilitation (can potentially consider pavement performance, pavement use and users' costs directly, but this is very difficult to calculate); and
- Vehicle-kilometers traveled (VKT) over pavements in good condition as opposed to those in poor condition (indirectly considers all aspects of rehabilitation benefit and is easy to calculate).

Each of these measures has its advantages and disadvantages; however, the last benefit measure, VKT on good pavements, provides some strong advantages, including ease of calculation, ease of understanding by the engineer, policy maker, and funding agency, as well as by nontechnical persons. VKT on good pavements was selected as the benefit measure in this analysis, although ILLINET software will calculate all of the other benefits.

$$\begin{aligned} \text{VKT(10 years)} = {} & \text{mean(ADT)} * 365 \\ & * \text{length section (km)} \\ & * \text{rehabilitation life(years)} \end{aligned}$$

The rehabilitation life in this equation begins from the time the rehabilitation is constructed until the pavement reaches a terminal condition level, even if the life extends beyond the 10-year analysis period.

A "good" pavement condition can be defined many ways. In this analysis, pavement condition is defined as the Illinois condition rating survey (CRS) value (*1*), which is a visual subjective indicator of pavement deterioration. The CRS ranges from 9 (new pavement) to 1 (totally deteriorated pavement). Although the CRS is based on visual deterioration of the pavement surface, it has been shown to relate well to measured roughness. The network benefit can also be presented as the amount or the percentage of all VKT traveled on good pavements. "Good" pavements are defined as those having a CRS greater than 6.0, and "deteriorated" pavements are those having a CRS less than 5.0, which is a very rough condition requiring extensive maintenance.

Network Costs

The total cost of applying the rehabilitation program is the sum of the cost of rehabilitation for all sections in the network over the 10-year analysis period. Only pavement-related rehabilitation costs are included in this analysis.

Alternative Project Rehabilitation Selection Methods

Four different project-level rehabilitation alternatives were available plus a maintain-only alternative.

1. Concrete pavement restoration without overlay,
2. 3-in. AC overlay,
3. 5-in. AC overlay, and
4. Reconstruction.

ILLINET includes four different project-level rehabilitation alternative selection methods.

1. User-specified rehabilitation for any section in any year,
2. Specified single rehabilitation alternative for all sections,
3. Decision tree with varying CRS trigger values for each rehabilitation alternative,
4. Selection based on life-cycle cost analysis of all rehabilitation alternatives.

The analyses conducted in this case study for the AD HOC and RANKING methods used the life-cycle cost analysis procedure for project-level rehabilitation-type selection. The incremental benefit cost (IBC) and multiyear optimization (OPT) procedures allow all rehabilitation alternatives to be considered at the network level.

Alternative Pavement Network Management Algorithms

Four different methods of selection of projects and types of rehabilitation were used in this study. They represent a range of procedures being used today by highway agencies.

In addition, an unrestrained funding rehabilitation needs method was used to estimate the funding to maintain all sections in the network above a trigger CRS value. The same annual funding limit was used for all methods (except NEEDS) over a 10-year analysis period. For this case study, all highway sections were allowed to deteriorate until they reached a CRS of 6 or less. At that point they became "deficient" and candidates for rehabilitation.

AD HOC Method

Highway sections with CRS = 6 or less were randomly selected each year until the yearly funding was exhausted. One rehabilitation alternative is selected for each section using the project-level rehabilitation selection routine. The AD HOC method is intended to simulate agencies that do not have a structured management system. Rehabilitation projects that are not funded in 1 year are delayed until the next year, when they compete for funding again in the same manner.

RANKING Method

One rehabilitation alternative is selected for each deficient section (CRS of 6 or less) using the project-level rehabilitation selection routine. The sections are then ranked from lowest to highest CRS. Rehabilitation projects are then selected for the first year starting with the lowest CRS until the yearly funding is exhausted. Projects that are not funded in 1 year are delayed until the next year, when they compete for funding again in the same manner.

IBC Method

All four rehabilitation alternatives are considered for each deficient section. For each section and rehabilitation alternative, the benefit is calculated as the VKT on the section during the time that the CRS is greater than 6. The total cost is the associated rehabilitation cost over the 10-year period for that section. The IBC is based on yearly optimization (maximization) of pavement rehabilitation benefits as compared with the multiyear optimization as in the case of OPT. IBC easily considers yearly funding limits. Projects with higher IBC are chosen first every year in the analysis period until the yearly funding is exhausted. The objective is to maximize yearly benefit within a yearly funding limit. IBC is also capable of considering all pavement rehabilitation type tradeoffs for all deficient sections every year in the analysis period. Rehabilitation timing tradeoffs are not directly considered since all deficient sections that qualify for funding are delayed and considered for funding in the next year.

OPT Method

The four rehabilitation strategies (rehabilitation type and timing over the 10-year analysis period) are generated for each deficient section in the network, and the benefit and cost are calculated for each strategy. The goal of the OPT method is to select rehabilitations for every deficient pavement section in the network such that the total network benefit is maximized for a 10-year funding limit. In this approach, all rehabilitation types and timings are considered such that the timing and type that provides the maximum network benefit are selected. There is no yearly funding restraint and thus the required funding varies considerably from year to year, which is of course not practical.

NEEDS Determination

The NEEDS method was used to determine the total needed cost to maintain all sections above a given trigger CRS value of 6, irrespective of funding restraints. This estimate provides the maximum level of funding needed over the 10-year period to keep all sections above a selected condition level.

Description of Case Study

Each of the four methods of programming rehabilitation projects was applied to the Interstate highway network in the Chicago metropolitan area over a period of 10 years. This network includes 322 one-directional pavement sections (two to five lanes in one direction) with a total length of 665 one-directional km on eight Interstate routes. The pavement sections were built from the 1950s through the 1980s. All pavement sections in this network were originally built as either jointed reinforced or continuously reinforced concrete pavements (JRCP and CRCP) as shown in Figure 1. Many of these sections have been subsequently overlaid with asphalt concrete (AC).

The age of these sections range from 1 to 30 years as shown in Figure 2. The data base for the network includes several data items for each pavement section in the network, including identification, design, traffic, climate, distresses, and condition. The average annual daily traffic (AADT) for both directions ranges from 18,000 to 273,000 vehicles/day with an average of 90,000 vehicles/day as shown in Figure 3. The annual 18-kip equivalent single-axle load (ESAL) for the network ranges from 1 to 9 million ESALs in one direction in the driving lane.

The current pavement condition of the network is shown in Figure 4. Approximately 73 percent were in good condition, 18 percent in fair condition, and 9 percent in poor condition.

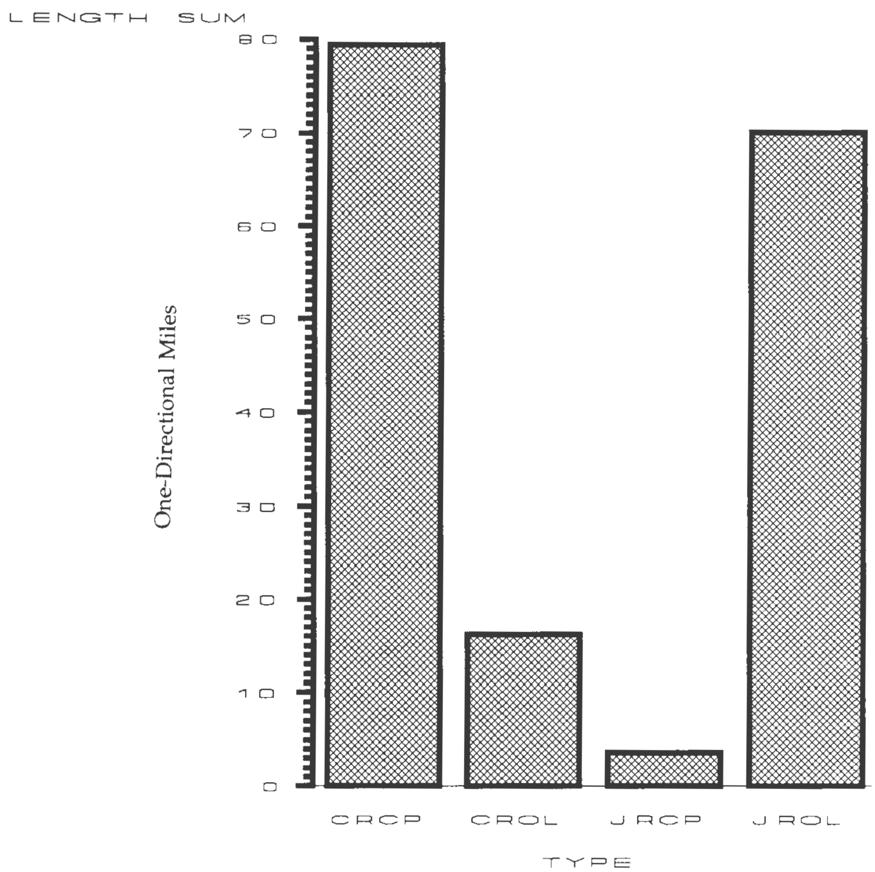

FIGURE 1 Types of pavements in Chicago case study. CRCP = continuously reinforced concrete pavement, CROL = AC overlay of CRCP, JRCP = jointed reinforced concrete pavement, JROL = AC overlay of JRCP.

Results From Case Study

The ILLINET software provides a complete 10-year rehabilitation plan for each section in the highway network. Several network-level statistics that are part of the ILLINET network summary output can be used to compare the benefits and costs of the four alternate network management methods. The NEEDS algorithm was run to determine the total funding to maintain the network above a certain condition level (CRS > 6 used in this example because this is the minimum wanted by IDOT). The result was $330 million over 10 years (note that this funding is for pavement rehabilitation only and does not include any other costs such as bridges, major reconstruction, adding lanes, etc., which combined would be several times this value). Different levels of funding were considered; however, only the $264 million funding will be discussed in detail. This would represent a funding of approximately 80 percent of full needs. Table 1 gives the results obtained from ILLINET.

Total Network Cost

Each network method was limited to $26.4 million/year pavement funding, or approximately $264 million over the 10-year period. Thus, the total expenditures were approximately equal for each network rehabilitation selection method over the 10-year period. The OPT method did not have any yearly funding limits, however.

VKT on Deteriorated Pavements

The percent VKT of travel on deteriorated poor pavements (meaning CRS < 5) over the 10-year period for each method shows some differences. The AD HOC method for selection of rehabilitation projects resulted in over 25 percent VKT on deteriorated pavements as compared with 17 to 23 percent for other methods. The 25 percent can be interpreted to mean that 1 of 4 miles driven over the 10 years will be on a rough, deteriorated pavement.

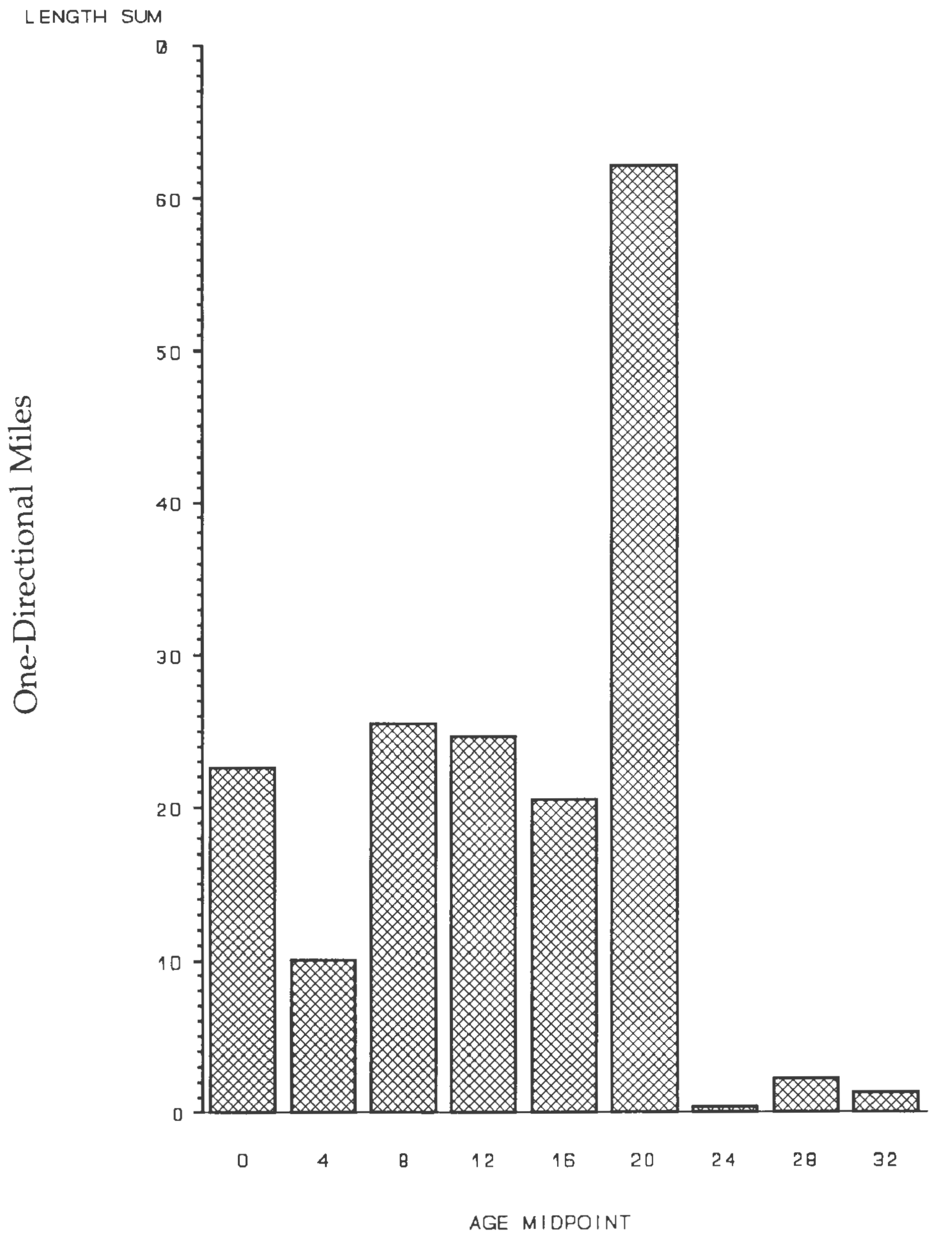

FIGURE 2 Age distribution of sections in Chicago case study. (Note: Age of AC overlays is counted from time of overlay.)

VKT on Good Pavements

The total VKT in billions of kilometers traveled over the 10-year period shows considerable difference between network rehabilitation selection methods. The results are summarized as follows:

Network Selection Method	*VKT (billions) on Good Pavements*	*Ratio*
AD HOC	80	1.0
RANKING	96	1.2
IBC	206	2.6
OPT	220	2.7

The AD HOC method of rehabilitation selection results in the lowest total benefit (VKT on good pavements). The RANKING worst-first method improves the benefit VKT by 20 percent. The IBC method of selection improves VKT on good pavements by 260 percent and the OPT method 270 percent. Note that the total 10-year cost is the same ($264 million) for each of these network selection methods.

An overall indicator is obtained by dividing the total benefit (VKT in billions of kilometers on good roads times 10) by the total cost of rehabilitation over the 10 years. IBC and OPT produce a far higher benefit/cost ratio than the AD HOC approach or even the worst-first RANKING approach. Although the OPT shows better results than

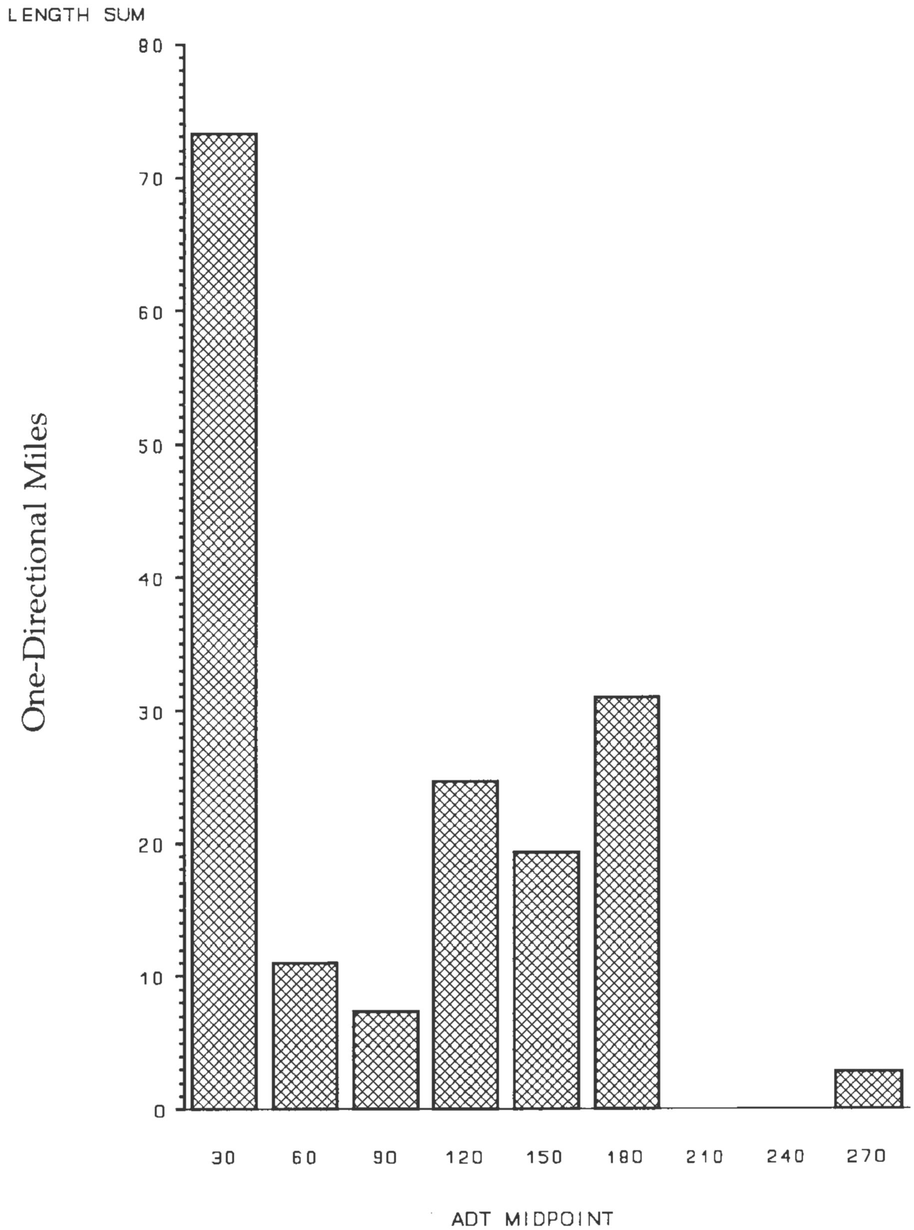

FIGURE 3 ADT levels of Chicago case study. (Note: ADT is in two directions and thousands of vehicles.)

the IBC, the results are approximately the same. In actuality, the OPT funding varies greatly from year to year making it an impractical solution. The IBC optimizes within each year and easily provides a rehabilitation program within the yearly funding limit.

Remaining Life

The mean remaining life per kilometer of highway network at the end of the 10-year period of all sections is given in Table 1. This is an important index because it essentially represents the condition of the network at the 10th year. These numbers appear to be low; however, their units are given as the mean remaining life per kilometer.

The important concept is to observe the difference in this mean value between network rehabilitation selection methods. The AD HOC is the lowest, RANKING has a 1.8 times greater remaining life, and IBC and OPT have 1.9 times greater remaining life than the AD HOC method. These results show that any of the rational ways of developing a multiyear rehabilitation plan results in a highway pavement network that has about twice the mean remaining life as the AD HOC method.

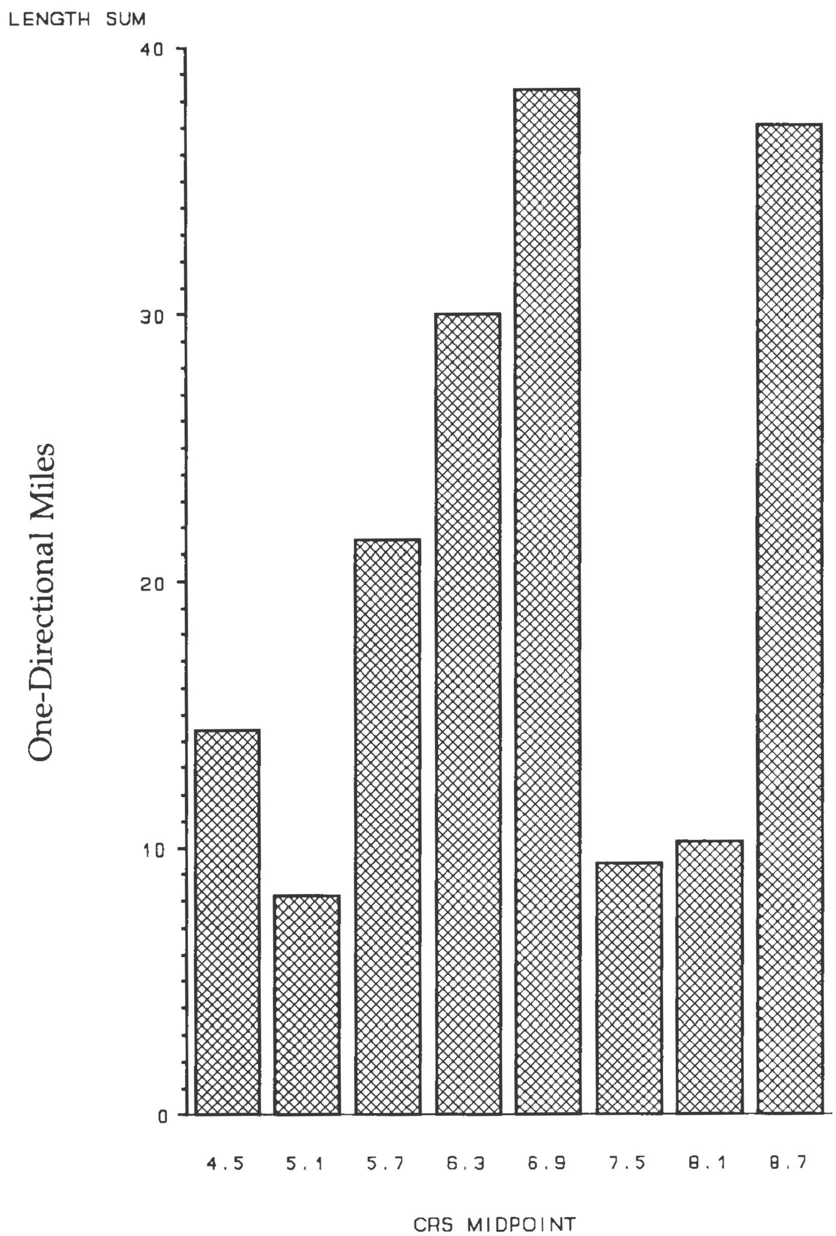

FIGURE 4 Distribution of CRS rating for Chicago case study. CRS = 9 is new pavement; CRS = 1 is very deteriorated pavement.

Use of Benefits in Managing Pavements

Maximizing the desired benefits, while working within funding and other constraints, would appear to be a major objective of highway agencies. For example, maximizing the VKT on good pavements using the IBC network algorithm would result in a given multiyear program. This program is very different from that obtained from neglecting benefits altogether using the AD HOC or RANKING methods.

In addition, maximizing some other type of benefit, such as the area under the performance curve, or the added life after rehabilitation, or direct user costs, would lead to other different multiyear programs.

Most agency policy makers and funding authorities are not even aware that there would be such different multiyear programs resulting from these different methodologies in network selection. Pavement management systems in use today have only one algorithm for developing a multiyear program and no one knows how good a multiyear program it produces. Results such as these might stimulate considerable discussion among engineers, planners, policy makers, and funding authorities about which benefits should be maximized, how to go about accom-

TABLE 1 Summary of 10-Year Costs and Benefits for Chicago Metropolitan Freeway System Case Study

Network Parameter	NEEDS	Ad Hoc Method	Ranking Method	Incremental Benefit-Cost	Optimization
10-Year Funding (million $)	----	264	264	264	264
10-Year Expenditure (million $)	330	264	262	260	263
Percent VKT On Deteriorated Pavements	17.1	25.6	23.6	20.7	17.1
Benefit: VKT Good Pavements (Billions Km)	176	80	96	206	220
VKT Benefit*10 / Cost	5.3	3.0	3.7	7.9	8.4
Remaining Life (years/network kilometer)	1.9	1.2	2.2	2.3	2.3

plishing this, and the consequences for not even trying. There is obviously a lot of work to be done in this area in future studies.

Conclusions and Recommendations

A reasonable and meaningful indicator of user's benefits is VKT over pavements in good condition. Engineers, planners, top management, and others can readily understand and appreciate the desire to program rehabilitation projects so that future travel on pavements in good condition would be maximized (within a given funding constraint). However, other measures of benefit exist and a full evaluation of all measures needs to be conducted.

The results from the Chicago case study (and also from similar more rural areas) clearly show that different network rehabilitation selection methods produce very different long-term pavement conditions and costs. If this study was conducted over a longer period, perhaps even more dramatic results would be obtained. Any rational method in selecting pavement sections for rehabilitation (like RANKING or IBC) results in a better network performance when compared with an AD HOC selection for the same cost. The AD HOC method is not part of ILLINET but was included to demonstrate the typical results when essentially no structured management system is used.

RANKING by worst-first selection resulted in a 20 percent increase in VKT traveling on good pavements over the 10-year period when compared with the AD HOC rehabilitation selection for the same funding.

Using either the IBC or the OPT optimization methods results in far better use of scarce funds and better pavement performance in comparison with RANKING methods. The IBC method provides the best and most practical network-level pavement rehabilitation optimization algorithm that allows yearly funding constraints. IBC resulted in a 214 percent increase in VKT traveled on good pavements over the 10-year period when compared with worst-first RANKING for the same funding. IBC provides similar solutions when compared with the more complicated optimization algorithm; however, it is a much more computationally efficient and more easily understood algorithm. In addition, IBC provides a much greater remaining life (almost twice) of pavement sections at the end of the analysis period than AD HOC or RANKING.

Another interesting conclusion can be drawn from the results in Table 1. The unrestrained NEEDS method produces less benefit for more cost than the IBC or OPT methods. This result is probably due to the optimization algorithm in IBC that maximizes the VKT on good pavements. The NEEDS, on the other hand, simply selects every section that reaches the trigger CRS value. Thus, even if an agency has the full funding needed, it is still desirable to maximize the VKT benefit of the network. Therefore, NEEDS is not the best way to allocate the resources for rehabilitation if it is desired to maximize any given benefit obtained such as VKT.

Method	*Cost ($ Millions)*	*Benefit (VKT on Good Pavements, km billions)*
RANKING	262	96
NEEDS	330	176
IBC	260	206

This case study shows a clear advantage of managing pavements using a rational method for selection of rehabilitation.

REFERENCE

1. Mohseni, A., M. I. Darter, and J. P. Hall. *Alternative Methods for Pavement Network Rehabilitation Management, Report 529-1.* Illinois Department of Transportation, 1992.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TRB	Transportation Research Board

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