CONFERENCE PROCEEDINGS 1

Third International Conference on Managing Pavements

Volume 1

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Third International Conference on Managing Pavements

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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 ENHANCING APPROPRIATE SYSTEMS

Planning and Design of a New Project-Level Pavement Management System

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Pavement design is one of the major activities at the project level of pavement management. A pavement design system takes into account not only material characteristics and effects of traffic and environment, but also pavement performance and associated economic implications during a life-cycle period. Other elements at the project level, such as construction quality, ongoing maintenance, and future rehabilitation, are also considered. Therefore, a pavement design system is often referred to as a project-level pavement management system. The planning and research effort initiated recently by the Ministry of Transportation of Ontario to update its pavement design system, Ontario Pavement Analysis of Cost (OPAC), is described. Considerable emphasis was directed at investigating the functional and user requirements of the new OPAC. This investigation included the examination of several existing pavement design methods, such as the AASHTO method and those of the Shell International Petroleum Company, the Portland Cement Association, and others. Also included were a review of the structure of an "ideal" pavement design system and a survey of user requirements as the basis for the design of the new system. Finally, a functional design or framework for OPAC 2000 and the steps involved in bringing it to a fully operational stage were established.

The original focus of pavement management in the 1960s and 1970s was largely at the project level. During the past decade or more, however, the focus has been almost exclusively on network-level pavement management. Most agencies have continued to use the project systems in their original design scope. The Ontario Ministry of Transportation (MTO) is such an agency, with its pavement design system, Ontario Pavement Analysis of Cost (OPAC).

OPAC was developed in the 1970s. It had a number of noteworthy features, such as performance prediction models that separate the effects of traffic and environment on total deterioration; a comprehensive life-cycle economic evaluation subsystem; a user delay cost model; and an optional distress-estimation subsystem for fatigue cracking, rutting, and low-temperature cracking. However, the OPAC system was developed primarily for new pavement design conditions, for traffic conditions of 20 years ago, and for a number of other conditions that preclude its being as useful today as it was originally. Consequently, MTO decided in 1992 to embark on a strategically based development and implementation of a new OPAC. In effect, the decision presented a unique opportunity to develop a project-level pavement management system relevant to current requirements and demands.

The planning and design of OPAC 2000, the new or updated version of the existing OPAC, are addressed, in particular,

1. Identification of the system requirements, including a summary of a comprehensive system user survey;
2. Assessment of candidate alternative systems as well as components of such systems [including those of

AASHTO and others, and including specific performance models and MTO's Pavement Rehabilitation Life-Cycle Economic Analysis Model (PRLEAM)];

3. Description of the overall functional design of OPAC 2000;

4. Description of the operating features of OPAC 2000, including inputs, models, and outputs; and

5. Discussion of the implementation plans for the new system and the strategy for future updates.

Requirements of Ideal Pavement Design System

As shown in Figure 1, the three major components or classes of activities in a general framework for a pavement design system are as follows (*1*):

1. Input information—relating to materials, traffic, climate, and costs, plus selection of a design period and structural and economic models, the identification of objectives and constraints, and variance data on the inputs to the model;
2. Generation of alternative design strategies; and
3. Structural analysis and economic evaluation of the alternatives and optimization to select the best strategy for implementation.

The framework applies to both flexible and rigid pavements.

Input Information Needs

The top row of Figure 1 identifies the information and models that should be available or should be obtained before alternative design strategies are generated. Available materials, expected traffic, climate factors, and costs are often the first data acquired.

The structural models can range from simple empirical to complex ones. Obviously the data acquired on materials properties, traffic, climate, and other factors must suit these models. The other key models involve economic evaluation. They should consider the entire design period or life cycle selected. In the pavement field the present-worth method is the most widely used; it should consider all present and future costs over the design period.

The item "Available Variance Data" on materials, traffic, climate, construction, maintenance, and so on is listed as input information in Figure 1. Whereas most design methods are deterministic in nature, the method in the 1986 *AASHTO Guide* (*2*) incorporates a measure of the observed variance in pavement performance into the design equation. The role of reliability (which requires such variance data) in pavement design is considered further in a subsequent section, Role of Reliability Analysis in Pavement Design.

The objectives established for design should be related primarily to performance, safety, and economy. For example, they might involve minimum levels of serviceability for different road classes. Constraints on design might

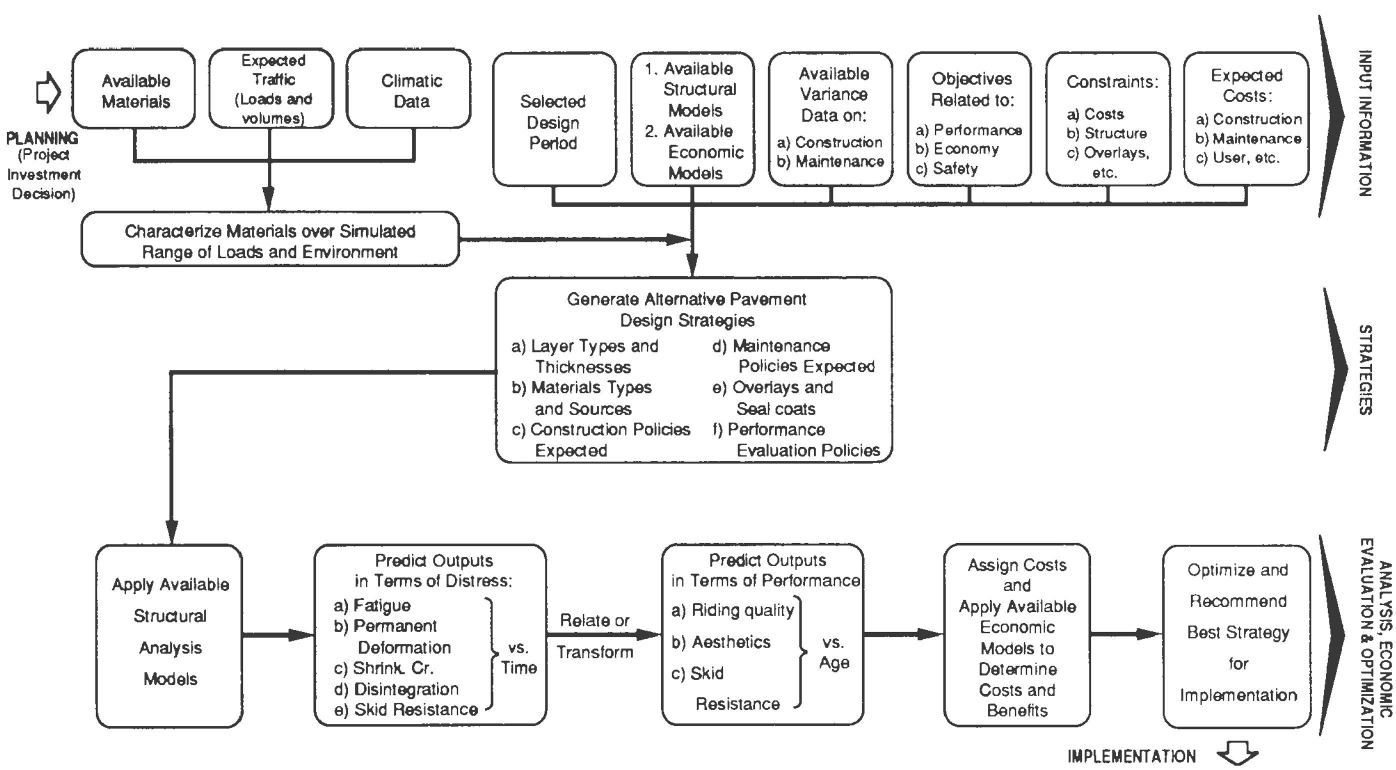

FIGURE 1 Framework for pavement design (*1*).

include, for example, limits on costs, minimum time between major rehabilitations, minimum or maximum layer thickness, and so forth. Expected costs are a vital part of the input information needed for design. Among the major cost items, both present and future, are construction, maintenance, and user costs.

Generation of Alternative Design Strategies

The term *strategies,* as related to design (see the middle row of Figure 1), is used to emphasize that, in addition to layer and material types and thicknesses, a design alternative should or can include future rehabilitation actions, policies on expected construction and maintenance, and perhaps even policy on periodic performance evaluation. For example, different construction policies (i.e., method versus end-product specifications) and maintenance policies (i.e., extensive preventive maintenance earlier in the life of the pavement versus corrective maintenance at or near the minimum acceptable serviceability level) can significantly affect performance. In addition, traffic-handling policy can provide important information for periodic updates of the original design estimates.

Structural Analysis, Economic Evaluation, and Optimization

The bottom row of Figure 1 gives the key elements that would ideally be involved in the structural analysis, economic evaluation, and optimization of the various alternative design strategies. Although most design methods do not now include all these activities, design methodology seems to be moving toward this idealized form. For example, the Superpave program, to come from Strategic Highway Research Program (SHRP), will have test methods and models for predicting fatigue cracking, rutting, and low-temperature cracking in flexible pavements.

Comprehensive structural models would first therefore be able to predict distress, using certain calculated responses such as stresses, strains, or deflections, and then be able to predict performance in terms of serviceability versus age. The economic evaluation models should involve the assignment of costs to the various alternatives, including those associated with the initial construction of the new pavement or rehabilitation, plus future costs of rehabilitation and maintenance over the design period or life cycle. Furthermore, user costs associated with the various alternatives (i.e., vehicle operating costs) and user delay costs during construction and maintenance should be included, at least as an option to the designer, so that a decision can be made about whether to consider them in the final selection.

When all the feasible design strategies have been analyzed and evaluated, the design process concludes with optimization (which may be a true optimization using an objective function and considering all possible strategy combinations or simply a ranking from least cost to most expensive), which includes selection of the best alternative and recommendation of it (with full documentation) for implementation.

Role of Reliability Analysis in Pavement Design

Reliability analysis has been applied successfully to commodities for a long time. In the area of pavements, the definition of reliability is given by the 1986 *AASHTO Guide* (*2*): "The reliability of a pavement design performance process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period."

It is well known that uncertainty is bound to prediction, particularly for long-term forecasts. A pavement design period typically spans 20 to 30 years. It is not possible at this time to describe the whole performance process accurately. Like any other civil engineering design, pavement design has to tackle numerous variances. Materials, traffic estimates, construction quality, and environmental factors are among possible sources of variance (*1*).

A rational design system should reflect performance under realistic operating conditions (*3*). One of the advantages of reliability analysis is the recognition that variance and uncertainty represent reality. Thus, the analysis tries to quantify them in terms of variance and to incorporate them into the design equation. For example, Appendix EE of the 1986 *AASHTO Guide* (*2*) provides the guidance necessary for any user to develop levels of overall variance (S_0). From the point of view of performance modeling technology, this probabilistic approach is an advance over the deterministic one.

The requirement for implementing a reliability analysis involves a substantial amount of long-term performance and traffic data collection. In addition, data on individual distresses, such as cracking, potholes, and so forth, need to be observed consistently over a period of 10 to 20 years. At present, both these requirements are only met to a limited degree in Ontario. However, both the SHRP Long-Term Pavement Performance (LTPP) results per se and the impetus SHRP has created for agencies to do LTPP monitoring themselves should provide a basis for directly incorporating reliability analyses into pavement design in the foreseeable future.

Requirements of Pavement Design in Ontario

The following studies were performed as part of the effort to ensure that the updated OPAC system meets the pavement design needs in Ontario.

MTO Pavement Design Procedure

MTO divided its pavement design procedure into two stages: preliminary design and detailed design. Preliminary pavement design serves the purpose of pavement selection, and detailed pavement design is used for contracting and actual construction. The Ministry's Pavement Selection Policy is given in Directive B-82 (*4*). Against a background of increasing costs and uncertain supplies of asphalt cement, the policy emphasized the following aspects:

1. The most appropriate pavement alternatives of both rigid and flexible types need to be considered.
2. The pavement design recommended by Regional Geotechnical Sections should consider conservation of mineral aggregates and maximization of the use of local materials.
3. Life-cycle costs of pavement alternatives are to be analyzed using OPAC; the pavement is to be designed to a minimum thickness. In the case of rigid pavement, OPAC is still to be used for calculating initial construction costs. (It might be noted that in this case it is really a cost calculator.)

Both the preliminary design and the detailed design are required to be implemented using the OPAC pavement design system.

Review of OPAC and PRLEAM

The current version of OPAC was originally developed in the 1970s; it was rewritten in 1989, which has been the only update. It is now called OPAC 2M in the *User's Manual* (*5*). There are two major subroutines in the existing OPAC: pavement performance prediction (*6*) and economic analysis (*7*). The basic equations for the performance prediction subroutine are as follows:

$$H_e = h_1(M_1/M_2)^{1/3} + h_2(M_2/M_2)^{1/3} + h_3(M_3/M_2)^{1/3} \quad (1)$$

where

h_1, h_2, h_3 = actual thicknesses of the asphalt, base, and subbase layers;
M_1, M_2, M_3 = moduli of the asphalt, base, and subbase layer materials; and
H_e = equivalent granular thickness.

This calculation of equivalent granular thickness allows the pavement to be transformed into a two-layer-equivalent structure, and thus the (Odemark) subgrade deflection, W_s, can be calculated as follows:

$$W_s = \frac{P}{2M_sZ\left[1+\left(\frac{a}{Z}\right)^2\right]^{0.5}} \quad (2)$$

where

P = total load (i.e., 40 kN on a dual tire),
M_s = modulus of subgrade,
Z = $0.9H$, and
a = radius of loaded area (i.e., approximately 163 mm for an equivalent circular imprint of a dual tire).

The foregoing then allows calculation of the riding comfort index (RCI) losses due to traffic, ΔRCI_T, as follows:

$$\Delta RCI_T = 2.4455\Psi + 8.805\Psi^3 \quad (3)$$

where $\Psi = 3.7283 \times 10^{-6} \times W_s^6 \times N$, N = number of (80-kN or 18-kip) equivalent single-axle load (ESAL) applications, and the RCI losses due to environment, ΔRCI_E, can be calculated as follows:

$$\Delta RCI_E = \left(RCI_0 - \frac{7.5}{1 + 2.362W_s}\right)(1 - e^{-0.06Y}) \quad (4)$$

where RCI_0 is the initial RCI, and Y is the number of years.

A key and most important feature of the foregoing formulation is the capability of separating RCI loss due to traffic and environment. This capability is a significant advance in pavement performance modeling; it has provided the basis for a number of cost-allocation studies (in which it is essential to be able to separate the damaging effects of traffic from the total damage or deterioration).

There are, however, several limitations or weaknesses in the current OPAC. Many of them are attributable to the limited data base available in the early 1970s and the focus of most of the attention at that time on the design of new pavements rather than on rehabilitation. In addition, traffic volumes and loads were substantially lower than they are today. Following are some of the specific weaknesses:

- The performance prediction model for environment-associated loss is not very reliable beyond about 8 years (which was the life of the Brampton test road at the time OPAC was developed). In effect, only one "environment" was used. Also, the model for traffic-associated loss is not very reliable beyond about 7×10^6 ESAL applications. Figures 2 and 3 show the inadequacy of the performance prediction models as found in a recent study of 48 cases.
- The user cost model is based on vehicle operating cost relationships from the mid-1970s; furthermore, it is not clear from the output whether the user cost item listed for each alternative contains both vehicle operating costs and traffic delay costs during future resurfacing.
- The concept of reliability associated with alternative designs and their costs is not incorporated into OPAC.

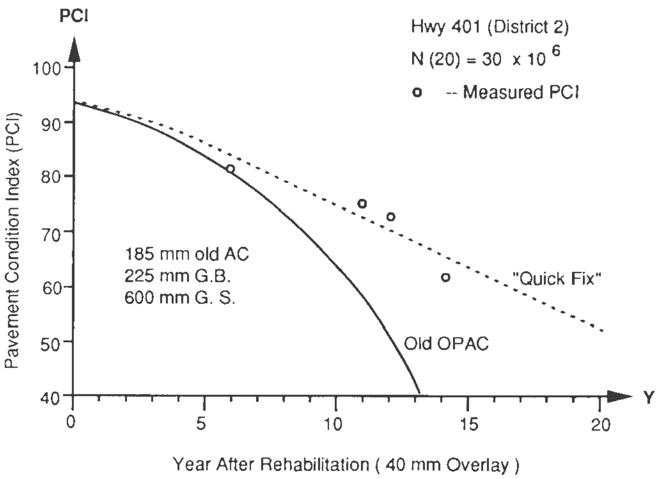

FIGURE 2 Illustration of overestimation of traffic-related performance losses.

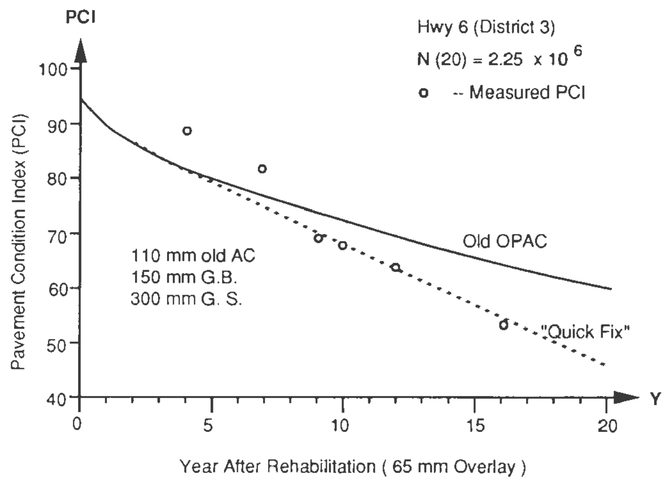

FIGURE 3 Illustration of underestimation of environment-related performance losses.

- The computing environment for OPAC is not user friendly. For example, operation requires a tedious and time-consuming series of steps, there is little flexibility, and there are no graphic presentation capabilities.
- OPAC handles only designs for flexible pavement. It does not include composite or rigid pavements. Also, the overlay design model in OPAC does not work particularly well, and OPAC is not able to consider the other rehabilitation design alternatives that exist today.

Remedies for these weakness can also be considered requirements for an updated or modified OPAC.

MTO also uses a computer software program, PRLEAM, for the evaluation of different pavement rehabilitation alternatives (*8,9*). PRLEAM is a comprehensive cost/benefit calculator that considers four sets of costs: construction of the rehabilitation, maintenance, user delay during construction, and salvage value at the end of the life cycle. It provides quantitative decision support to pavement designers in selecting project-specific rehabilitation treatments. The key features of PRLEAM can be summarized as follows:

- The program is very user friendly: all communication with the program is interactive, using menus with self-explanatory notes.
- The mandatory inputs include the following:
  - –Two or more treatment strategies covering the life-cycle period (although one can be run if only cost calculations are desired for it),
  - –Cost estimates for all initial and future rehabilitation and maintenance treatments,
  - –Life-span estimates for all rehabilitation treatments, and
  - –Discount rate and length of analysis period (maximum of 30 years).
- The optional inputs (for effectiveness and user delay cost calculations) include the following:
  - –Estimates of pavement condition index before, immediately after, and at the end of the life span of the rehabilitation treatments;
  - –Car and truck volumes (initial and rate of change); and
  - –Parameters to estimate traffic delays during construction.
- The program can easily be used to evaluate the effect of different life spans, discount rates, costs, and so forth, by simply changing input values on the screen. Results from previous runs as well as input values are stored and can be recalled for comparison.
- The program can rank the rehabilitation alternatives in ascending order of cost-effectiveness, where this factor is calculated as the ratio of effectiveness to total present worth of life-cycle costs.

It should also be noted that although PRLEAM can quantify costs and benefits of alternative rehabilitation strategies, it is not a design or optimization tool. It can only consider those alternatives provided by the designer; that is, the "best" alternative may not have been included for analysis. Nevertheless, PRLEAM can be a most useful complement to OPAC 2000.

Survey of System Users

To further explore the need for changes in OPAC as seen by OPAC users, a questionnaire survey of MTO regional geotechnical staff was carried out. The main objectives of the survey were to

- Identify the deficiencies of the current OPAC from users' perspectives,

- Determine the general requirements of the system functions to ensure that OPAC 2000 will meet the Ministry's current and future needs in pavement designs,
- Identify the specific requirements for input-output factors and models for pavement performance and economic evaluation, and
- Involve OPAC users in the updating (which is important because such a project cannot succeed without participation of and acceptance by the users).

The findings from the survey can be briefly summarized as follows:

- The new pavement design system should be capable of designing all three major types of pavement.
- The current pavement design procedure in the Ministry requires OPAC 2000 to act as both a cost calculator and a comprehensive design tool with outputs that can be used for pavement selection and for part of a Pavement Design Report accordingly.
- It is important that rehabilitation design be incorporated into OPAC 2000. With the mature highway network in Ontario, there is far less pavement design for new alignment than for rehabilitation. In fact, some regional staff estimate that over 90 percent of their pavement design work is for rehabilitation.
- Pavement performance models in the current system should be improved for handling high traffic volumes (as high, perhaps, as 300,000 annual average daily traffic), and yielding more accurate pavement lives and costs. The option of a user-defined model would be useful for dealing with unconventional materials.
- For the Ministry's pavement selection policy, the designs with minimum thicknesses should be reported. This suggests that the design outputs from the system should be ranked in different ways, such as by the total Granular A equivalent, initial costs and rehabilitation costs, and so forth, in addition to the total costs of the pavement alternatives.
- The computing environment should be more user friendly; ease in operation, help files, and a better user's manual might be included. It is important to link OPAC 2000 with the data system in the Ministry's Pavement Management System. This would facilitate both pavement designs and pavement management in the Ministry.

Review of Alternative Pavement Design Methods

To assist in developing the optimum pavement design method for Ontario conditions and to identify the strengths of other pavement design systems for possible use in developing the framework and methodology of OPAC 2000, some of the available pavement design systems or methods are evaluated with respect to their methodology, advantages, and disadvantages. The intention here is not to present a complete list, but to choose those systems being used extensively in North America and other places in the world. They are the AASHTO method and those of the Asphalt Institute (AI), the Federal Highway Administration (FHWA), Shell International Petroleum Company (Shell), and the Portland Cement Association (PCA). The discussion of the design systems includes the methods and their associated computer programs.

Assessment of Alternative Methods

A summary of the evaluation of features of the various methods is contained in Table 1. Although most of the items are self-explanatory, some additional comments on these design methods follow.

- The methods developed by highway agencies, such as the AASHTO and VESYS (*10,11*) methods, are based on pavement performance, which is related to pavement distress, whereas methods of AI (*12*), Shell (*13*), and PCA (*14*) are based on mechanistic analysis of stresses and strains in the pavement layers. Although the design criteria of these methods are distress based, they are not directly related to pavement performance.
- The VESYS, Shell, and PCA methods do not include a cost analysis. The cost-analysis procedure in the AASHTO DNPS860 program has no user cost elements in the calculation (*15*). The AI method carries out a life-cycle cost analysis separately by the computer program LCCOST (CP-5).
- According to the framework of a pavement design system presented in Figure 1, selection of the best design alternative will be based on the cost analysis of the structurally sound alternatives. In the pavement design systems evaluated, the AASHTO DNPS860 program can make the structural and cost analysis, and then carry out an optimization, of which only the least-cost alternative is reported. Other design programs either do not have a cost-analysis procedure, or, as with AI's LCCOST program, carry out cost analysis separately. In those cases the users select a pavement structure using their own judgment.
- Among the methods evaluated, the AASHTO method is the most developed for a computerized pavement design system. It can be used for flexible pavement, rigid pavement, and overlay designs, whereas others work only on flexible or rigid pavement design. Some of the methods do not provide an overlay design procedure. The pavement performance concept (present service ability index), the load equivalency factors, and axle load calcula-

TABLE 1 Summary of Features of Different Pavement Design Procedures

	STRENGTH	WEAKNESS
AASHTO (DNPS86O)	1. Design procedure for flex., rigid pvts and overlays 2. ESAL calculation (LEF of SN=5, Pt=2.5 is used by AI) 3. Drainage condition being considered 4. PSI concept being developed to measure pavement performance 5. Optimization (least cost solution)	1. No user costs 2. Gives only one design alternative
AI (HWY, LCCost)	1. Consider climatic impact on material properties: a) Effects of temp. on the dynamic modulus of asphalt mixtures b) Freeze/thaw effects on the base and subgrade material c) Guideline for selecting asphalt grade under various climates 2. Design procedure for emulsified asphalt pavement 3. Provision for stage construction 4. Overlay design and LC cost analysis procedures available	1. No drainage provision 2. Not related to performance 3. No comprehensive program which can generate alternatives, perform structural and cost analysis, and then carry out optimization
FHWA (VESYS)	1. Prediction model for perf. and distress (cracking, rutting) 2. A "closed-form" reliability method based on statistical distributions of inputs and a standard statistic subroutine 3. Adaptability to various traffic & environment	1. Too many inputs, time consuming 2. Predicting models of performance and distress only good for the first 5-7 years 3. Gives only one alternative 4. No overlay design procedure and cost analysis
SHELL (Computer Program Package)	1. Works on "real" properties of materials, so it is widely adaptable to various traffic and climate conditions and materials 2. Design Reliability can be determined by specifying different confidence levels to the subgrade strain criterion 3. Rut depth prediction subroutine 4. Overlay design procedure available	1. Not related to pavement performance directly 2. No cost analysis 3. Lack of systematic functions to generate design alternatives and carry out optimization
PCA (PCAPAV)	1. Applicable to all kinds of PCC pavements (plain, reinforced, continuous reinforced) 2. Takes into account the effects of concrete shoulder, curb or gutter, etc. 3. Easy to use	1. No drainage factor 2. Not related to performance 3. No cost analysis

tion method (ESAL) used by AASHTO are followed by many other methods.

• For both flexible and rigid pavement design, the previously mentioned methods can be categorized as empirical or mechanistic. Empirical methods, such as the AASHTO method, take into account factors that highway engineers commonly meet; thus they are more practical. However, it has been realized that empirical methods are difficult to apply if the conditions are different from those for which the methods were developed. Other methods summarized in Table 1 are mechanistic methods that can be adapted to a wider range of traffic and climate conditions, but they often require as inputs actual axle loads (weights and repetitions) and material properties determined in situ or in the laboratory. If estimated traffic, material, and climate data are used, the accuracy of outputs relies largely on the quality of the estimates and thus there are no prominent advantages over empirical methods. In this regard, a rational pavement design method should have the advantages of both empirical and mechanistic methods, or in other words, a mechanistic-empirical method, as referred to in Part IV of the *AASHTO Guide* (2).

Implications for OPAC Updating Project

From a review of the current OPAC and the alternative systems, it can be seen that OPAC has the strengths of both mechanistic and empirical methods. In a mechanistic sense, the pavement is modeled as a multilayer system that is subjected to a standard 80-kN ESAL; the subgrade deflection is calculated with the Odemark method. In an empirical sense, OPAC is similar to the AASHTO method in two ways: (*a*) OPAC is performance based; the two performance models use RCI (analogous to PSI) or PCI as the performance parameter; (*b*) OPAC employs granular base equivalency (GBE) factors to represent the pavement material properties, which are similar to the AASHTO layer coefficients, a_i. OPAC can thus be classified as a mechanistic-empirical method. The mechanistic-empirical characteristics mentioned here should be retained in OPAC 2000.

The functions of the OPAC system are still very powerful compared with those of some of the evaluated systems. To overcome limitations of the current OPAC and enhance the functions of the OPAC pavement design system, the following recommendations are made:

1. Material and Environment Inputs: To incorporate the effects of environment on the material properties, the GBE factors should be improved in the following ways:

a. For asphalt materials (asphalt concrete, polymer-modified asphalt materials, recycled asphalt mixtures, etc.), different weighted mean annual air temperatures (w-MAAT) should be used for south and north Ontario to modify the GBE factors. The w-MAAT concept is employed in the Shell method and the VESYS structure subsystem.

b. For untreated gravel and subgrade, drainage factors should be used to modify the GBE factors. This is similar to the drainage coefficient, $m_i s$, in the AASHTO method (2, Table 2.4, Part II).

In addition to these considerations, a simplified way to deal with frost effects is to set up a guideline of minimum structure depth in the program to maintain an adequate depth of the granular subbase depending on the frost penetration depth of the area (*16*, p.139, Figures 3.4 and 3.5). This verification should be related to the type of the subgrade soil (frost-susceptible or not).

2. Pavement Model: As mentioned earlier, it is recommended that the Odemark analysis method and the use of GBE factors be retained in the new OPAC 2000 system. Furthermore, this model should be capable of being extended to rigid (composite) pavements and overlay designs. Other types of rehabilitation, such as cold milling and microsurfacing, can also be handled by assigning different GBE values. If this indeed proves to be feasible, OPAC 2000 will have a salient advantage over many other pavement design systems, many of which can deal with only one type of rehabilitation (asphalt concrete overlay).

3. Distress Prediction: The Shell rutting-depth calculation method should be "borrowed" for OPAC 2000. It would act as an optional function for rutting-depth assessment of otherwise structurally adequate pavement alternatives. Fatigue cracking is not a major problem on Ontario highway pavements, but reflection cracking prediction would be of practical significance. The WATMODE model (*17*) developed for Ontario, which predicts rutting, fatigue cracking, and low-temperature cracking, can be assessed for incorporation into the system.

4. Reliability: The methods evaluated here deal with reliability in the pavement design in three ways:

a. The AASHTO pattern: The reliability factor $Z_R S_0$ in the AASHTO pavement design equations is in a log relationship with W_{18}. This factor controls the output of the design, as W_{18} represents the pavement life.

b. The VESYS pattern: As was mentioned by Kenis (*10*), the "closed formed" design reliability is presented as mean values with variance coefficients for both inputs and outputs.

c. The Shell pattern: Design reliability is controlled by giving different confidence levels to the regression model of the subgrade strain criterion. Although the default confidence level is 50 percent, models based on 85 percent and 95 percent confidence levels are also available.

Framework Design for OPAC 2000

On the basis of Figure 1 and the investigation of Ontario pavement design needs and the assessment of the alternative design methods, a framework for the updated pavement design system has been established, as shown in Figure 4. Although the pavement performance prediction models are currently being updated and further developed in MTO, the new system has been designed to have the following major functions:

1. The system function has been extended to analyses of flexible, rigid, and composite pavements for both new designs and rehabilitation. Flexible and rigid pavement designs are handled by separate models in the system. Users can choose pavement types by inputting different types of materials. The extension of rehabilitation design and related economic evaluation is based on the Ministry's overlay design method.

2. The users of OPAC 2000 can choose to use the system either as a design tool or as a cost calculator. PRLEAM is incorporated in the system for cost analysis using the "user-defined" model.

3. Improvements to environmental and traffic inputs have been taken into account—for example, w-MAAT, drainage factor, and ESAL calculation.

4. The output format of OPAC 2000 has been designed to meet the requirements and, in effect, to be parts of the Ministry's Pavement Selection Report and Pavement Design Report.

5. The following efforts make the system user friendly:

a. Screens employing drop-down menus and spreadsheet format, which are easy to operate;

b. Default input values, used extensively with the help of the setup command and numbered option keys (which includes making use of the Ministry's Material Costs Estimation Package);

c. On-line help and a file menu. (A well-developed user's manual is recommended for additional user friendliness.)

The structural basis of OPAC 2000 continues to be the Odemark elastic layer analysis method and the GBE factors of pavement materials, and the GBE concept has been extended for rigid pavement and rehabilitation designs. For portland cement concrete and some new asphalt materials, such as polymer-modified or premium

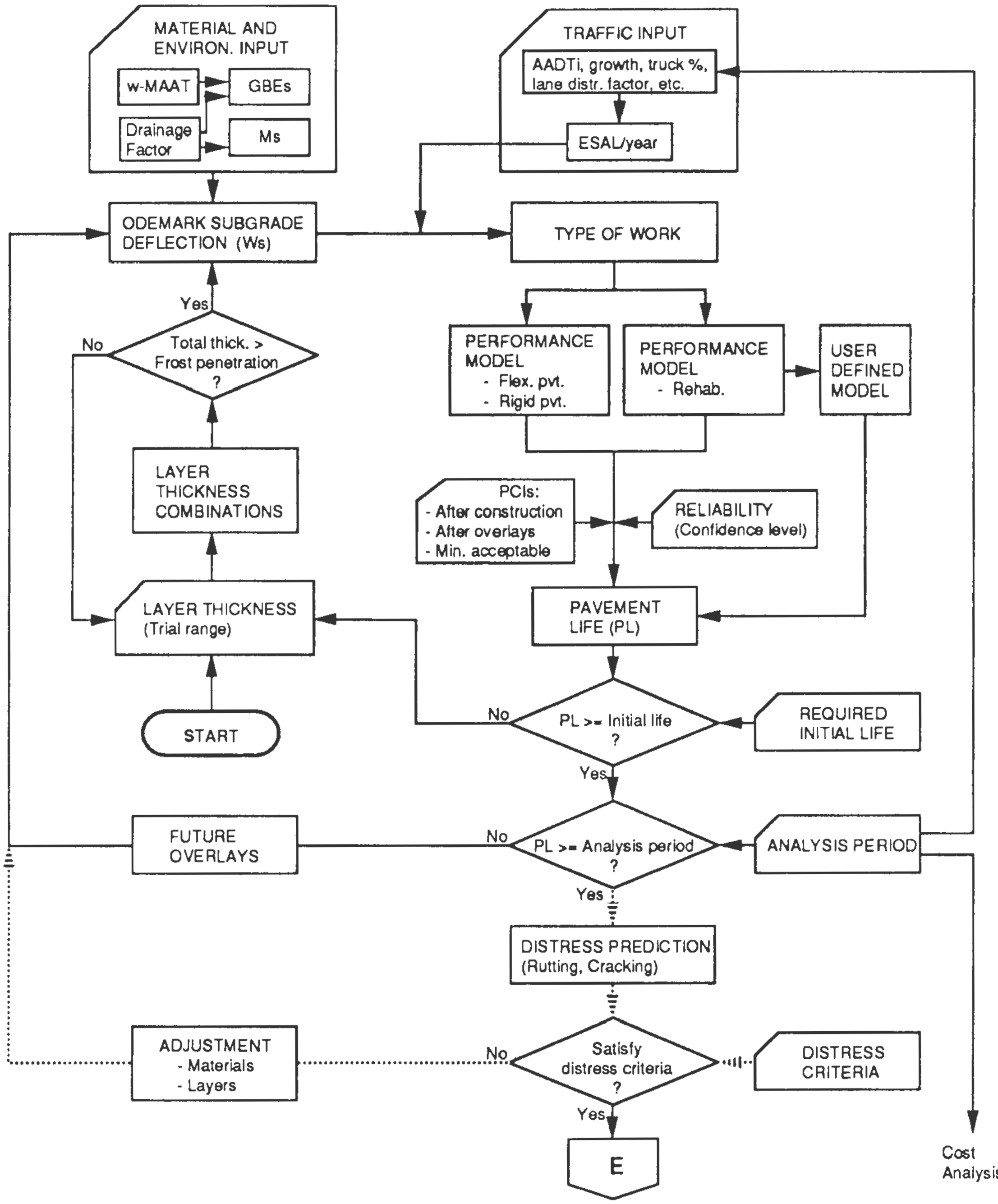

FIGURE 4 **Flow diagram of OPAC 2000** *(continued on next page).*

asphalt and asphalt mixture with geosynthetics, the GBE factors should be related not only to the elastic moduli (M_i's) of the material but also to the pavement performance. In OPAC 2000, GBE factors have been modified by the local temperature and the drainage condition of the highway section. For rehabilitation designs, the GBE factors of the existing pavement layers have been further modified by the surface deflection values from Dynaflect or falling-weight deflectometer surveys. Perhaps future updates of the GBE factors will be more performance based when the results of the SHRP LTPP projects become available.

The foregoing material and the discussion of the preceding sections represent Stage 1 in the development and implementation of OPAC 2000. It might be noted that the framework design summarized in this section also includes a comprehensive set of menus plus input and output screens. In effect, these mock-ups represent the framework specifications, or what the system will look like to users; they incorporate typical, realistic numbers.

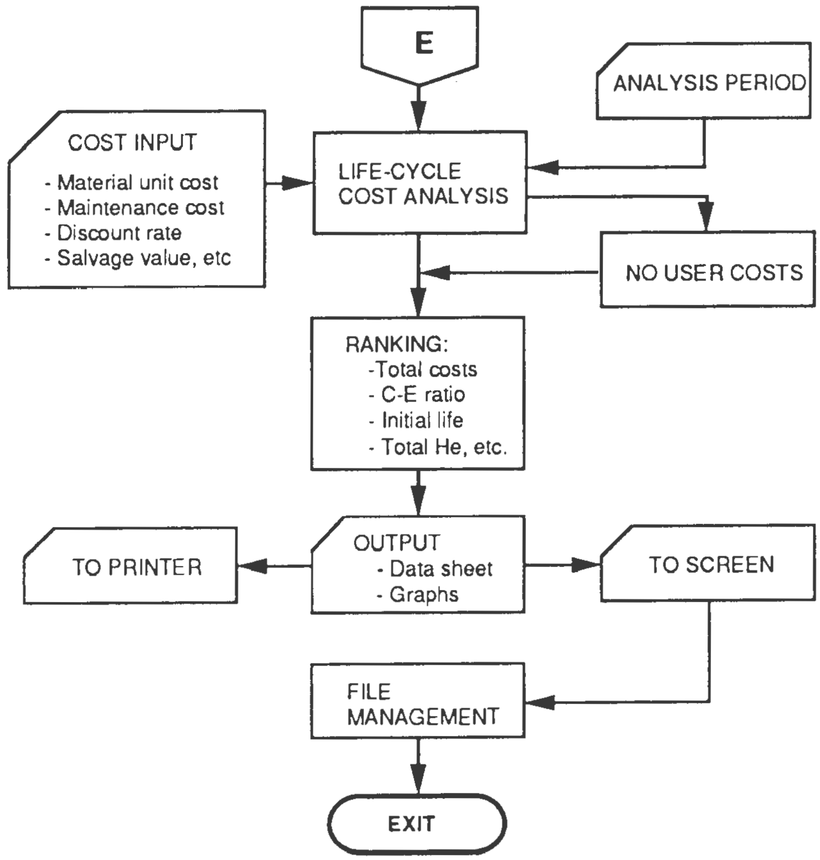

FIGURE 4 *(continued)*.

Strategy for Further Development

The OPAC updating project is planned to be implemented in four stages. Stage 2 has as its primary objective completion of the detailed system design and with that, determination of all input data items and files required plus the selection or development, as appropriate, of all necessary models or subroutines. Some of the elements of the detailed system design are as follows:

- Particular functions of and relationships between each subsystem or subroutine in flowchart form;
- A detailed flowchart for each subroutine in the system;
- Data items (types, units, etc.) and files plus numerical variances of the major variables; and
- Detailed designs for the prompt texts and graphs on the screen and in the printouts.

Stage 3 involves coding the system on the basis of the selected computer language or languages, data base manager, and so forth, preparing the documentation and user manuals, and implementing trials and modifications as required.

Stage 4 involves a series of training sessions for users of OPAC 2000 and ongoing system support plus periodic updates, as required.

Summary and Conclusions

This paper addresses the fundamentals of an ideal pavement design system from the viewpoint of project-level pavement management. The general strength and limitations of the existing OPAC and PRLEAM and of some major pavement design methods are examined. One of the major focuses has been on identifying the requirements for the updated pavement design system in Ontario. These have provided guidance for the functional design of the new system, OPAC 2000. Future development and implementation will include the following:

1. OPAC 2000 will incorporate as many of the key elements of an ideal pavement design system as possible. These fall into three major classes: input information, strategies, and analysis, economic evaluation, and optimization.
2. Provision will be made to incorporate reliability analysis (i.e., estimating the probability that a given design will achieve its intended performance or life, or spec-

ifying a reliability level that a design must achieve) as more Ontario variance data are acquired on the input factors and as SHRP data become available.

3. The current capability of OPAC to model traffic- and environment-associated deterioration separately will be retained, even though evidence from a limited number of situations (which may all have been overdesigned with regard to their ability to carry ESALs) suggests that only age, as a surrogate for environment, is related to deterioration.

4. OPAC 2000 will also be able to handle rigid and composite pavements and various types of rehabilitation. Because performance models do not exist or may not be reliable for some of the rehabilitation designs, OPAC 2000 will contain a default type of performance prediction model (using GBE factors for the existing pavement and analyzing the rehabilitated pavement design with the new pavement deterioration model) or, as an option, use PRLEAM, in which the designer inputs a straight-line deterioration model.

5. The requirements of OPAC 2000, according to a survey of users from the MTO regions, are very relevant and reasonable and will be reflected in the update. These relate to certain general provisions, inputs, performance models, economic evaluation, outputs plus user friendliness, versatility, and flexibility.

6. Explicit links between OPAC 2000 and the Ministry's data base in its pavement management system will be developed.

7. The basic approach to economic evaluation in the current OPAC is entirely applicable in OPAC 2000, but it will contain the option of not including calculations for vehicle operating cost or user delay cost (during rehabilitation or maintenance), if the designer wishes. Also, the basic relationships for vehicle operating cost and user delay cost calculations will be updated.

8. The framework or functional design of OPAC 2000 in Stage 1 of the overall development will be used as a basis for the detailed system design of Stage 2.

9. The strategy for work subsequent to Stage 1 will be one of continuing stages; that is, detailed system design and further model development in Stage 2; coding the system, documentation, and trial implementation in Stage 3; and training sessions plus ongoing system support in Stage 4.

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Development of Road Management Systems in Southern Africa

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Work carried out during the design and implementation of new road management systems developed to support the activities of the road agencies in southern Africa is described. A systems approach was applied to study the requirements of each part of the road agencies and then to define a logical framework for the system. The resulting system consists of a number of modules, or subsystems, that can be implemented individually to suit management and organizational priorities as resources become available. The constructive participation of the road agencies during each stage of the development was found to be essential in ensuring the success of the road management system. The work described is an amalgamation of projects carried out in southern Africa; it covers the design and implementation of a modular road management system comprising a central data base, a data collection and entry subsystem, a planning subsystem based on the use of HDM-III, a mapping subsystem that incorporates a geographic information system, and other subsystems that perform specific tasks.

Many developing countries are reviewing and modifying the way in which they manage their road transport infrastructure. Countries in southern Africa have recently taken an active role in developing a practical approach to the implementation of road management systems. This paper describes an approach evolved from experience gained in developing road management systems for two countries in southern Africa. The overall objective in each country was to develop a road management system that would meet the immediate information needs of the road agencies. In addition, the road management system would be used to define the most cost-effective design and maintenance standards for the road networks. The administrative and organizational structure of the agencies implementing road maintenance were considered so that the system developed would promote the best operational, managerial, and technical means of carrying out cost-effective road maintenance.

The World Bank Highway Design and Maintenance Standards Model (HDM-III) (*1*) was used to establish optimum design and maintenance standards. The model required comprehensive information about the road network to be assembled and analyzed. The limited time available for the development work often placed significant constraints on the implementation of the road management system, which had to be developed from an initial requirements analysis to the final production runs in less than a year.

The management and organization of road agencies is critical to the success of any computer system that supports their activities. This paper deals only with the development of computerized road management systems. The institutional aspects involved in improving the management and organizational structure are described in these Proceedings by Pinard et al.

Program of Work

This section describes the events undertaken during the development and implementation of a road management system that ideally comprises several interconnected tasks. Figure 1 illustrates the sequence of tasks undertaken in the development of such a system for one country in southern Africa. Early in the development cycle, a systems analyst investigated the needs of each part of the road agency. Then, through a series of meetings in which the road agency provided additional guidance on the integration of different requirements, the analysis was further refined to produce the overview outlined in the next section.

The sustainability of the road management system was an important consideration during design, since it is essential that it be maintained and operated by local staff. The systems analysis illustrated that a number of interacting modules were needed rather than a single complex computer system. This setup allows the system to be implemented in stages.

The requirements analysis was developed during an initial intensive period of activity and was then used as the basis of a functional specification of the system. The "road network matrix" concept, which will be described later, was also defined during this period. A survey of most of the road network was carried out toward the beginning, and the resulting data were entered into the system by local staff. Before data collection could proceed, it was necessary that the road network be specified and data collection forms be designed. HDM-III calibration was carried out in parallel in preparation for the analysis.

Hardware and software had to be procured and installed before work could continue. The software system was implemented in consultation with local staff, allowing training on the data entry system to start at an early stage. In this way, data entry for some parts of the network was achieved concurrently with data collection for other parts.

Maps of the road network were initially digitized with the intention of providing a definitive road network for data collection, but further updates and corrections were needed before the data were suitable for the production of maps. Finally, data were extracted and automatically formatted for input to HDM-III analysis runs, producing results for input to other modules of the road management system.

To ensure the sustainability of the system, and despite the rapid time scale for this work, local staff performed all the data collection and input tasks, and counterpart staff in the road agency did much of the processing. This approach also provided useful and constructive feedback into the development process.

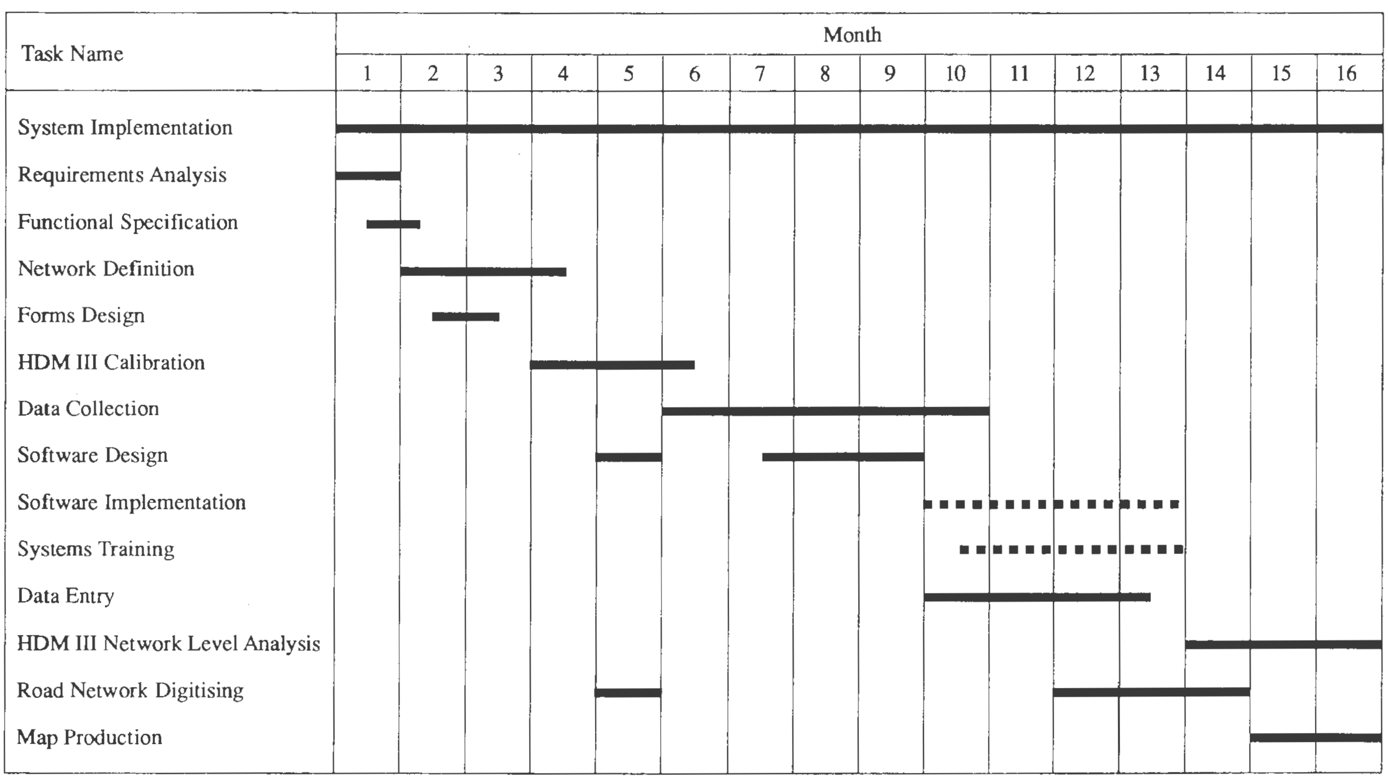

FIGURE 1 Typical program of work.

SYSTEM OVERVIEW

The results of the systems analysis are illustrated in Figure 2. The framework was developed through the consultation process with the road agency, and current literature on road management systems was considered, including recommendations from the World Bank (2).

Figure 2 shows the division of the overall road management system into subsystems, with a central or core data base surrounded by satellite subsystems that are both providers and recipients of data from the center. The function of the central data base is to hold validated summary data from the subsystems and to control transfer of those data between subsystems.

One key feature of this approach is that the road management system can operate with less than the full complement of subsystems. It was recognized that incorporating all of the features of a complex system into an existing organization would require a large investment in skills and resources, and that introducing all components at once was likely to be both impractical and undesirable. A modular approach allows parts of the system to be introduced separately as required. For example, if there were no funds or expertise available to implement a bridge management subsystem, then the central data base could be loaded with summary data on bridges, perhaps generated by hand or by simple spreadsheet applications. Other subsystems could use this information as required.

Thus, with a modular structure to the road management system, the detail and design of each individual subsystem can be hidden from other subsystems. This structure permits flexibility for growth of the road management system: individual subsystems may be changed without it affecting any of the others. The subsystems can even be implemented using different software and hardware solutions, depending on the availability of computer skills within the road agency, although it is preferable to maintain a common computer platform.

Another important feature is that each subsystem is managed by the appropriate branch or section within the road agency. Individual parts of the organization can be responsible for their own systems and data and hence are likely to have a greater interest in ensuring that the information is accurate, up to date, and consistent.

However, the modular approach does not mean that the subsystem users can simply take summary data from

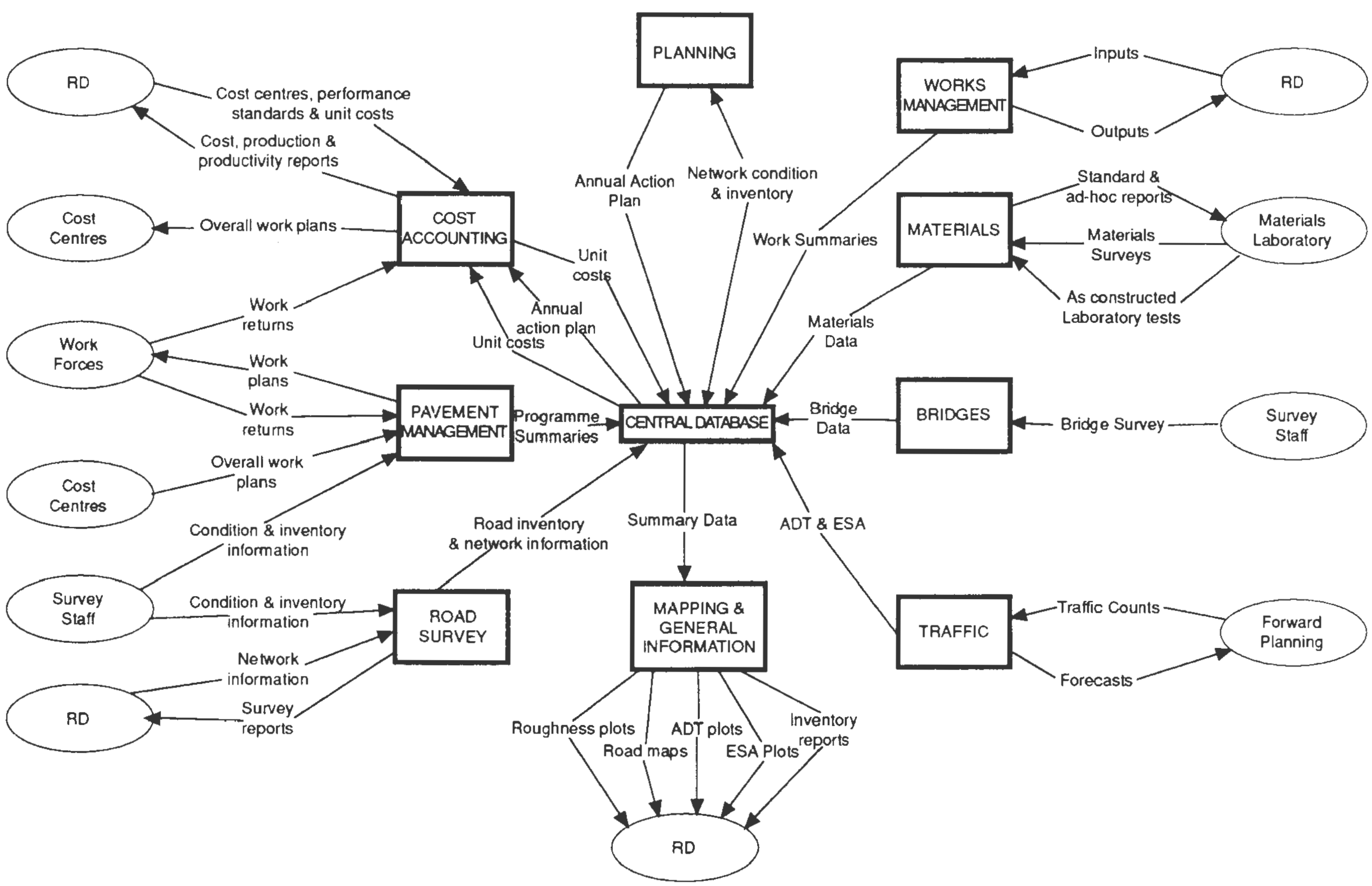

FIGURE 2 Road management system framework.

other subsystems as immutable fact. Awareness of the information itself is required, especially in respect of probable accuracy and suitability to requirements. Liaison and management within the organization are necessary to ensure the proper functioning of the road management system. Much emphasis has been placed on making sure that the human organization is both willing and able to support the needs of the computerized system.

Resources: Software, Hardware and People

The choice of standard personal computers as a hardware platform was largely influenced by the knowledge and familiarity of local staff with the personal computer and with the availability of technical support and maintenance for these products in the region. More powerful workstations were considered, but they were rejected because of doubts about the amount of training and support available and because day-to-day systems administration of such machinery is more complex and time-consuming. Using a local area network was considered inappropriate at the time for similar reasons.

Because of the very large volumes of data to be stored and analyzed, simple personal computer-based spreadsheets and data base software packages were considered insufficient. In addition, if the road management system is to migrate to other hardware and operating system environments in the future, it is important that the applications can be transferred with little or no modification. Again, the availability of local technical support and professional training influenced the eventual choice of data base software from among those that provide powerful fourth-generation language capabilities.

It should be emphasized that the logic of how the data should be stored and analyzed in a data base is more important than the actual software package used. In this case, the data base software was chosen for its combination of functionality, availability on different computer systems, and local support.

Certain computer skills will generally be available within many road agencies in developing countries, including word processing, spreadsheet analysis, and computer-aided drafting. The choice of software was therefore influenced by the need to make appropriate use of existing skills. In the design of the software for the road management system, it was decided to implement routine tasks using a combination of menus and standard forms so that administrative staff who already have typing skills could easily be trained to use the system.

Network Definition

For general public use, a road network usually has a route numbering system that makes it straightforward to follow frequently used routes. However, for data collection and storage purposes, an accurate system of road referencing is required as a framework on which to locate any data. This storage framework is separate from route numbering, which may change over time. The road referencing system also localizes the effect of any changes in distance measurements that may result from realignments or road improvements.

The standard method of defining links is according to lengths of road for which the level of traffic is relatively constant. In practice, this results in nodes at every town or junction, with links in between. All information about a link is then referenced by its distance along the link from the node at one end. Hence the network definition only needs to be updated when a road is physically altered or new roads are included in the network. Changes to surfacings or other parameters are just changes to the attributes of the link.

It is essential to define the road referencing system before data collection begins so that all data forms can be readily identified and data can be correctly referenced. All links should have numbers that indicate the administrative district in which the link is located, and all nodes should be given names corresponding to the town, village, or junction where they are situated. Noting the names of both nodes together with the link and the chainings on each form verifies that the link number is correct. Locally understood names are easier to get right than arbitrarily assigned node numbers.

The road referencing system provides the essential common referencing system between the different modules of the system, and any revisions to this referencing system must be carried out in a systematic and methodical manner to minimize the chances of any incompatibility between the different modules.

Data Collection

A comprehensive survey of the entire road network at a general level of detail is often more useful than detailed surveys of parts of the road network. A rapid method for visual inventory and condition survey was therefore developed. One objective when collecting comprehensive data is that the data should assist in locating areas for more detailed investigation where serious deterioration has occurred. In the future, automated methods of data collection for the road network may allow the collection of more detailed data.

During the first survey of a road network, two main types of data are necessary. The first is inventory data, which essentially define the assets for which the road agency is responsible for maintaining. The second is condition data, which indicate the state of these assets. Inventory data can be further subdivided into two types:

(a) attributes that extend over lengths of road, such as the type of road surface defined by start and finish distances within the link, and (b) features that can be located by a single distance along the link. Two data collection forms were designed for the inventory surveys, one for continuous parameters such as the pavement surface type or roadway width and the other for point features such as culverts and bridges.

Road condition can be measured in many different ways, depending on the level of detail, frequency, and accuracy required. These characteristics have implications on the quality of the data obtained (2) as well as the resources required for data collection. The experience gained working in southern Africa led to the decision to adopt simplified manual data collection procedures. Road condition was defined in subjective terms as parameters averaged over each kilometer by the observer. More detailed observations would have taken much more time and would have involved more training for each observer. Nine condition parameters were estimated for each kilometer and recorded on a four-point scale (e.g., defect severities and extents could be recorded as none, minor, significant, or severe). Manuals and training to assist in estimating each parameter were provided. An example of the data collection form designed for the initial rapid condition survey is shown in Figure 3.

All of the forms were designed to facilitate rapid data entry into the road survey subsystem by administrative staff. The overall objective adopted was to minimize the number of data items to be collected. Only data items required within the road management subsystems should be collected. Consequently, the need for input data for HDM-III was a strong influence on the data parameters collected. When selecting the parameters, it was intended that the central data base should contain a comprehensive set of data from which other analyses might later be carried out. In addition, the HDM-III planning subsystem has other data requirements that would not normally be included in the road network survey. These had to be assembled separately and directly stored within the planning subsystem to be used in HDM-III analyses.

Planning Subsystem

The HDM-III model was designed to analyze projects, not to complete road networks, so it has some limitations on how it may be used. Consequently, the concept of a road network matrix was developed to facilitate HDM-III analyses of entire road networks.

The road network matrix can be used to analyze the physical characteristics, condition, and performance of an entire road network. It provides a method of modeling the road network to study the effect of networkwide policy changes—for example, proposed changes to maintenance funding levels, network restructuring, and maintenance and rehabilitation standards. In addition, it allows screening of sections of the road network for further analysis—for example, short lists of upgrading projects—as well as for rehabilitation and maintenance projects.

The road network matrix comprises up to 50 logical road links or matrix cells formed by aggregating physical road sections in the road network with the same characteristics, as shown in Figure 4. Each logical link can contain up to 10 pavement sections that can be used to model differences in pavement structure and condition. The maximum of 50 links is governed by the limit in the expenditure budgeting model, which is used to conduct the benefit maximization analysis. For example, in one country, HDM-III analysis was permitted for subnetworks for paved, gravel and earth, and sand roads, each with up to 20 links. The division of the road network into subnetworks was done according to differences in traffic composition and the implications on vehicle operating costs.

Figure 5 shows a typical framework for the road network matrix, in which the cells are divided according to functional road class, road type, and traffic group. Physical road links with similar traffic levels are grouped into logical links, and the total length of roads with similar pavement construction and condition are then grouped into one of the 10 sections within each logical link.

The ranges of attributes and condition parameters for each section are defined within the planning subsystem through a series of data entry forms. The whole road network is automatically grouped into the appropriate logical links and sections within the road network matrix by a transfer process between the central data base and the planning subsystem. It would be extremely time consuming to carry out this process manually.

The HDM-III model can then be used to analyze the logical links in the road network matrix to produce a preliminary road development plan. The plan contains a prioritized list of road sections within the road network matrix and defines the characteristics of roads that would be suitable for funding under medium- to long-term capital budget constraints. Candidate projects for the road development plan are derived from two sources. First, from a short list of roads whose conditions exceed maximum maintenance and rehabilitation standards derived using HDM-III. Such roads may require rehabilitation for which funding would be outside the provisions of the recurrent maintenance budget.

The second source of candidates would be roads with traffic levels greater than the threshold defined for upgrading road standards within each functional road class. The corresponding physical road links in the network that carry traffic levels above the threshold need to be assessed individually by conducting a full-scale economic appraisal using actual physical parameters such as road condition, traffic loading, and predicted traffic growth. The benefits

ROAD CONDITION SURVEY	Link No	Road	Date
	From		To
District			
Inspector			
Average condition to the end of the km:			

			A
General Road Surface Condition		Good	1
		Moderate	2
		Bad	3
		Failed	4
			B
Type		PAVED	1
		UNPAVED	2
			C
DEFECTS	Potholes	None	1
		Minor	2
		Significant	3
		Severe	4
			D
	Rutting	None	1
		Minor	2
		Significant	3
		Severe	4
			E
	Cracking or Surface Looseness	None	1
		Minor	2
		Significant	3
		Severe	4
			F
	Irregularities or Corrugations	None	1
		Minor	2
		Significant	3
		Severe	4
			G
	Ravelling or Gravel Loss	None	1
		Minor	2
		Significant	3
		Severe	4
			H
	Edge Damage	None	1
		Minor	2
		Significant	3
		Severe	4
			J
Shoulders		Good/None	1
		Moderate	2
		Bad	3
		Failed	4
			K
Drainage		Good/None	1
		Moderate	2
		Bad	3
		Failed	4

FIGURE 3 Road condition assessment form.

calculated for the improvement alternative are then used to determine the final ranking for upgrading.

Mapping Subsystem

The system overview shown in Figure 2 includes a mapping and general information subsystem. Maps of the road network are one method of visualizing the information stored in the central data base of a road management system, but it should be emphasized that this is only one subsystem rather than the center of the system. In this case, a geographic information system (GIS) provides a conceptual window as a tool through which to look into the data base, but this process must not control or restrict the design of the data base.

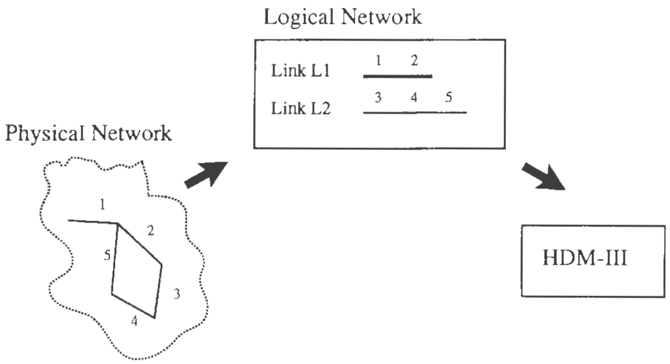

FIGURE 4 **Logical network analysis.**

	Paved Roads Traffic Groups			Gravel/Earth Traffic Groups			Sand
ROAD CLASSES	High	Medium	Low	High	Medium	Low	All
Primary							
Secondary							
Tertiary							
Access							

FIGURE 5 **Road network matrix.**

The mapping subsystem is designed to allow the production of maps of the road network. This subsystem incorporates a commercial GIS that interfaces with a computer-aided drafting package and the relational data base at the core of the road management system. The mapping subsystem can be configured to display and plot any attribute data of any link provided that the data are available in the central data base. Links may be differentiated in terms of line type, thickness, and color. The system can be set up to display road classification, average road condition, and average daily traffic for individual links, as well as any development plans derived from HDM-III through the planning subsystem. It is also possible to produce strip maps for individual links showing road condition parameters and road features inventory data.

During one of the implementations in southern Africa, some problems were encountered during the process of digitizing the road network from 1:250,000 maps. Some road locations had changed and new roads had been built since the maps were last published. Digitizing facilities were subsequently provided to the road agency to enable future modification of the graphical representation of the road network or administrative boundaries.

Further Development

The main advantage of the modular structure is that parts of the system illustrated in Figure 2 can be implemented in stages. For example, in one country only the road survey data base and a mapping system were implemented, whereas in another the central data base, road survey subsystem, planning subsystem, and mapping subsystem were implemented. The modular design means that subsystems can be added progressively.

In one country, further development of the traffic subsystem has been undertaken. This development plays an important role in defining one of the key parameters for the economic analysis and prioritization carried out by the planning subsystem. The traffic subsystem takes discrete traffic counts from individual counting stations and converts them into estimated traffic levels for associated links in the road network. This procedure demonstrates the value of a modular system that permits individual subsystems to be updated without disrupting the operation of other subsystems.

Another example of the versatility of the modular structure in one country is the addition of a pavement management system (PMS) within the overall road management system framework shown in Figure 3. The PMS requires more detailed pavement condition surveys, and data from these surveys are fed into both the planning subsystem and the PMS subsystem through the central data base. Preliminary investigations of the work required to implement the cost accounting and materials subsystems have also been undertaken.

The rest of the road management system can be implemented over time at a rate that suits both the resources available in a country and the requirement for a reasonable pace of change in working methods in order to integrate the new subsystems effectively.

Conclusions

The paper has described the development of a framework for a sustainable road management system adapted over relatively short periods of time to the specific needs of individual countries in southern Africa. The overall system design took into account the organizational structure of the road agencies, resulting in a modular approach that should ensure sustainability and flexibility in future.

A comprehensive survey of the road network needs to be undertaken that incorporates a road inventory and condition survey tailored to provide the data required for the various subsystems and, in particular, for road network planning when using HDM-III. A network matrix concept was devised to allow HDM-III to analyze a complete road network within only a very small number of computer runs.

This paper has illustrated a methodology whereby a road management system is developed and introduced in stages as a tool to support the activities of road agencies in developing countries rather than as a dramatic technological change that might later become a constraint. A modular system is seen as a key requirement when implementing modern management methods in countries where the availability of skilled personnel is at a premium.

Acknowledgments

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Integration of Pavement and Bridge Management Systems: A Case Study

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The integration of pavement and bridge management systems is addressed for the New York State Thruway Authority. A phased plan provides a unifying framework for development and accommodates agency requirements. Early efforts focus on the development of the data base and analytical methodologies for pavement management. Subsequent work produces similar methodologies for bridge management, expands the data base to serve bridge management needs, and integrates the data base with pavement and bridge analysis programs. The requirement for integration is maintained throughout the entire planning, design, and implementation process. The integrated computer system is prototyped as Windows-based program managers using graphical user interfaces to unify C/C++ applications. Early prototypes highlight remaining issues of integration and facilitate the selection of appropriate procedures for interfacing the data base with the application programs. Important issues related to system integration are discussed. On the basis of developments to date, it is concluded that (*a*) efficient integration is facilitated by the preexistence of a plan that defines a common methodological framework and computing environment for all component systems, and (*b*) the most essential integration elements are a common referencing convention, data base, and computerized user interface.

An important goal of highway agencies is to identify the combination of pavement and bridge projects that makes optimal use of resources. However, the current lack of integrated program development tools inhibits the achievement of this goal. It is the broad objective of a cooperative research effort between the New York State Thruway Authority and Rensselaer Polytechnic Institute to address this need through development of an integrated pavement and bridge management system for the authority. The authority's goal is ultimately to implement a comprehensive infrastructure management system incorporating a pavement management system (PMS), a bridge management system (BMS), and similar tools for managing other types of physical facilities. The authority's system includes 1030 km (640 mi) of Interstate-type highway constructed primarily between 1954 and 1960. The bridge inventory includes 860 bridges of 24 types, with 7 major bridges, including the 5.0-km (3.1-mi) Tappan Zee Bridge that crosses the Hudson River at Tarrytown, New York.

The notion of an integrated system was conceived in 1987 during a review of authority maintenance practices and policies. The review identified needs for improvement to the information basis and decision methodologies used for planning and monitoring of the capital program. A staged implementation of the ultimate system is necessary because of differences in the scope of the developmental work for PMS and BMS, required resources, variations in the characteristics of the systems, established needs and priorities, and so on. Thus, the first stage of PMS development was initiated in 1988, and the first stage of BMS development began in 1991.

This paper presents experiences and observations based on the current development effort. General terminology is used whenever possible, but authority vocabulary is used when needed to explain the system in its operational environment. Where usage cannot be inferred by context, terms are defined briefly on first occurrence.

Methodological Content

PMS and BMS are concerned with the condition and needs of the two major components of Thruway infrastructure. In addition to competing for resources, the two systems must identify and select projects on the basis of their proximity, schedules, and other implementation aspects. Thus, the methodological frameworks of PMS and BMS are conceptually similar, because each system must support the same general tasks (e.g., condition assessment, economic analysis, etc.). However, the information basis and specific problem-solving techniques are significantly different for the two systems.

Information Basis

As discussed later, PMS and BMS have a critical mass of information in common that enables the development of a comprehensive data base to serve both systems. The most significant difference in the information basis is the condition data available for each type of structure.

Pavements are surveyed annually using a detailed visual technique to determine linguistic ratings of surface distress types, severities, and extents (*1*). The eight ratings recorded for each 160.9-m (0.10-mi) nominal road segment are combined into indexes descriptive of specific pavement components, such as slabs, joints, shoulders, or the entire pavement surface. The indexes are produced by a calculation method that accounts for the relative significance of each individual distress through the use of appropriate weighing factors (*2*).

Bridge condition is assessed biennially. Individual bridge elements and components are rated on a scale of 1 (potentially hazardous) to 7 (new condition), on the basis of hands-on visual inspection procedures developed by the New York State Department of Transportation (*3*). The condition of the bridge as a whole is also rated with a general recommendation that reflects an inspector's opinion of the maintenance needs of the bridge. Condition indexes representative of components, spans, and the bridge as a whole are produced by taking weighted averages of selected element ratings (*4*).

Project-Level Analysis

PMS and bridge management system have several methodological commonalities, because both support the same general tasks. The relationship between condition indexes, which are used both for project and network characterization, and treatment options provides an important link between project- and system-level methodologies. Techniques for summarizing and characterizing condition are similar, and cost estimation and life-cycle cost analysis procedures are essentially identical for both systems. However, the approach to treatment selection is quite different for pavements and bridges, primarily because of the varied information basis and the special considerations associated with bridges (i.e., structural safety, vulnerability, etc.) that do not apply to pavements. Details of the PMS methodologies are described by Schultz (*5*), Shen (*6*), and Ravirala (*7*). The corresponding bridge management system methodologies are under development, with early products being tested and used to adjust the authority's program.

System-Level Analysis

Formulation

In contrast to the project-level tasks, optimization and capital program development techniques must address pavements and bridges simultaneously to produce the needed optimal, unified program. A goal-programming optimization formulation is used that allocates funds from a common source and maintains specified condition levels for both pavements and bridges. The analytical expression for the objective function is as follows:

Minimize

$$\left\{\sum_{g\in G} (P_{og} d_g^{+} + P_{ug} d_g^{-}) - \sum_{v\in V} P_c X_v\right\} \quad (1)$$

subject to

$$\sum_{v\in V} (a_{gv} X_v) + d_g^{-} - d_g^{+} = b_g \qquad \text{for } g \in G \quad (2)$$

$$X_v,\ d_g^{-},\ d_g \geq 0 \qquad \text{for } g \in G \text{ and } v \in V \quad (3)$$

where

G = set of goals,
g = individual goal,
d_g^{+} = overachievement of goal g,
P_{og} = penalty associated with overachievement of goal g (d_g^{+}),
d_g^{-} = underachievement of goal g,
P_{ug} = penalty associated with underachievement of goal g (d_g),
P_c = benefit of combining neighboring pavement and bridge projects as compared with implementing each project separately,

X_v = "basic variables" used in optimization formulations for pavements and bridges (e.g., lane miles of pavement within each state that should receive each type of treatment in a given year, and square feet of deck area in each span family that should receive each type of treatment in a given year),
a_{gv} = coefficients of basic variables, and
b_g = targeted goals.

Illustrative Example

As an example, consider an illustrative case of two administrative regions with a total of three pavement projects, three bridges, and two sets of pavement and bridge projects that (with associated unit costs) are considered for each of the pavement and bridge projects. Combinations of treatment options for pavements and bridges yield four possible options for each of the combined projects. Budget and condition goals are specified separately for the two administrative regions and for the "system" as a whole. The formulation of this illustrative example has 118 variables, of which 64 are integer variables. The solution (with use of commercially available software) for the optimal capital program recommends a mixture of treatment options for the individual pavement and bridge projects, and it confirms combination of both the potential pavement/bridge combination projects in order to realize economies of scope and scale. All condition goals are met, and overall required budgets for the system and individual regions are within 2 percent of targeted levels. Further details of this illustrative example are given by Ravirala and Grivas (*8*).

COMPUTERIZATION

System Architecture

The conceptual high-level architecture for the integrated computer system is shown in Figure 1. As can be seen in Figure 1, the system consists of several layers. The user accesses information through a customized graphical user interface supported by Microsoft Windows. The developed methodologies are available as PMS and bridge management system functions coded in the C/C++ and Pro*C languages. Alternatively, ad hoc querying, data entry, editing, and reporting from the ORACLE data base can be achieved using the SQL Plus, SQL Forms, and SQL Report Writer commercial products.

The computer system is being developed to operate in a networked environment. The data base will reside on a mainframe server unit and be accessed from personal computers running a customized graphical user interface. Some elements of the system will be capable of being off-loaded to permit engineers to study the data and alternative hypotheses in greater detail without threat to the data about the parent system.

Development Process

The development of the computerized system is pursued in a phased manner. Individual programs that apply specific problem-solving techniques are initially created quickly to support small case studies, then gradually expanded to address features of larger studies. Several iterative cycles of improvement typically follow as the methodologies are refined and adjusted.

The main benefits of this approach are (*a*) to provide early products to assist agency operations, (*b*) to generate feedback on the methodological content of the systems, and (*c*) to allow individual methodologies to mature before pursuing the final coding and documentation of the system. Shortcomings also exist, particularly for complex systems such as PMS and BMS, and include cumbersome data transfer between applications, inconsistent user interfaces, and so forth. Therefore, as methodologies mature, the individual stand-alone computer programs are united under two Windows-based programs called WinPMS and WinBMS, which are the first prototypes of the authority's integrated computing system.

WinPMS and WinBMS

WinPMS and WinBMS are Windows-based interactive program managers that perform pre- and postprocessing

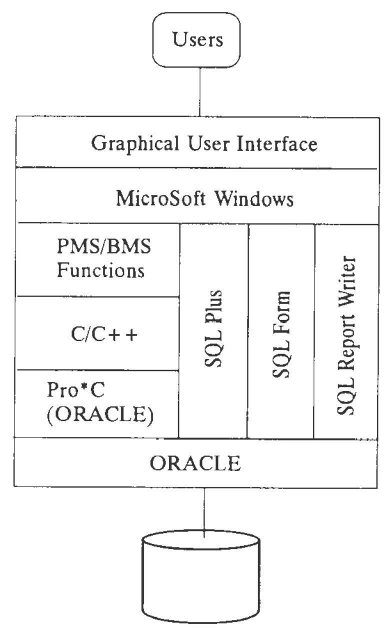

FIGURE 1 Conceptual high-level architecture of computer system.

as necessary to bring the individual PMS and BMS programs together under a menu structure that appears seamless to the user. Visual Basic is used to create a graphical user interface where most tasks are accomplished through "point and click" operations with a mouse. Analysis results are displayed graphically, such as the example screen shown in Figure 2.

The Windows environment and program design facilitates flexible use. For example, in the Condition Graphing session shown in Figure 2, the user has (*a*) invoked network characterization methodologies to evaluate pavement condition throughout the "Albany" region, (*b*) reviewed condition index values for a particular segment within the region, and (*c*) recalled information on the severity and extent of a specific distress at that location. Many such combinations of tasks are possible throughout the various program modules. Figure 3 illustrates a condition summary for the authority's entire bridge and pavement inventory obtained using WinPMS and WinBMS.

Important benefits of WinPMS and WinBMS include the following:

- Reduce user effort in performing operations and reduce learning curve,
- Facilitate computer system enhancement and growth through a prototyping approach,
- Provide flexibility in defining and revising screen and menu layout,
- Provide an additional forum for discussion of methodological content, and
- Uncover obstacles to integration of PMS and BMS and permit individual testing of potential solutions.

As further enhancements and refinements to the methodologies and user interface are completed, the computer codes are revised, and the functional and technical specifications for the computerized system are documented. These tasks are significant, because they enhance the future maintainability of the system.

Relational Data Base

The data base is created using the ORACLE relational data base management tool. A structured prototyping approach is followed during the functional and technical design, as well as implementation and data loading. The data base includes over 40 entities, such as pavement condition, bridge inventory and condition, vulnerabilities, maintenance history, contract history, traffic, accidents, salt application, climate, and the boundaries of political jurisdictions.

Information is accessed through a menuing system that provides dedicated screens, forms, and menus for report generation. Associated utility programs have been designed to facilitate automatic data conversion and loading and to perform a wide range of analyses (*9*).

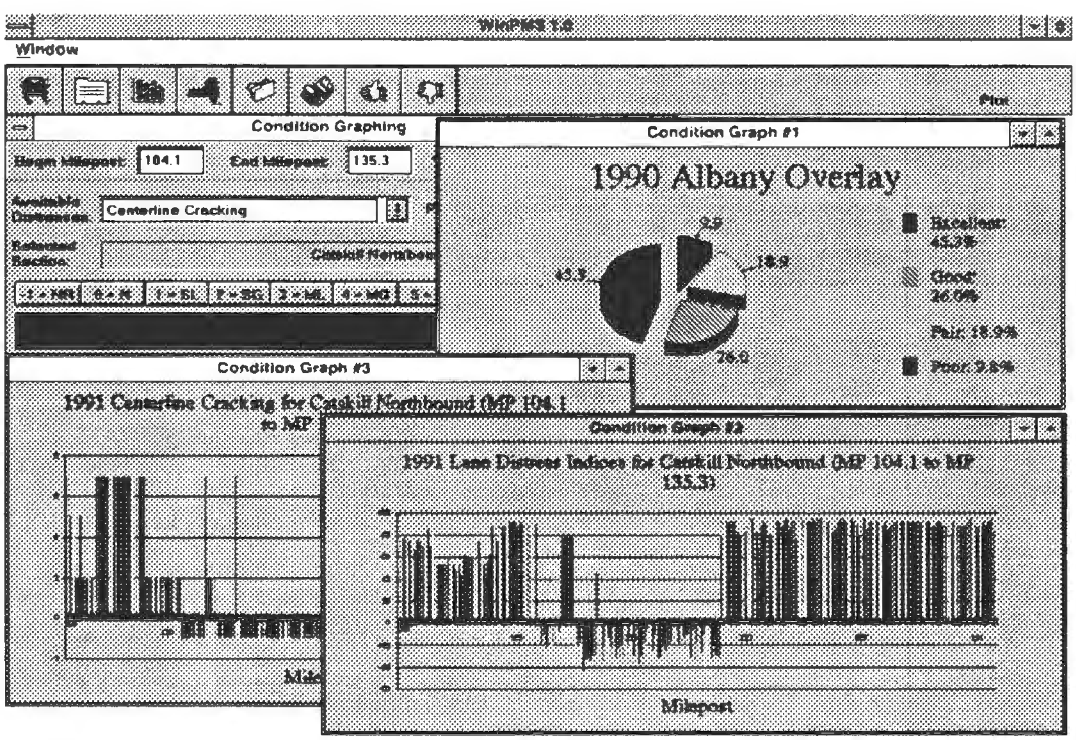

FIGURE 2 Sample display screen from WinPMS.

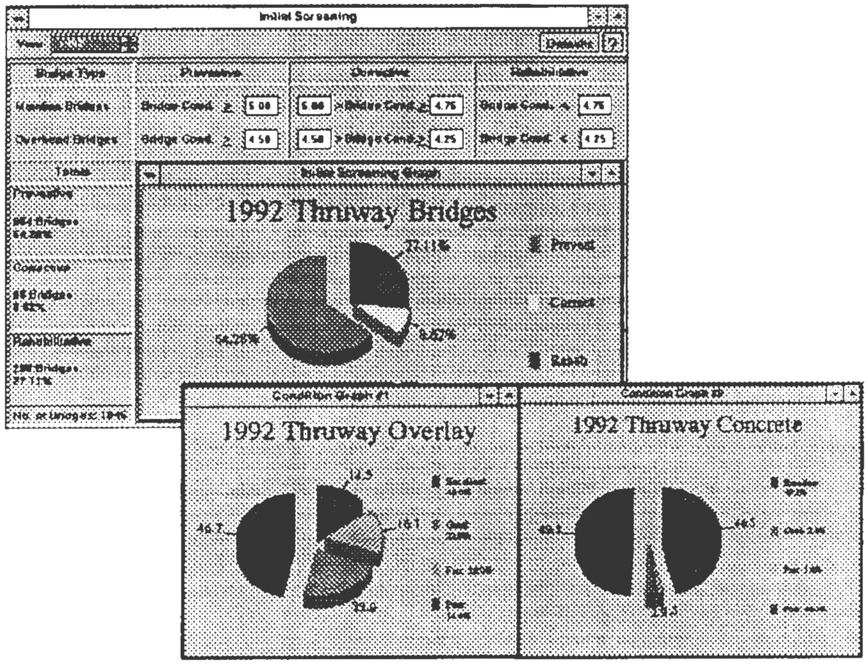

FIGURE 3 Sample WinPMS and WinBMS displays.

The extensive amount of effort required for functional and technical design, implementation and data loading, and development of user interfaces precludes the feasibility of recoding the data base during development of the integrated system. Rather, it was designed to operate initially as a stand-alone pavement management tool and then be expanded to serve bridge management needs and provide explicit linkages with the applications in the integrated system. The current version of the data base is operating in a single-user DOS environment.

Program Development

An important use of the integrated PMS and bridge management system is the development of the annual and multiyear capital programs. WinPMS and WinBMS currently facilitate this process by performing condition and economic analyses, screening for treatment options, and performing other methodological calculations. When the system is complete, it will provide the additional capabilities of (*a*) recommendation of optimal program solutions for a variety of goals and constraints, and (*b*) performance of "what if" analyses to project budget and condition implications.

The PMS and bridge management system methodologies are primarily condition driven and do not attempt to capture certain noncondition factors (e.g., changes in safety standards, availability of equipment, etc.) that affect planning, scheduling, and examination of highway work. Thus, significant departures from the recommended "optimal" solution may be required.

When optimization results are translated into a capital program, the network is considered to consist of "planning sections," which include pavement projects, bridge projects, and auxiliary items such as guide rails, lighting, interchanges, ramps, toll plazas, parking areas, signs, and slopes. Bridge projects include spans, and pavement projects include of "uniform sections," which are defined so that each section has distinctly different needs compared to those surrounding it.

The concept of "planning sections" is introduced to aid analysis of broad, long-term highway needs. The rationale for this concept includes two main considerations, namely, (*a*) the condition and requirements of auxiliary items can significantly affect the scope and cost of work required at a given location; and (*b*) for multiyear planning, it is prudent to coordinate work on adjacent highway sections, bridges, and bridge approaches in order to achieve economies of scale and scope and to minimize inconvenience to users.

Discussion of Results

Efficient integration is facilitated by the preexistence of a plan defining the methodological framework and computing environment for all component systems. This reduces the need to later rework common elements and is particularly critical for data base development.

Although phased development is commonly necessitated by agency resource constraints, it is not necessarily a detriment to the goal of integration. The existence of a unifying philosophy aids phased work efforts by identifying general requirements to be met by individual components of the complete system. In this case study, the choice to emphasize pavements in the early phase was driven primarily by needs and priorities of the agency, and it does not appear to have affected the potential for integration. One realized benefit of the phased approach is that aspects of bridge management system development, particularly computerization, have been expedited by the experiences gained during PMS implementation and enhancement.

Experiences to date indicate that the most essential elements required to create an integrated system are (*a*) a common location-referencing convention, (*b*) a common data base, and (*c*) a common computerized user interface. The current study has benefited because the authority's network is relatively simple and composed entirely of Interstate-type facilities. Also, a comprehensive location referencing system common to both pavements and bridges was in place before management system development was initiated. Thus, emphasis could be placed on methodological and computer developmental work without having to contend with overwhelming problems of physical inventory.

The human element of management systems is rarely considered explicitly. However, factors such as organizational structure, agency culture, and the unique aspects of bridges (structural safety, vulnerability, etc.) generate different perspectives between pavement and bridge groups. Developers of integrated systems must recognize and accommodate these differences while they engage both "cultures" toward cooperative development of a unified program. Thus, in addition to integration of methodological and computer aspects, the "cultural" differences between pavement and bridge engineering and management teams must also be addressed.

Summary and Conclusions

The development of an integrated pavement and bridge management system was presented for the case of the New York State Thruway Authority. It involved a phased approach with stages that address individual components of each subsystem (PMS and bridge management system) but are consistent with the integration plan. The planning for a staged implementation was necessitated by immediate needs and priorities and by demands for resources.

Achievements to date include the completion of the PMS components with enhancements well advanced and the methodological content of the bridge management system functionality. Experience with the prototype computerized systems (WinPMS and WinBMS) has generated significant feedback for the individual functions of the system and provided additional insights for the integration. Two useful lessons have been learned about the human component of system development. First, system developers must accommodate the "pavement versus bridge" perspectives, and engage both "cultures" toward defining commonalities, including a common language. Second, integrated systems require "integrated" developers and users who can accommodate both pavement and bridge perspectives in a unified program.

On the basis of the developments to date, the following conclusions may be drawn:

- Efficient integration requires the existence of a good plan prior to the development of the individual systems. By providing a common methodological framework, the need for later reworking of common elements is reduced.
- In addition to a unifying system development philosophy, a common referencing convention, data base, and computerized user interface are the most essential integration elements.

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Knowledge-Based Systems for Maintenance

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This research aimed at using the predictive capability of a network model, HDM-III, to optimize the maintenance schedule applied by an aggregated project-oriented maintenance management system, BSM. A knowledge-based approach was indicated in order to replicate the use of HDM-III by an expert so that the parameters used by BSM could be set at appropriate levels and so that the works list could be further optimized to obtain the best return for the maintenance money spent. The knowledge-based approach will facilitate the future use of other models. The research resulted in a number of modules that fall broadly into three program modules while exploiting common knowledge bases. The purpose of the modules is explained. Included are results of the application of the work to data obtained from the road network in Cyprus.

Researchers at the University of Birmingham have been involved in the development and implementation of road management systems in Europe, Asia, and Africa. These range from the United Kingdom Pavement Management System (UKPMS) currently being designed for both central and local authorities of the United Kingdom to relatively small but nonetheless important implementations in developing countries. The Research Group spent considerable time working on the aggregated project system BSM (*1*) and the network model HDM-III (*2*). As a result, the following conclusions have been reached:

1. It is relatively simple to provide aggregated project-level systems that can assess the ongoing requirements of individual road sections in an overall network from road condition and traffic data.
2. The cost of remedial work to address the engineering needs of every network examined exceeds the available maintenance budget.
3. It is possible to set priorities for remedial work using engineering and economic judgment as a proxy for a strategic economic analysis.
4. It is relatively simple to use economic models such as HDM-III to set maintenance standards and determine a global strategy for maintenance.
5. It is difficult to set such standards and strategies without appropriate models that are truly representative of the costs incurred.

As a result, the group conceived the idea, shown in Figure 1, that an overall management system operates at two levels—project and network—approximating engineering and economics. It is relatively simple to operate in one domain or the other, but considerable judgment is required to take account of both. It is simplistic to keep all roads at a high serviceability level. Similarly, it is not acceptable to allow the investment in a road structure to be lost because of lack of maintenance on minor roads if those roads have sociopolitical importance (*3*). What is required, therefore, is a tool that first considers both the engineering and the economic demands and is then able to present the findings to the road manager for further revision.

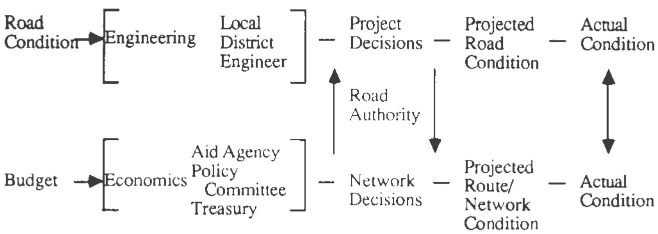


FIGURE 1 Integration of project and network approaches to pavement management.

To that end, the group developed aspects of an intelligent knowledge-based system (IKBS) capable of interfacing an aggregated project model to a network economic model. For the development work the group used the systems to which it has direct access: BSM and HDM-III. The group is aware of developments in both models and indeed has been instrumental in the further development of HDM-III.

Aggregated Project-Level System

The system used in this study was BSM. It has been used on a wide variety of networks, although the networks always consisted of bitumenized roads. The network is split up into political units (e.g., districts in Cyprus); all roads are numbered and divided into short homogeneous lengths equating the shortest likely length of road to which a periodic maintenance treatment would be applied. Every such length is categorized by geometry, road condition, and traffic.

Attached to every section is a set of minimum standards (intervention levels) in which each of a user-definable set of condition parameters may fall. As each standard is breached, a remedial treatment is required. This treatment selection process may be set up to operate in a relatively simple manner (i.e., the minimum standard breached for a condition parameter might trigger a single treatment) or in a more complex way (i.e., intervention levels for a number of condition parameters may trigger a combination of treatments).

The standards may be set in a number of ways. In peninsular Malaysia on the National Road System of about 28 000 km, the standards were set initially as a function of engineering judgment combined with custom and practice of the Malaysian Public Works Department. In Cyprus on a route network of fewer than 2000 km ranging from a major dual carriageway to minor mountain roads, the intervention levels were set using HDM-III. [Details of this may be found elsewhere (*4*).]

In an early implementation in Liaoning Province of China, the standards were varied until the remedial work suggested by the system matched the allocated periodic maintenance budget under the various treatment heads—the budget previously having been specified by the central government. Later implementations in China, notably in Yunnan Province, used HDM-III in a manner similar to that employed in Cyprus.

Except for the Liaoning Province implementation, all others required that work be given priorities because the value of remedial work selected for consideration far outstripped the available maintenance budgets. System BSM uses a relatively simple algorithm to put remedial work in priority order on the basis of traffic levels (as a proxy for economic importance of the road), type of deterioration observed, and its extent. [The procedure is fully covered elsewhere (*5*).]

The system has been extended to permit the engineer to group adjacent subsections requiring the same treatment into continuous "projects" of a more economic length. On instructions from the operating engineer, the system can select these "projects" for transmission either to a works program or for further economic analysis.

It is noteworthy that BSM was designed to operate on a microcomputer in a free-standing environment not reliant on a specific data base. This was deliberate. Although it has resulted in a relatively slow operation because of its file structure, it has been possible to implement the system with a minimum of delay in a wide variety of countries. Similarly its structure is relatively transparent to practicing highway engineers, who quickly become attuned to its use. They are then encouraged to seek appropriate developments of it for their own environment. Particular examples of this are China and Malaysia, where quick and easy implementations demonstrated the value of management systems and encouraged country-specific developments.

Economic Model

HDM-III is the model used by the group to determine intervention levels, the setting of priorities, and maintenance strategies. The model was developed using relationships derived from field experiments conducted in the Caribbean (*6*), India (*7*), Kenya (*8*), and Brazil (*9*). It was constructed in such a way that its relationships may be adjusted to suit local observations. Members of the Highways Group have been involved in the use of HDM-III in Europe, Africa, and Asia. In particular, it has been used in conjunction with BSM in China and Cyprus. During these projects it became clear to the group that there was scope for a more formal link between BSM and HDM-III. For example, it was simple to set intervention levels in BSM once HDM-III had been populated with data derived directly from the BSM data base.

Interestingly, the increasing use of and reliance on HDM-III also led to the belief that although it was excellent for the environments for which it was originally intended, if the philosophy embodied within it was to remain credible, other packages would have to be added. Those would include indirect user costs, largely associated with the value of time, which become significant with higher traffic levels. Nonetheless, HDM-III has proved to be a robust tool to use both in the field with live implementations of BSM and as a model in the development of the overall management system.

INTERFACE

The principal tasks of the aggregated project system are as follows:

1. To act as a data base of road inventory items concerned with road maintenance;
2. To act as a data base of condition surveys conducted over a number of years with respect to various surface condition elements and indicators of structural condition;
3. To make an initial treatment selection to ensure that each length of road for which there are data is of satisfactory serviceability;
4. To cost all periodic maintenance activities;
5. To make an initial prioritization of the remedial work;
6. To group subsections of road requiring treatment into cost-effective maintenance lengths or projects;
7. To audit all periodic maintenance activities year by year, to ensure satisfactory performance and compliance to agreed-upon standards; and
8. To produce work lists by network, district, or road.

The principal tasks of the economic model are as follows:

1. To assist in setting the intervention levels for various road types and traffic levels, taking into account progression from the time of survey to the likely time of remedial works;
2. To take initial maintenance projects suggested by BSM and determine the net present value (NPV) for each project;
3. To test that the initially selected treatment was the optimum economic solution and, if not, to replace it with a more appropriate treatment;
4. On any stretch of road, to optimize the economic return by grouping projects of the same or compatible works, even if it requires upgrading, or no or lower-level treatments on intermediate road lengths;
5. To recompute the NPV for the resultant aggregated projects; and
6. To supply these data for final priority listing by BSM.

In order to effect these tasks efficiently, a link between BSM and HDM-III was required. Originally this was a simple program known as LINK, which provided the initial maintenance project lengths to HDM-III and requested additional data from the user. It was quickly realized that this was inefficient in skilled engineer time, a commodity not always available in developing countries. Hence, an IKBS was constructed.

The IKBS contains a number of modules, written in PROLOG, that fall broadly into three programs known as INPUT, LEVEL, and JOIN, as shown in Figure 2. INPUT provides IKBS support for a user creating data files for HDM-III. It may be used when all the data are to be provided by the user, and it is an alternative to the editor supplied as part of the HDM-III package. LEVEL creates data files for HDM-III for links derived from the BSM data base. Many of the data are extracted directly from BSM files, and the rest are supplied by the user. The knowledge base concerning HDM-III data requirements is accessed by both INPUT and LEVEL. [Further details may be found elsewhere (*10*).]

As described by Kerali et al. (*4*), the output from HDM-III may be used to set the intervention levels in BSM at appropriate values. The LEVEL module applies postprocessing to the HDM-III output produced by the process previously described to provide values for the matrix of intervention levels in BSM for all combinations of traffic levels and construction types. The aim is to optimize the frequency of application of each maintenance treatment.

JOIN can then take the subsection treatments proposed by BSM and seek to join adjacent subsections into economic projects. This process may be seen as invoking economy of scale whereby it would be cheaper, for example, to structurally overlay seven adjacent subsections of road than to treat separately two blocks of three subsections that really require such treatment, separated by a single section that only needs a surface dressing. Figure 3 illustrates the principle. Treatment 1 is more expensive than 2 but is a suitable alternative to 2. If the areas of the sections are *A*, *B*, and *C* m^2 and the fixed (i.e., project mo-

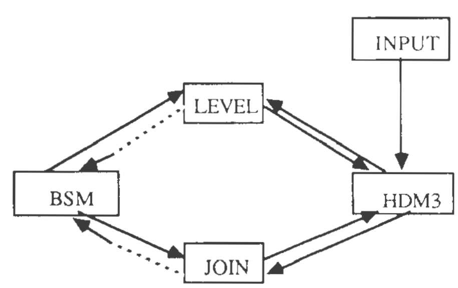


FIGURE 2 Interrelationships between IKBS modules and models BSM and HDM-III.

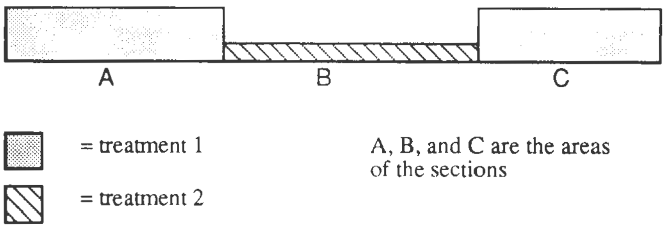


FIGURE 3 Combination of subsection treatments into economic projects.

bilization) costs and variable (i.e., conventional unit rate derived) costs are $\$F$ and $\$V$ with appropriate subscripts, the cost of applying separate treatments to the three sections is

$$(\$F_1 + \$V_1 \cdot A) + (\$F_2 + \$V_2 \cdot B) + (\$F_1 + \$V_1 \cdot C)$$

and if the sections were to be joined into a single project with treatment 1 applied throughout, then the cost would be

$$\$F_1 + \$V_1(A + B + C)$$

It follows that if

$$(\$F_1 + \$F_2)/(\$V_1 - \$V_2) \geq B$$

then it is economic to upgrade the middle section to the higher level of treatment. This basic logic is applied iteratively within a framework of rules that cater for tends of road links and allow for further combinations.

Once JOIN has created a set of projects by grouping adjacent subsections, it is necessary to establish priorities for these projects. HDM-III can be used to calculate the

TABLE 1 Selection of Treatment Intervention Levels by JOIN

		Traffic Level					
		1		2		3	
C.T.	Treatment	IL	NPV/C	IL	NPV/C	IL	NPV/C
1	Surface dressing	22.40	0.16	14.30	0.08	13.00	0.01
	Thin overlay	20.80	0.15	29.60	0.10	63.70	0.02
	Regulating overlay	0.00	0.15	0.00	0.11	0.00	0.02
	Structural overlay	87.40	0.05	84.70	0.04	94.90	0.01
	Combined		0.16		0.11		0.02
2	Surface dressing	11.10	0.36	17.80	0.06	0.00	0.01
	Thin overlay	48.20	0.31	20.80	0.07	48.20	0.01
	Regulating overlay	0.00	0.39	0.00	0.06	-	-
	Structural overlay	100.00	0.12	100.00	0.02	-	-
	Combined		0.25		0.07		0.01

C.T. = Construction Type

IL = Intervention Level.

Notes: Surface dressing is triggered by minor damage (% of road surface affected).

Thin overlay is triggered by major damage (% of road surface affected).

Regulating overlay is triggered by percentage of ruts exceeding 20mm.

Structural overlay is triggered by major damage (% of road surface affected). All NPV/C figures are per km.

The process involves translation between the trigger levels modelled in HDM-III and the ILs used in BSM.

Other traffic levels are present in the Cyprus network, but analysis shows that at a discount rate of 5% no treatment shows a positive NPV.

NPV for each project, and a module of JOIN can create the data files to run HDM-III for this purpose. The benefit-to-cost ratio for each project is thereby determined, and this may be used to set a priority value for each constituent subsection of each project within BSM. This enables BSM to produce costed work lists that will conform to given budget constraints while ensuring minimum total costs.

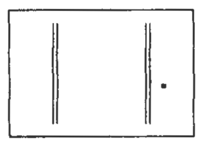
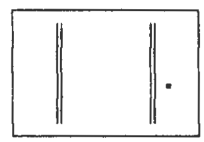
Example

Given the amount of data involved, it is difficult to offer a brief example that begins to answer the many questions that might arise. The process was developed largely as a result of work done in Cyprus and China. The work in Cyprus used considerable input from engineers for the setting of the intervention levels, selection of work, and

TABLE 2 Treatments to Routes Before and After Effects of JOIN Algorithm to Gain Economies of Scale

Legend:
A = Surface Dressing
B = Patching
C = Thin Overlay
D = Regulating Overlay
E = Structural Overlay
H = other works

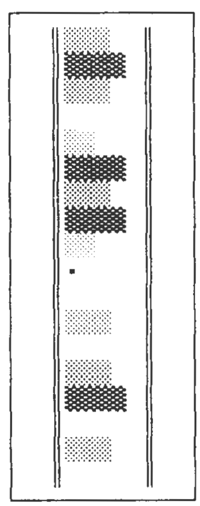
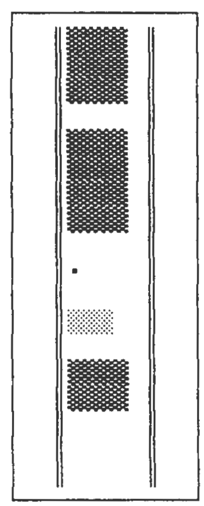
Route B0003	Before	After
Rec 1 to Rec 22	*	*
Rec 23 to Rec 66	*	*
Rec 67 to Rec 68	H	H
Rec 69 to Rec 89	*	*
Fixed + Variable costs	2000 + 790	2000 + 790
Total	2790	2790

Before:  After: 

Route E0304	Before	After
Rec 90 to Rec 133	*	*
Fixed + Variable costs	0 + 0	0 + 0
Total	0	0

Before:  After: 

Route E0305	Before	After
Rec 134 to Rec 135	D	E
Rec 136 to Rec 136	E	E
Rec 137 to Rec 139	D	E
Rec 140 to Rec 171	*	*
Rec 172 to Rec 172	C	E
Rec 173 to Rec 180	E	E
Rec 181 to Rec 181	D	E
Rec 182 to Rec 184	E	E
Rec 185 to Rec 186	C	*
Rec 187 to Rec 187	B	B
Rec 188 to Rec 194	*	*
Rec 195 to Rec 199	D	D
Rec 200 to Rec 209	*	*
Rec 210 to Rec 210	D	E
Rec 211 to Rec 214	E	E
Rec 215 to Rec 222	*	*
Rec 223 to Rec 224	D	*
Rec 225 to Rec 232	*	*
Fixed + Variable costs	131000 + 113463	57000 + 126090
Total	244463	183090

Before:  After: 

Route E0306	Before	After
Rec 233 to Rec 237	*	*
Rec 238 to Rec 238	B	B
Rec 239 to Rec 242	*	*
Fixed + Variable costs	2000 + 6170	2000 + 6170
Total	8170	8170

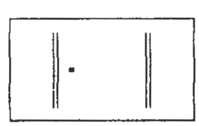
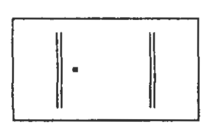
Before:  After: 

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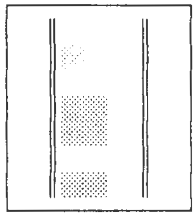
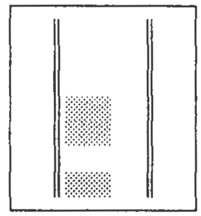
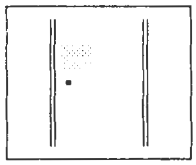
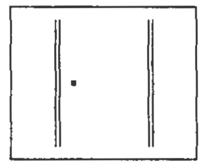
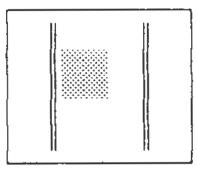
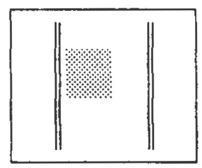
TABLE 2 *(continued)*

Route E0307				
Rec 243 to Rec 278	*		*	
Rec 279 to Rec 280	C		*	
Rec 281 to Rec 289	*		*	
Rec 290 to Rec 290	D		D	
Rec 291 to Rec 299	D		D	
Rec 300 to Rec 304	*		*	
Rec 305 to Rec 318	D		D	
Fixed + Variable costs		34500 + 54832		20000 + 53136
Total		89332		73136
Route E0309				
Rec 319 to Rec 329	*		*	
Rec 330 to Rec 331	C		*	
Rec 332 to Rec 334	B		B	
Rec 335 to Rec 336	*		*	
Rec 337 to Rec 340	*		*	
Fixed + Variable costs		6500 + 11244		2000 + 9132
Total		17744		11132
Route F0310				
Rec 341 to Rec 345	D		D	
Fixed + Variable costs		10000 + 13795		10000 + 13795
Total		23795		23795
Route F0314				
Rec 346 to Rec 365	*		*	
Rec 366 to Rec 367	D		D	
Rec 368 to Rec 375	D		D	
Rec 376 to Rec 379	*		*	
Rec 380 to Rec 380	*		*	
Fixed + Variable costs		20000 + 23856		10000 + 23856
Total		43856		33856
Route F0315				
Rec 381 to Rec 386	*		*	
Fixed + Variable costs		0 + 0		0 + 0
Total		0		0
District Total		430150		335969
saving			94181	

(Note that the project formed by the BSM sections marked as records no. 290 to 299 are of a construction type not modelled by HDM3)

the setting of priorities. The testing of LEVEL and JOIN has so far been based on the Cyprus network. Table 1 shows the matrix of intervention levels for two types of construction and three levels of traffic and four treatments. The table also gives the NPV divided by the cost for each intervention level.

The investigation of intervention levels summarized in Table 1 required 24 runs of HDM-III, each modeling 10 alternatives against a base case over a 20-year lifetime. An attempt to do this work preparing all the data files manually would present a daunting prospect.

The rows labeled "Combined" in Table 1 give the NPV/cost figure when the intervention levels, which have been found to be optimal when applied singly, are applied in combination. There is scope for further extension of the analysis by using refined ranges of values to find a better set of intervention levels. However, it is important not to lose sight of the primary purpose of the intervention levels, which may be regarded as initial screening. There is little point in detailed analysis of projects that will receive a priority rating such that the budget is fully allocated on higher-priority projects.

The intervention levels are used by BSM in the process of selecting subsections for treatment. These are combined into economic projects; Table 2 gives an example of the use of JOIN to achieve this. Each subsection is identified by the route and a record number along the route. The treatment selected by BSM for each group of subsections is specified along with a diagrammatic representation of those treatments. The effect of the JOIN process is shown by the treatment proposed for each group of subsections and a diagrammatic representation of the revised treatment list. The total budget requirement for each route, before and after joining, is also given.

Table 3 shows the evaluation of the projects proposed by JOIN. The analysis required further use of HDM-III with the data files being generated by JOIN.

Conclusion

The concept of the aggregated project-level model operating with a network-level economic model is attractive, because it avoids unnecessary oversimplification of economic or behavioral modeling. The use of IKBS techniques in the process outlined also has the advantage of allowing the subsequent use of any suitable front-end management system, and indeed any suitable economic model, by supplying appropriate knowledge bases rather than a complete system rewrite. Hence, as advances are made in either or both, they may be used through the IKBS modules that have been developed and through their future derivatives.

It is envisaged, for example, that the current work of the Birmingham group will provide an enhanced project-level structural diagnostics procedure (again based on an IKBS) that will feed into the aggregated project-level system. Also, as noted previously, work is under way in association with the Asian Development Bank, the Overseas Development Administration, the Swedish National Road Administration, the World Bank, Malaysian Public Works Department, and others to further enhance the existing capabilities of the HDM-III procedures to enable a truly universal economic model to be available.

Thus, the work outlined in this paper serves a number of purposes. It provides a methodology for use today by practicing road engineers and at the same time it enables further enhancements to be incorporated.

TABLE 3 NPV/Cost Ratio for Each Joined Project Detailed in Table 2

Project	Treatment	No. of Sections	Construction Type	Traffic Type	Roughness (mm/km)	NPV/C
1	E	2	1	3	4750	13.70
2	E	1	1	3	3200	14.10
3	B	1	1	3	3400	0.00
4	D	5	1	3	4800	20.83
5	E	1	1	3	5500	18.75
6	B	1	2	3	2450	0.00
7	D	14	2	3	4755	26.90
8	B	3	2	3	2959	0.00
9	D	5	1	4	4550	3.57
10	D	2	1	3	4350	21.67

ACKNOWLEDGMENTS

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Total Cost Rehabilitation Design Method for Use in Pavement Management

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The deteriorating condition of paved road networks and the limited resources available for rehabilitating these roads are challenging highway administrators and managers in both developing and developed countries. Research conducted in Brazil allowed the development of performance prediction models for pavement roughness, raveling, potholing, rutting, and cracking as a function of significant variables that define pavement structure, environment, and traffic loads. These models were incorporated into a microcomputer program that generates alternative rehabilitation strategies, predicts the performance of each strategy that meets the allowable criteria, and produces a set of the five best feasible strategies according to the predicted total cost. Presentation of the analysis package and demonstration of its application are achieved by discussion of the background, rationale, and summary of the performance models; a brief review of the structure of the package; and presentation of a case study. This method of analysis can be used as a project-level pavement management tool compatible with the needs of low- to medium-volume road links in tropical and subtropical environments or for evaluating a network of roads requiring rehabilitation. For applications at the network level, a key feature is its full compatibility with the Expenditure Budgeting Model (EBM), which means that its output can be used as input to EBM to address the budgetary-constraint problem.

Highway administrators and managers are faced with increasing challenges to keep the paved road networks in serviceable condition despite shrinking resources. This situation occurs not only in developing countries but worldwide. Deferred maintenance is becoming a regular option despite a lack of information about the economics of such actions.

A long-term pavement monitoring program conducted in Brazil between 1975 and 1985 allowed the development of performance prediction models for as-constructed and rehabilitated pavements. The models, developed through multiple regression techniques and probabilistic time failure analysis, can be used to predict pavement roughness, raveling, potholing, rutting, and cracking as a function of significant variables that define pavement structure, environment, and traffic loads. These models were used to develop a design method that selects the optimal rehabilitation strategy over a defined analysis period. The design approach has been implemented as a microcomputer program that generates alternative strategies, predicts the performance of each strategy that meets the allowable criteria, and produces a set of the five best feasible strategies according to the predicted total cost. In this paper total cost includes rehabilitation and routine maintenance as well as road user costs.

This method of analysis can be used as a project-level pavement management tool compatible with the needs of low- to medium-volume road links in tropical and subtropical environments. Existing road investment analysis packages (e.g., HDM-III, RTIM2) have large data requirements and are cumbersome to operate. This method is devoted only to the problem of optimally allocating limited resources to asphalt pavement rehabilitation, and thus it is easy to use. The main value of this procedure is that it considers the do-nothing option and compares alternative treatments with that option.

This paper presents the analysis package and demonstrates its application, briefly reviewing the structure, background, rationale, and summary of the performance models, and then presenting a case study.

Structure of Design Method

Figure 1 shows a flow diagram of the structure of the method. Usually a backlog of rehabilitation needs exists, and initially only those roads that have reached a warning or terminal condition would be included in the analysis. The design method is not restricted to these roads, because certain sections in good condition at the time of the analysis may require attention during the review period of 5 to 10 years. Information on three properties—traffic, structural characteristics, and condition—used to run the design method is required for each road. These requirements are discussed in the following section.

After the input information has been prepared, the cost and condition streams for the do-nothing and the rehabilitation options are calculated. The five most cost-effective rehabilitation options are presented for each road and are saved on a file for further use in the Expenditure Budgeting Model (EBM) (*1*). After evaluation of all the roads that require attention, the EBM is run to determine the effect of budget constraints. The final step in the process is to list the selected options for a given budget.

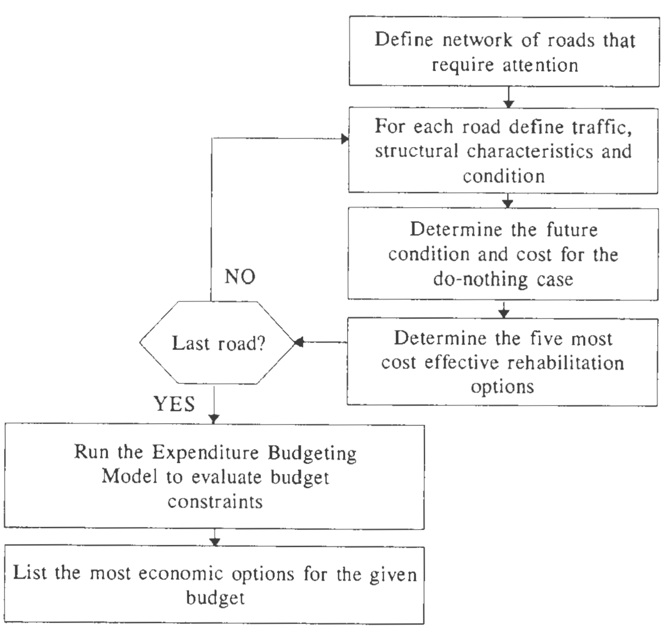

FIGURE 1 Flow diagram of the analysis procedure.

Background of Design Method

In this paper the principles of the method are developed, and its feasibility is demonstrated. The actual models that are used can be those applicable to a specific environment; the Brazilian models used in this paper are purely for illustration. Queiroz et al. (*2*) presented the models, which were one set developed from the research carried out during the United Nations Development Program's Brazilian study and subsequent continuation between 1975 and 1985. Another set are those used in HDM-III (*3*).

The scope of this rehabilitation design method encompasses slurry seals, single- and double-surface treatments, and asphalt concrete overlays. Only feasible treatments are considered for each road. An advantage of the method is that it can be used to predict both the required maintenance of pavements being designed and, by considering the existing condition, the maintenance of those that have already deteriorated. (This is because the performance models were developed from field observations of pavements that exhibited a range of conditions and received a variety of treatments.)

The experimental sections used to develop the performance models are representative of unbound, granular-base flexible pavements located in a tropical to subtropical climate. Rainfall at the sections ranged from 1200 to 1700 mm/year. The sections were trafficked by between 500 and 5,000 vehicles/day, of which between 20 and 60 percent were heavy vehicles.

The models that are incorporated into the rehabilitation method are limited to the prediction of pavement condition in terms of roughness, cracking, and raveling. Cracking is considered to include the occurrence of potholes and subsequent patching. Rut depths were consistently small on the experimental sections during the observation period and were not considered a significant design criterion for this method. This imposes a limitation on the applicability of the model, because it cannot apply to materials that are prone to rutting. Furthermore, the models were developed on pavements that performed reasonably well in practice, so they cannot be used on pavements with deficient materials or compaction.

Each condition variable is associated with several models, as shown in Table 1. These models provide the ability to predict the initiation of cracking and raveling and the progression of all condition variables before and after a rehabilitation treatment. The improvement in roughness achieved by an overlay is also modeled. In the method, slurry seals and surface treatments do not improve roughness, as is well known.

The Benkelman beam deflection was found to be a highly significant independent variable for predicting roughness and the cracking of overlays. Changes in deflection as a result of an overlay are therefore important and are modelled. The following prediction model formats were used:

TABLE 1 Performance Prediction Model Types

Condition	Nature of Model	Surfacing Type[a]
Roughness	Progression	EP, OL, SST, DST, SS
	Improvement due to treatment	OL
Cracking	Initiation	OL, SS
	Progression	EP[b]
	Progression	OL
	Initiation/ progression	SS
Ravelling	Initiation	EP[c], SST, DST
	Progression	EP[c], SST, DST

[a]EP = existing pavement, either surface treatment or asphalt concrete; OL = asphalt concrete overlay; SST = single surface treatment; DST = double surface treatment; and SS = slurry seal.
[b]Only if it is an existing asphalt concrete surfacing.
[c]Only if it is an existing surface treatment.

- Roughness = f[surfacing age, cumulative equivalent single-axle loads (ESALs), corrected structural number, Benkelman beam deflection].
- Roughness after asphalt concrete (AC) overlay = f(roughness before overlay, overlay thickness).
- Crack progression of existing pavement = f(age, Benkelman beam deflection, cumulative ESALs).
- Crack progression of AC overlaid pavement = as for existing pavement and f(AC thickness).
- Crack initiation of AC overlaid pavement = f(cracking before overlay, AC thickness, deflection after overlay, ESALs after overlay).
- Cracking of reseals = f(new surfacing age, deflection, cracking before treatment).
- Raveling of seals = f(average annual ESALs, age of surfacing).
- Deflection after AC overlay = f(deflection before overlay, AC overlay thickness).

Most pavement rehabilitation design methods use only the road authority costs to determine the feasible treatment solutions. Particularly in the case of holding-action treatments, the potential impact of road user costs on the national economy should not be neglected. In this rehabilitation methodology, vehicle operating costs (VOCs) are included, because it is well known that rough roads increase road user costs. The selection of the optimum alternatives for each road is based on minimizing the total costs, which comprise the sum of rehabilitation costs and VOCs.

Pavement Performance Prediction Models

The prediction models used in the package are presented here, although any set of models could be used.

Roughness Models

In this paper, roughness is considered in terms of the quarter-car index (QI), which is a standard roughness summary statistic that can readily be calculated from surface profile measurements (e.g., using the rod-and-level procedure or some other profilometry technique) and also yields strong correlations with the output of response-type roughness instruments (*4*). As indicated in Table 1, two types of roughness models were incorporated. (All terms used in these and subsequent models are defined in the list of symbols, abbreviations, and units at the end of this paper.)

The roughness progression for both original and rehabilitated pavements was adapted from a study by Queiroz (*5*). This model expresses QI as a continuous function of age, traffic, structural variables, and initial roughness.

$$QI = 0.373A + 8.66\log N/SNC + 0.0000707(B \cdot \log N)^2 - DQI \qquad (1)$$

In the case of an asphalt concrete overlay, the structural capacity is upgraded, in which case $SNC = SNCa$, and $B = Ba$, which was estimated by use of the deflection prediction model discussed in a later section.

The term DQI is a constant offset term to ensure that the predicted QI value at age A is equal to the roughness measured at age A in the case of an existing pavement or is equal to the predicted QI after overlay ($QIIA$) in the case of rehabilitation by AC overlay. The value $QIIA$ is estimated by use of Equation 3.

Because the QI model (Equation 1) is logarithmic in nature, it is not reliable for pavement or overlay ages and accumulated traffic close to zero. Consequently, the following transformation is used to yield more realistic QI trends at early ages:

$$A' = (2/3)A + 0.5 \qquad (\text{if } A < 1.5)$$
$$A'' = A \qquad (\text{if } A > 1.5) \qquad (2)$$

Roughness immediately after an AC overlay is expressed as a function of existing roughness and overlay thickness:

$$QIIA = 19 + (QIb - 19)/(0.602H + 1) \qquad (3)$$

As was noted earlier, the $QIIA$ value is used to determine a new DQI offset for Equation 1 for continuing prediction of the roughness progression of the overlay.

Cracking Models

In the context of this design method, cracking values (measured as a percentage of total pavement area) represent the occurrence of Class 2 cracking or worse (i.e., a crack width greater than 1 mm) and include the presence of potholes and patching. Four cracking models are used to predict the age at which cracking first appears and the rate of progression of a cracked area of an existing asphalt concrete pavement, an AC overlaid pavement, and a slurry-seal-treated pavement. In this method cracking is assumed to be the primary distress determinant for pavements with asphalt concrete or slurry seal surfaces but not for single- and double-surface treatments.

The cracking progression for an existing asphalt concrete pavement is as follows (6):

$$CR = B \cdot \log N(0.0456 + 0.00501A) - 18.53 - DCR \qquad (4)$$

The term DCR is a constant offset term calculated so that cracking values conform to the defined extent of cracking at the start of the analysis period. If the existing pavement has no cracks, it is assumed that it will begin to crack at the start of the analysis period.

Cracking initiation for an AC overlaid pavement is expressed as a function of cracking in the existing pavement before overlay, thickness of overlay, surface deflection after overlay, and traffic since overlay:

$$AICR = (212.8 - 0.917\,CRb)\,(H^{0.681})/\{[(Ba - 19.45)AANC^{0.336}] + 0.01\} \qquad (5)$$

Because this expression includes the term $AANC$, it must be evaluated iteratively for nonzero traffic growth rates. A minimum limit of Ba, the Benkelman beam deflection after overlay, of 20 is assumed.

The cracking progression model for an AC-overlaid pavement has a form similar to, and is related to, the progression model for an existing AC pavement, with the addition of the overlay thickness term:

$$CR = Ba \cdot \log N(2.257 + 0.248A) \cdot H^{(-1.806)} - DCR \qquad (6)$$

In this case the DCR offset term is calculated to ensure that predicted cracking progresses from zero after age A equals $AICR$. As in the case of the roughness prediction model, the age transformation given in Equation 2 is used when $AICR$ is less than 1.5 to avoid inaccuracy of the logarithmic model at early ages.

Cracking initiation and progression of a pavement that was rehabilitated with a slurry seal surface is expressed as a function of deflection and cracking before treatment and of age since the slurry seal application (7):

$$CR = (0.219B + 1.43CRb) \cdot Y \qquad (7)$$

where $Y = A - (10/CRb)$ for $Y > 0$, otherwise $Y = 0$.

Raveling Models

Cracks on surface-treated pavements are often difficult to identify because of the open texture. The alternative approach, which is used in this design method, is to quantify distress of surface treatments in terms of the amount of raveling caused by traffic and environmental effects. As with cracking, separate models are used to predict the onset of raveling of either an existing or a new surface treatment and to predict the progression of raveling.

The initiation of raveling in a surface treatment is expressed as the surface treatment age at the onset of raveling as a function of surfacing quality and average annual heavy traffic:

$$\ln AIR = 2.465 - 0.45\,CF - 0.189\,AAHV \qquad (9)$$

where

$$AAHV = 0.00001327N/A \qquad (10)$$

Equation 10 was developed from a study of the relative distribution of heavy-vehicle axle groups (single, double, and triple) that prevail in Brazil.

The progression of the extent of raveling is expressed as a function of average annual heavy traffic, age, and age of onset of raveling:

$$RA = (2.226AAHV + 16.6) \cdot (A - AIR) \qquad (11)$$

Surface Deflection Model

Another model that was developed from the data base of experimental overlay sections has been incorporated to predict surface deflection after an overlay as a function of average deflection before the overlay and overlay thickness. The field data suggest that deflection after the overlay decreases gradually over a 1- to 2-year period following placement of the overlay and finally reaches a "stabilized" value, which is denoted Ba.

$$Ba = B^{(1-0.0687H)0.4153} \qquad (12)$$

The design method assumes that the surface deflection *B* for any pavement configuration remains constant throughout its service life until it is adjusted by the addition of an AC overlay. No reduction in deflection is attributed to slurry seals or surface treatments that were used as rehabilitation measures.

VOC Models

The road user prediction models were developed during the Brazilian study from road user surveys and fuel consumption experiments. These models [reported by Wyatt et al. (*6*), Harrison and Swait (*7*), and Chesher et al. (*8*)] were used because they were simple to apply but covered the important road condition aspects.

Some adjustments were made to reflect current vehicles. For example, the fuel consumption of the articulated vehicle was almost 50 percent higher than is found in practice, and a new model was developed from a vehicle simulation program. In all cases VOCs were related to road roughness. In addition, vehicle utilization was adjusted to reflect conditions more representative of developing countries than were found in Brazil.

Five vehicle types were used, namely, a medium passenger car/pickup, a bus, a medium two-axle truck, a heavy three-axle truck, and an articulated truck. VOC includes the following, which are influenced by road condition:

- Depreciation and interest cost,
- Fuel consumption cost,
- Tire cost, and
- Parts and maintenance cost.

Pavement Performance Outputs

The package has the capability of producing pavement performance results in terms of roughness, cracking, and raveling for the existing pavement as well as for the rehabilitated section. Figures 2 and 3 give such results for a typical pavement, ROAD2, whose properties are shown in Table 2. Intervention levels depend on user-defined values, or the most economic situation may be determined by iteration. Invariably a road authority would specify a terminal roughness condition based on user perceptions.

Application to Small Network

To demonstrate the value of this method, a small network consisting of three roads was used. These sections could be different roads or different sections on the same route. One of the options is the do-nothing condition in which the only maintenance would be a reseal after the total area had cracked or raveled.

The network consists of roads in varying stages of deterioration, as shown in Table 3. This means that the roads would require different rehabilitation actions at different times. The variety of actions will further assist in demonstrating the value of the design method.

When the do-nothing option is seen, no condition limits are specified except that the maximum extent of cracking or raveling is 100 percent, and a resealing action is programmed. In addition, the five least-costly alternatives over an analysis period (usually 10 years) are calculated, together with the predicted annual condition. This would

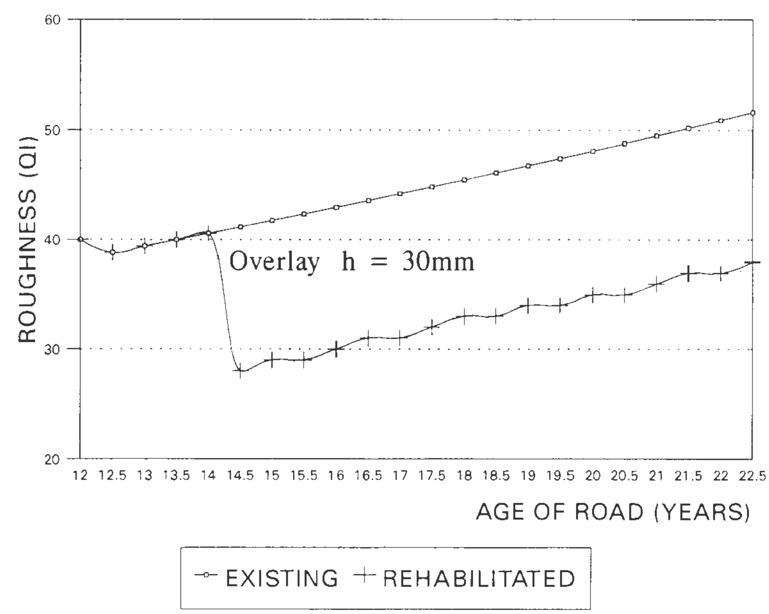

FIGURE 2 Roughness for the do-nothing and rehabilitated ROAD 2.

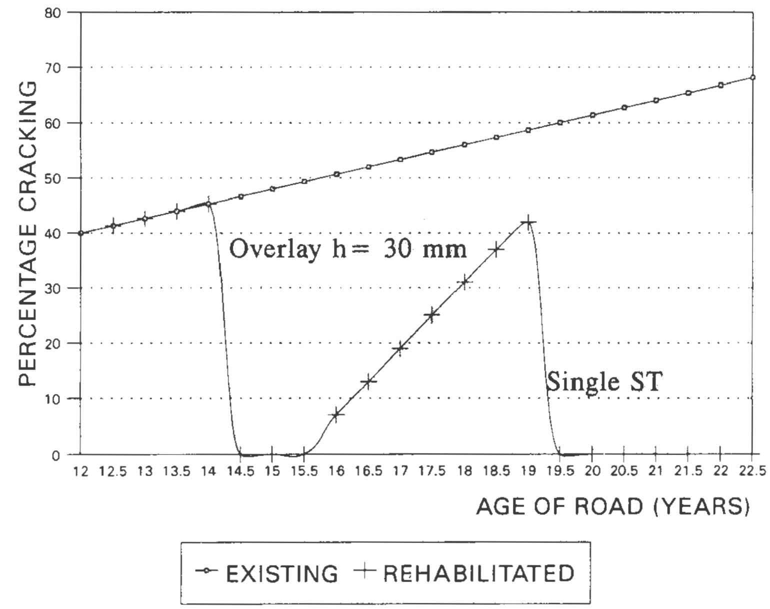

FIGURE 3 Cracking for the do-nothing and rehabilitated ROAD 2.

TABLE 2 Input Information for ROAD 2

1.	Existing data		
	Identification of subtitle		ROAD2
	Condition survey date (MM/YY)		03/93
	Type of existing surface	Asphalt Concrete Overlay	
	Length of homogeneous subsection	(km)	1.00
	Structural number corrected		4.00
	Quarter car Index Roughness	(QI)	40.0
	Percentage class 2 and above cracking	(%)	40
	Percentage ravelling	(%)	0
	Benkelman beam deflection	(.01 mm)	70
	Age of existing pavement	(years)	12
	Pavement width	(m)	7.0
2.	Traffic data		
	Initial yearly E80's	500000	
	E80's Growth rate	(%/year)	1.00
3.	Unit costs		
	Date of valuation of prices (MM/YY)		03/93
	Slurry seal	($/square m)	1.90
	Single surface treatment	($/square m)	3.63
	Double surface treatment	($/square m)	5.46
	Asphalt concrete overlay	($/cubic m)	530.00
4.	Overlay surface characteristics		
	Double surface treatment thickness	(cm)	2.0
	Double surface treatment structural coefft	(/cm)	0.04
	Asphalt concrete minimum thickness	(cm)	3.0
	Asphalt concrete maximum thickness at one time	(cm)	4.0
	Asphalt concrete max rehabilitation thickness	(cm)	12.0
	Asphalt concrete structural coefficient	(/cm)	0.17
5.	Constraints		
	Maximum permissible roughness	(QI)	40
	Maximum percentage of cracking	(%)	40
	Maximum percentage of ravelling	(%)	50
	Analysis period	(years)	10
	Minimum time between overlays	(years)	5
	Maximum number or overlays within analysis period		2
6.	Construction costs		
	Maximum initial construction costs	($/km)	300000.00
	Maximum persent value of future costs	($/km)	200000.00
	Average discount rate	(%/year)	8

TABLE 3 Summary of the Road Characteristics Forming the Network

Road Number	Age years	Current condition Roughness (QI)	Extent of cracking (%)	E80/year	Corrected struct no
Road2	12	40	40	500 000	4.0
Road4	6	40	10	600 000	4.0
Road5	20	50	20	200 000	3.0

TABLE 4 Output for ROAD 2

30 physically feasible alternatives examined
30 economically feasible alternatives found
5 least cost alternatives selected

REHABILITATION ALTERNATIVES VERSUS TOTAL COST

No	TOTAL COST ($/km)	REHAB. OPTION	DATE	COST ($/km)
1	110248	ASPHALT CONCRETE (h = 3.0 cm)	1995	95422
		SINGLE SURFACE TREATMENT	2000	14826
2	117102	ASPHALT CONCRETE (h = 3.3 cm)	1995	103374
		SINGLE SURFACE TREATMENT	2001	13728
3	117723	ASPHALT CONCRETE (h = 3.0 cm)	1995	95422
		DOUBLE SURFACE TREATMENT	2000	22301
4	124023	ASPHALT CONCRETE (h = 3.3 cm)	1995	103374
		DOUBLE SURFACE TREATMENT	2001	20649
5	124535	ASPHALT CONCRETE (h = 3.5 cm)	1995	111325
		SINGLE SURFACE TREATMENT	2001	13210

The performance models for single surface treatment were obtained from limited experimental evidence. It is recommended that a double surface treatment be used instead of a single, until more evidence is available to evaluate the models used.

result in the lowest road authority outlay. An example of such an output is shown in Table 4.

Once the information on condition, particularly road roughness, is available, the resultant VOC can be calculated. This information is also required to determine economic optimality.

For the preparation of the input for the EBM, the user benefits of the rehabilitation are required. These are obtained by first calculating the VOCs on the road without rehabilitation and subtracting the VOCs for the five rehabilitation alternatives. The savings of any reseals in the do-nothing case are also included as benefits and are added to the user benefits in the appropriate year. The costs are those incurred for the different rehabilitation actions. To evaluate the do-nothing case as an alternative, no user benefits or costs are assumed. By including this alternative, the do-nothing option is selected when the available budget is less than the total needs.

In the EBM the net present value of the selected alternatives is calculated. A zero discount rate is used, because the cost and benefit streams used as input are already discounted. For the case when available funds are less than the needs, the do-nothing alternative is selected for the least-effective option as reflected by the ratio of net present value to costs. Table 5 shows the EBM outputs for an unlimited budget and for a restricted one. In the first case a rehabilitation alternative was selected for every road, but for the second case the base or do-nothing alternative was selected for ROAD2.

TABLE 5 Outputs from Optimization with EBM ($\$10^6$)

No budget constraint, optimal level 0.28

PROJECT	ALT SELECTED	PREDET'NED CHOICES	NET PRESENT VALUE	RATIO OF NPV/COST
ROA2	ALT1		.572	5.192
ROA4	ALT1		.361	6.236
ROA5	ALT1		3.091	28.246

TOTAL NPV = 4.02 AT .0% DISCOUNT
TOTAL NPV/COST = 14.500

Budget constraint of 0.20, optimal level 0.17

PROJECT	ALT SELECTED	PREDET'NED CHOICES	NET PRESENT VALUE	RATIO OF NPV/COST
ROA2	BASE		.000	.000
ROA4	ALT1		.361	6.236
ROA5	ALT1		3.091	28.246

TOTAL NPV = 3.45 AT .0% DISCOUNT
TOTAL NPV/COST = 20.634

In the VOC models that were used, it was assumed that there would be no user benefits from a roughness less than 40 QI or better than a present serviceability index of 2.5. All rehabilitation strategies that provide a quality better than this threshold roughness would have the same user benefits, and the road authority's least-cost option would always be selected. However, where funds are severely restricted, intervention levels may result in a road roughness in excess of the threshold value, and in such cases user benefits play an important role in determining the most economic option.

Discussion of Results

The design method was demonstrated on a limited network where the salient features were presented. It was used as a stand-alone option in which information for the different roads was input into the special program. In this format it is handy to evaluate roads within a small network either at the project level, in which a road may consist of a number of different homogeneous sections, or at the design stage, in which rehabilitation requirements during the life of a pavement have to be evaluated.

This design method can also be incorporated into a formal pavement management system, in which it uses the information on the data base directly. All the roads on the network can be evaluated, but only those roads that reach an intervention level would appear on the analysis outputs. The main benefit of this method is the inclusion of road user benefits instead of simply taking into account the authority costs. Using this type of evaluation also ensures that engineers have the necessary information to justify rehabilitation expenditures.

Conclusions and Recommendations

The aim of this paper was to demonstrate an analysis procedure that considers the sum of user and road authority costs in deciding on rehabilitation alternatives. A range of rehabilitation options, which include asphalt concrete overlays, surface treatments, and slurry seals, is evaluated. This method was demonstrated on a limited network, but the method is equally suitable for incorporation into a formal pavement management system. The advantage of the method is that it evaluates the do-nothing option, which is becoming a frequent alternative in light of dwindling resources in many parts of the world. The cost implications are also given; those could then be used to motivate additional allocations. It is recommended that the proposed method be incorporated into existing pavement management systems for planning future rehabilitation programs.

Symbols, Abbreviations, and Units Used in Models

QI = quarter-car index, or prediction of roughness (counts/km)
A = age of pavement since original construction or since subsequent AC overlay or slurry seal (years)
N = cumulative number of applications or equivalent standard (8.2-ton) axle loads, corresponding to age *A*
SNC = modified structural number for the existing pavement
B = Benkelman beam maximum deflection for the existing pavement (0.01 mm)
DQI = initial QI offset term, calculated at the start of the analysis period or after an overlay
SNCa = modified structural number for a pavement with an AC overlay
Ba = equilibrium Benkelman beam deflection after an AC overlay (0.01 mm)
QIIA = predicted QI immediately after an AC overlay
QIb = QI value immediately before an overlay
H = overlay thickness (cm)
CR = predicted extent of Class 2 or worse cracking at age *A* for a pavement with AC surface (original or overlaid) or slurry seal surface (percentage of pavement surface area)
DCR = cracking offset term calculated to ensure that predicted cracking conforms with the initial value at the start of analysis or to ensure that *CR* equals 0 before the onset of cracking
AICR = age since the last overlay when cracks first appeared (years)
CRb = extent of cracking before overlay or slurry seal (percentage of area)
AANC = average annual traffic in the period between overlaying and appearance of the first crack (ESAL/year)
AIR = age of surface treatment when raveling appeared (years)
CF = construction quality indicator for surface treatments; here it is assumed that *CF* equals 1 for a single-surface treatment; *CF* equals 0 for a double-surface treatment
AAHV = average annual heavy-vehicle traffic in the period between surface treatment and onset of raveling (100,000 ESAL/year)
RA = predicted extent of raveling at age *A* for a surface-treated pavement (percentage of surface area)

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PERFORMANCE PREDICTION

Pavement Deterioration Modeling in India

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The large and ever-increasing investment demands for the upkeep and for ensuring the desired level of serviceability of road infrastructure facilities that were created at great cost have concerned administrators, policy makers, and highway professionals in India, and caused them to seek appropriate solutions, in view of resource constraints, for road maintenance and rehabilitation problems. The development of a pavement management system for different conditions prevailing in the country is a step in this direction. A number of studies have been completed for achieving this objective, and a long-range project entitled the Pavement Performance Study (PPS) is in progress; its goal is to develop data for a total transportation cost model for Indian conditions. The part of the PPS project on Existing Pavement Sections was completed recently, and pavement deterioration models have been developed. Separate models are available for estimation of different modes of distress for different types of surfaces. The study plans and the models developed under the study are presented, their limitations are described, and future work plans are discussed. The influence of pavement structure, traffic, and environmental factors on the progression of cracks and roughness is illustrated.

An efficient and adequate transportation system is one of the key indicators of a nation's prosperity, its developmental status, and overall economic growth. India, being the second most populous and the tenth-largest industrialized country in the world, has an extensive road transportation system. The roads pass through areas with extreme climatic conditions—from heavy rainfall to desert conditions; diverse terrains—from plains to extremely high mountain peaks; and varying soil subgrades—rocky and gravelly to marshy land. Over the past four decades, the share of total rail and road traffic carrying passengers and goods has gradually increased from about 24 percent and 11 percent, respectively, in 1951 to about 80 percent and 58 percent, respectively, in 1990. Road length has increased correspondingly, from 0.4 million km in 1951 to 2 million km, giving a road density of 59 km/100 km^2. Because of fast and ever-increasing industrial, commercial, and other socioeconomic development activities, the road transport vehicle population, particularly vehicles carrying goods, has also increased phenomenally during this period.

Efforts are under way in India to develop rational pavement design procedures that are based on mechanistic principles (critical strain criteria) to replace current pavement design methods, such as the California bearing ratio (CBR), which are based on an empirical approach. Construction in stages is currently in vogue because of the paucity of resources. Manual construction methods, used for many years, are gradually being replaced by mechanized methods, especially for the arterial road network and high-density corridors. The engineer's judgment and experience are relied upon heavily in decision making for maintenance and rehabilitation (M&R) of the road network. Ad hoc M&R norms are established for assessing maintenance budgets; such norms are not based on scientific or systematic studies undertaken for the purpose.

Because of economies in road transportation, overloading by truck operators is common. The majority of the arterial road system experiences overloading, as much as 18- to 20-tonne axle loads versus the permissible legal limit of 10.2 tonnes. The existing road network has shown signs of premature distress because of the unexpected demands of growing traffic volume and heavier axle loads. The network has fallen short of its structural capacity and hence it is greatly overstrained. The funds allocated for road development programs have been decreasing constantly over the years as a percentage of the gross national product (GNP). The majority of allocated funds are utilized for providing M&R measures to the existing network rather than for new construction. The funds being provided for the arterial road network are on the order of 50 to 60 percent of the amount needed.

On the basis of recent studies, it has been determined that 3 km of every 5 km (*1*) of the arterial road network (national highways and state highways) is below required standards and needs upgrading. The studies also indicate that the country is losing about Rs 60 billion (U.S. $2 billion) per year in additional vehicle operation costs because of poor road conditions. A Road User Cost Study in India completed in the early 1980s and updated recently has successfully brought out the road user cost models (vehicle operating costs, accident costs, travel time costs, etc.) under varying traffic, roadway, and climatic conditions. It has been estimated that about Rs 600 billion (U.S. $20 billion) would be needed up to the year 2000 for improving and upgrading the national highways (*2*).

Need for Pavement Deterioration Modeling in India

The concept of total transportation cost/life-cycle cost and the application of pavement management techniques have been recognized in India recently as versatile tools for tackling road maintenance and rehabilitation problems to achieve efficient and effective utilization of meagre available resources. Some studies have already been completed and others are in progress. The results are being used for developing a suitable pavement maintenance management system for Indian conditions (*3*).

Pavement performance data are required for the development of appropriate pavement deterioration models. A number of studies have been conducted to achieve this objective. Most of the studies, such as the AASHO Road Test, and the Kenya and Brazil studies, were completed for local conditions. The World Bank model, HDM-III (*4*), was developed on the basis of data from studies on Kenya, Brazil, and the Caribbean. It is currently finding global application after being calibrated for local conditions. Some studies were also conducted in India recently. During the mid-1980s, the Central Road Research Institute completed a short-term study on development of riding-quality models for purposes of maintenance accountability (*5*). But the analysis was based on two series of observations and because there was no in-depth characterization of materials in the laboratory, the predictions were useful only as a rough tool for planning. The University of Roorkee developed models for predicting the life of an overlay (*6*). These models are based on performance data from overlaid flexible pavements for the period 1980 to 1990. The models indicate that there is an exponential variation of characteristic deflection, rut depth, crack length, and maintenance cost with time. In addition to the models for individual distress modes and soil types, a general model was also developed for considering the data for all of the test sections; it predicts the life of overlays of different materials and thicknesses.

Because of a lack of adequate data to generate comprehensive deterioration models and to cover a variety of parameters, a long-term study sponsored by the Indian Ministry of Surface Transport was initiated in 1985. The details of the study and the models developed are described in this paper.

Pavement Performance Study

Broad Objectives

The Pavement Performance Study, a sequel to the already-completed Road User Cost Study, was undertaken for the primary purpose of developing data for a total transportation cost model through the following:

1. Development of pavement performance data for pavement materials normally used in the country;
2. On the basis of performance data, development of layer equivalencies, as feasible;
3. Conduct of limited studies of the effect of the maintenance level on pavement performance; and
4. Generation of data on the construction and maintenance inputs of different pavements.

The study comprised two parts:

1. The study on Existing Pavement Sections (EPS), conducted on in-service road sections for expeditious development of approximate pavement deterioration models; and
2. The study on New Pavement Sections (NPS), to be conducted on specially designed and constructed experimental sections on in-service highways. NPS will provide more accurate data generation, refinement of models developed under the study on Existing Pavement Sections,

and detailed coverage of parameters over a period of about 10 years. This part of study, still in its initial stage, is scheduled for completion by the year 2000.

Study on Existing Pavement Sections

A total of 113 test sections, each 500 m long, on the existing highways were selected for collecting periodic pavement performance data over a period ranging from 3 to 5 years. The parameters included in the study are as follows:

1. Pavement state
   Original construction
   Overlaid <5 years
   Overlaid >5 years
2. Traffic
   Medium: 0.4 million–0.8 million equivalent standard axles (MESA)/lane/year [600 to 1,200 commercial vehicles per day (CVPD)]
   High: >1.0 MESA/lane/year (>1,500 CVPD)
3. Climate
   Dry/semiarid (rainfall <500 mm/year)
   Moist/subhumid (rainfall >500 mm/year)
4. Pavement condition
   Good (no distress)
   Fair/poor (>10% distress)
5. Pavement surfacings
   Premix carpet with seal coat
   Asphalt concrete
   Semidense carpet
6. Maintenance
   Deferred level
   Normal level
   Higher than normal level

Field Investigations and Performance Monitoring

Six series of periodic performance observations, at 6-month intervals, were made on 40 sections, and 10 series of observations were made on 73 sections, for a total of 113 test sections. The periodic observations and measurements taken included the following:

- Roughness (fifth-wheel bump integrator),
- Deflection (Benkelman beam),
- Pavement surface distress (actual measurements of various modes of distress),
- Subgrade moisture content,
- Traffic volume (72-hr count),
- Axle load survey (annually, random sampling for 72 hr on 35 selected locations),
- Transverse profile, and
- Lateral placement of vehicles (two times during the sixth and tenth series of performance observations on selected locations).

Data Management and Analysis

The data collected from the office records and the field were computerized and analyzed in three categories.

Static Pavement Characteristics

Static data on pavement characteristics included the category of road type, pavement thickness, and composition of different layers, pavement width, shoulder details.

The pavement strength was expressed as a structural number (SN). The strength coefficients assumed for different layers and materials are given in Table 1. The structural number was improved by including the effect of subgrade strength, as follows, and termed the modified structural number (MSN).

$$MSN = SN + 3.51 \log (CBR) - 0.85 (\log CBR)^2 - 1.43 \quad (1)$$

where CBR is the percentage of in situ CBR at field density and moisture content.

In some cases, because of inadequate sample size, the CBR at field conditions could not be determined in the laboratory, so it was estimated from the following correlation developed by subjecting the available data to regression analysis (t values are indicated in parentheses):

$$\begin{aligned} CBR = {} & -14.004 + \underset{(4.54)}{0.345} (+2.36 \text{ mm \#}) + \underset{(4.05)}{0.141} (SC) \\ & + \underset{(2.37)}{0.154} (PI) + \underset{(2.30)}{17.247} (FDD) \\ & - \underset{(2.36)}{0.345} (FMC) \qquad R^2 = 0.73 \end{aligned} \quad (2)$$

where

CBR = CBR at field condition,
+2.36 mm # = fraction retained on 2.36-mm sieve (%),
SC = sand content (%),
PI = plasticity index,
FDD = field dry density (gm/cc), and
FMC = field moisture content (%).

A plot of observed and estimated values is given in Figure 1.

TABLE 1 Strength Coefficients

Layer	Coefficient
Surfacing	
Asphaltic concrete (AC) 40mm/25mm	0.2/0.18
Semi-dense carpet (SDC) 25mm	0.16
Premix carpet (PC) 20mm	0.12
Base Course	
Bituminous macadam (BM)	0.14
Built-up spray grout (BUSG)	0.13
Thin bituminous layer (BT)	0.12
Water bound macadam (WBM)	0.12
Subbase	
Water bound macadam (oversized) (WBM-OS)	0.12
Brick soling	0.10
Brick ballast	0.10
Kankar	0.08

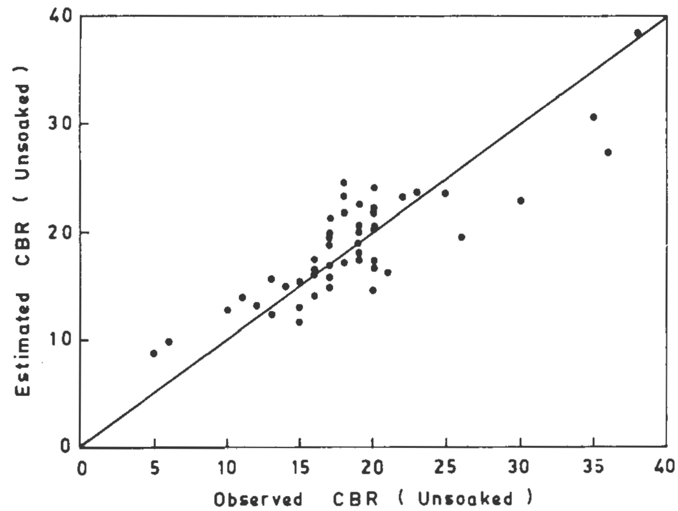

FIGURE 1 Plot between estimated and observed CBR values.

Dynamic Pavement Condition

Dynamic data on pavement condition included periodic pavement performance data such as roughness (mm/km), characteristic deflection (mm), subgrade moisture content (%), and different forms of pavement distress expressed as percentage of area with respect to total pavement surface area.

Traffic Characterization

Traffic characterization data included the details of traffic volume (time of day, direction, and average daily commercial traffic) and axle loads. The damaging effect of vehicles was expressed by the vehicle damage factor (VDF). Equivalent standard axles were calculated for each series from the traffic data and the VDFs. The cumulative standard axles were derived for each series of observation periods. A typical plot of the VDFs and equivalent single-axle loads (ESALs) as observed on some of the experimental sites at different periods during the course of study is given in Figure 2.

Data Sorting and Smoothing

As is expected from a study of this nature and magnitude,

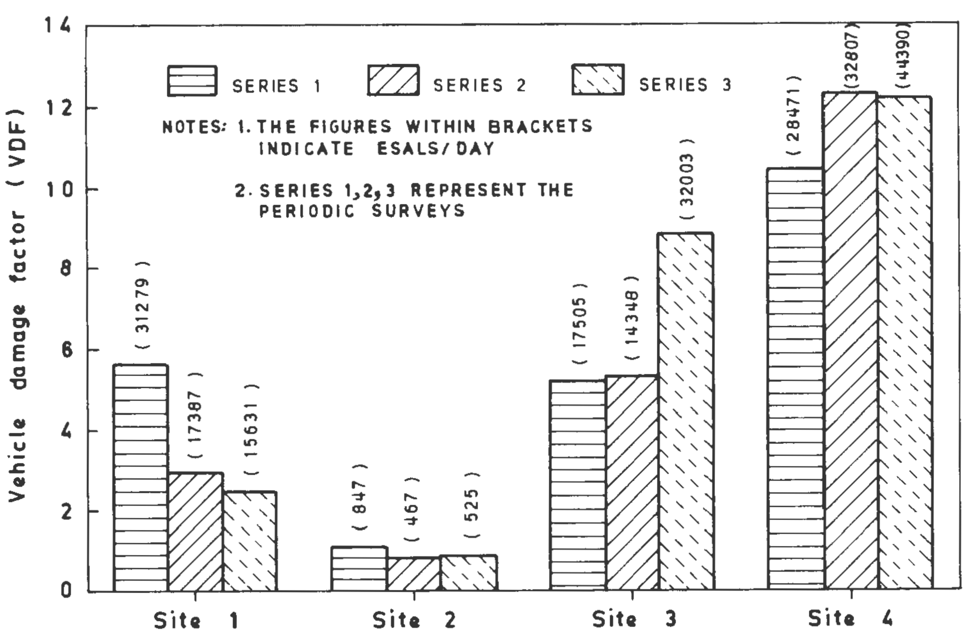

FIGURE 2 Variation in VDF and ESALS per day on some experimental sites during the study period.

a large variation in the performance data was observed. Some of the data trends were not justifiable. In order to overcome the large data variation, particularly that in roughness because of random and systematic errors, the exercise of sorting and smoothing data was undertaken. Data that were unconvincing and extremely out of the population were excluded from the analysis. The plots of roughness for each section for different series of measurements were examined individually in the light of maintenance input data provided by the field engineers. In the absence of any supporting data for the improvement in roughness, the roughness being a monotonically increasing function with time and axle loadings (if resurfacing or rehabilitation is not done), such data were removed, and the whole observation period was divided into subperiods.

The loss of excluded data was mitigated by processing the time-series data to determine the section-specific rate of roughness progression over time by a log linear regression of roughness against time. This was done to minimize the impact of random errors in roughness. The roughness was estimated by using the following equation for model development:

$$\log Rg = a_0 + a_i PAGE \quad (3)$$

where Rg is the observed roughness (mm/km) and $PAGE$ is pavement age (months).

Model Development

The large amount of data collected was subjected to the following forms of analysis: graphical, linear or nonlinear regression, and multivariate linear or nonlinear analysis.

Data reviews were undertaken from time to time, and trends between different independent parameters, namely, MSN versus deflection, roughness versus cumulative standard axles (CSALs), distress versus CSAL, pavement age versus roughness, and so forth, were plotted to examine the behavior and interactions of different parameters. The incremental approach, taking the difference between the two successive observations, was adopted in multivariate regression analysis as the most logical approach available for time-series data analysis for the predictions of change over the preceding value.

The range of parameters covered in the data analysis for model development is given in Table 2. As seen from the table, the wide variation in pavement conditions normally observed in India was covered in the study. The values in Table 2 are the changes in different parameters between the two sets of observations included in the data analysis after the sorting and smoothing of the data. These changes are over a period ranging from 0.417 to 1.917 years for premix carpet and from 0.333 to 1.333 years for asphalt concrete. The negative changes in some of the parameters are due to improvements in surface condition resulting from maintenance inputs made from time to time during the study period.

Different forms of statistical models were developed for prediction of pavement deterioration from the data obtained after the sorting and smoothing techniques. The general form of models for the prediction of change in roughness and cracking are as follows:

Change in roughness = *f*(current roughness, change in surface condition, traffic volume and loading, pavement age, pavement strength, maintenance inputs)

Change in distress = *f*(current surface condition, traffic volume and loading, pavement age, pavement strength, maintenance inputs)

Separate models developed for roughness progression and crack progression and for asphalt concrete and premix carpet surfaces are given in Table 3. These models permit the prediction of change in roughness and cracking over time. Plots of observed and estimated values for roughness and crack progression for a premix carpet surface are given in Figures 3 and 4.

Discussion of Models

Separate models were developed for two different types of pavement surfaces normally used in India. The models were partly validated also with the data available from some of the experimental sections. It was found that predictions for pavement deterioration, especially in terms of roughness, can be made with reasonable accuracy. Though the experiment provided for the study of the effect of different levels of maintenance on pavement performance, the same could not be quantified because of a lack of feedback on maintenance inputs. For the purpose of these models, it was assumed that the test sections were provided with routine maintenance only.

Conclusions and Future Plans

The models presented in this paper are based on the typical traffic, environmental, and pavement conditions on the major highways in India. These models will provide useful input for the development of an appropriate pavement management system for maintenance planning and for setting priorities. There is still much data available for other forms of analysis. In view of the limitations of these models, further work on different aspects of modeling is being continued. The inclusion of deflection in the models as an indicator of pavement strength is under ex-

TABLE 2 Range of Study Parameters

Sl. No.	Parameter	Range			
		Premix Carpet		Asphaltic Concrete	
		Minimum	Maximum	Minimum	Maximum
1	ΔPH_t	- 0.830	1.500	-0.777	1.400
2	ΔCR_t	-37.690	52.900	-2.550	18.760
3	ΔPW_t	- 6.910	14.460	-8.610	5.350
4	ΔDEP_t	- 3.900	2.680	-1.000	2.380
5	ΔRg_t	15	1786	-433	995
6	$\Delta CSAL$	0.001	11.080	1.029	12.910
7	MSN	1.200	4.480	3.250	5.024
8	PAGE	0.083	11.670	0.833	11.667
9	t	0.417	1.917	0.333	1.333
10	Rg_i	1338	6651	1334	2866
11	CR_i	0.000	90.000	0.000	27.900

where

ΔPH_t = Change in potholes (%) over a time t (years)

ΔCR_t = Change in Cracking (%) over a time t (years)

ΔPW_t = Change in patch work (%) over a time t (years)

ΔDEP_t = Change in depression (%) over a time t (years)

ΔRg_t = Change in roughness (mm/km) over a time period t (years)

Rg_i = Initial roughness (mm/km)

CR_i = Initial cracking (%)

PAGE = Pavement age since last renewal/strengthening (years)

t = Time interval (years)

MSN = Modified structural number

$\Delta CSAL$ = Change in cumulative standard axles (msa)

TABLE 3 Roughness and Crack Progression Models

Sr. No.	Equation form	m	R^2	SE	Surface type
1.	$\Delta Rg_t = 3212.26\ \Delta CSAL.MSN^{-5}.e^{m.PAGE} + m.Rg_i.t$ (2.26) (13.90) $+446.19\ \Delta PH_t + 4.50\ \Delta CR_t + 13.08\ \Delta PW_t + 81.72\ \Delta DEP_t$ (4.48) (2.14) (2.03) (3.03)	.14	.63	262.28	PC
2.	$\Delta CR_t = 328.56\ \Delta CSAL.MSN^{-5}.e^{m.PAGE} + m.CR_i.t$ (7.94) (3.53)	.21	.35	5.68	PC
3.	$\Delta Rg_t = 9830.05\ \Delta CSAL.MSN^{-5}.e^{m.PAGE} + m.Rg_i.t$ (2.20) (2.50) $+222.09\ \Delta PH_t + 18.40\ \Delta CR_t + 16.91\ \Delta PW_t$ (3.96) (1.73) (1.57)	.09	.24	230.84	AC
4.	$\Delta CR_t = 0.55\ \Delta CSAL.MSN^{-5}.e^{m.PAGE} + m.CR_i.t$ (2.34) (3.33)	.86	.22	3.49	AC

where

m = Environmental factor

PC = Premix carpet surface

AC = Asphaltic concrete surface

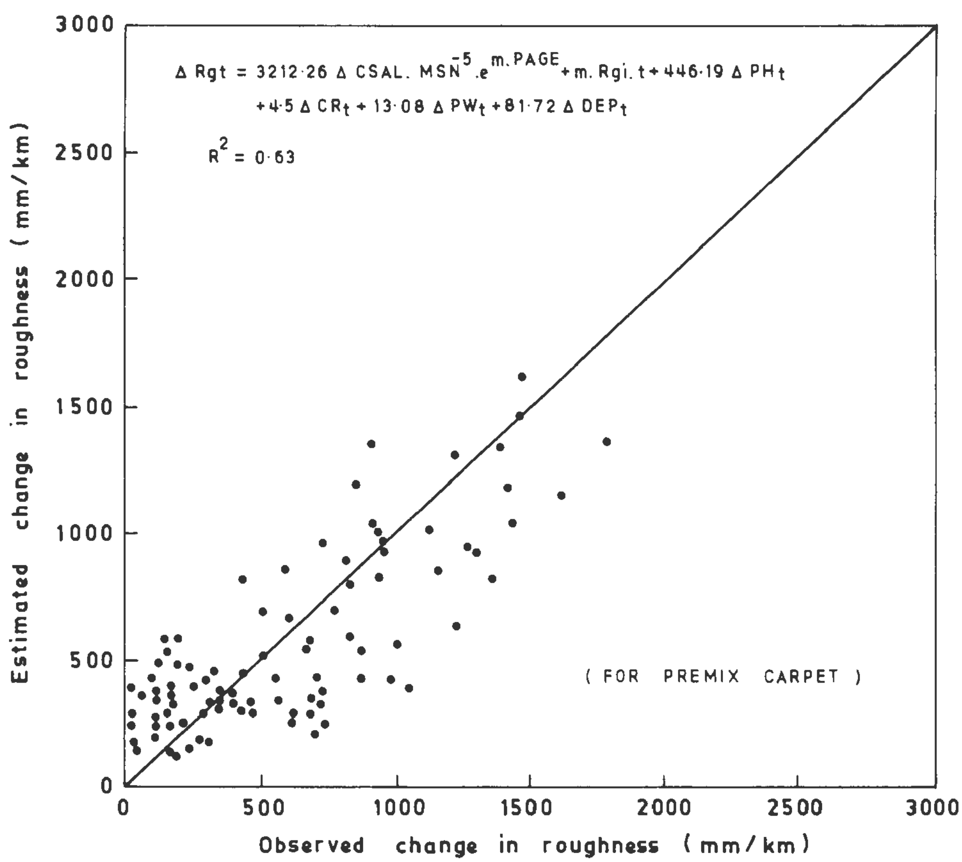

FIGURE 3 Plot between estimated and observed change in roughness.

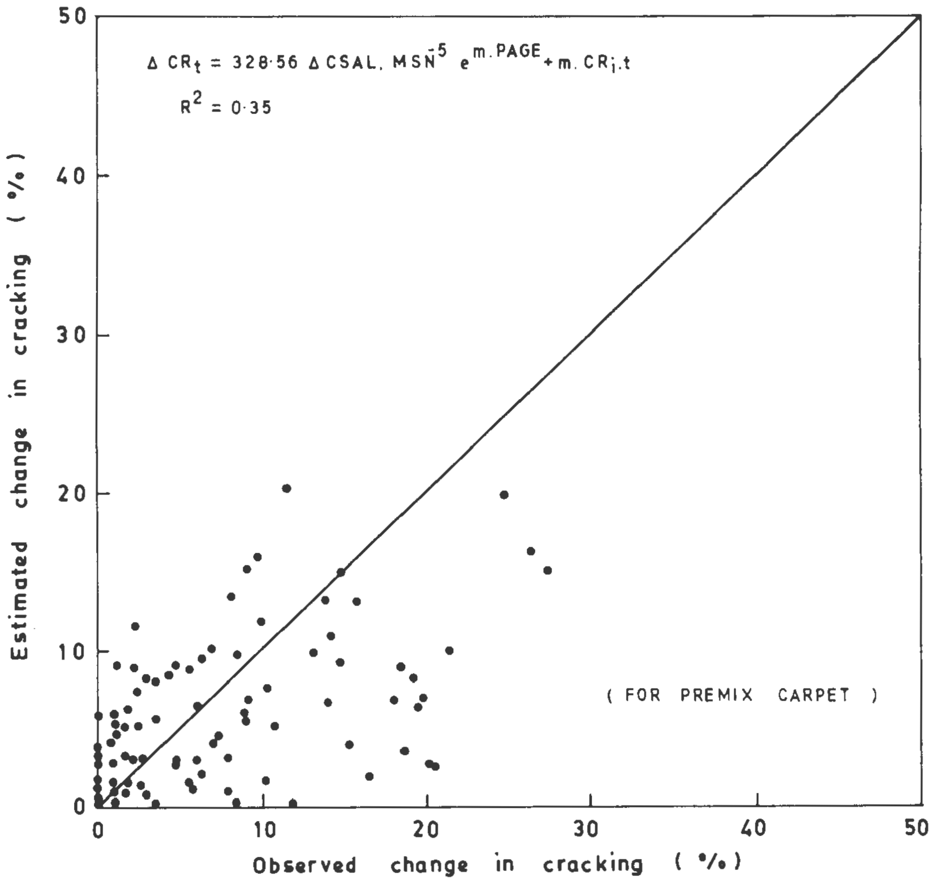

FIGURE 4 Plot between estimated and observed change in cracking.

ploration. Analysis is also planned for prediction of deterioration in terms of combined distress by assigning suitable weighting factors to different modes of distress. More refined models are expected to be available from the study on New Pavement Sections, which has already been launched.

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Predicting Roughness Progression in Flexible Pavements Using Artificial Neural Networks

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To develop a balanced expenditure program for a highway network, the rate of deterioration of the pavement and the nature of changes in the condition need to be predicted so that timing, type, and cost of maintenance can be estimated. A pavement deterioration model, or pavement performance, is therefore a key component of the analysis supporting pavement management decision making. Models for predicting roughness progression have been developed on the basis of traffic and time-related models, interactive time, traffic, or distress models. These models differ in form, in level of initial roughness, and in the influence of roughness on the subsequent progression rate. A characteristic feature of the models is that they are formulated and estimated statistically from field data. To date, modeling pavement performance has been extremely complicated; no pavement management system (PMS) can consider more than a few of the parameters involved, and then only in highly simplified manner. The capabilities of artificial neural networks (ANNs) are evaluated in predicting roughness progression in flexible pavement from structural deformation, which is the function of modified structural number, incremental traffic loadings, extent of cracking and thickness of cracked layer, incremental variation of rut depth; surface defects, which are the function of changes in cracking, patching and potholing; and environmental and non-traffic-related mechanisms, which are the function of pavement environment, time, and roughness. ANNs have attracted considerable interest in recent years because of growing recognition of the potential of these networks to perform cognitive tasks. The tasks include prediction, knowledge processing, and pattern recognition. ANNs offer a number of advantages over more traditional statistical prediction methods: they are capable of generalization, and because of their massive parallelism and strong interconnectivity, they are capable of offering real-time solutions to complex problems. The back-propagation algorithm, which uses supervised learning, is used to train the networks.

Road roughness is defined as the deviation from a true planar surface with a characteristic dimension that affects vehicle dynamics, ride quality, dynamic loads, and drainage. Roughness, which is the irregularity of the road surface familiar to all road users, and the perceptions of the riding quality of a road have long been considered criteria for the acceptability of the service provided by the road. Roughness affects the dynamics of moving vehicles, increasing the wear on vehicle parts. It also increases the dynamic loadings imposed by vehicles on the surface, accelerating the deterioration of pavement structure as discussed by Paterson (*1*).

Predicting the progression of roughness during pavement design life is very important for pavement management decision making, pavement design and evaluation, and road pricing. Many different models for characterizing roughness progression in flexible pavements systems are shown in Table 1. The merits and drawbacks of traffic, time-related, and interactive time-traffic models have been discussed by Paterson (*2*). New transferable causal

TABLE 1 Selected Previous Model Forms for Characterizing Roughness Progression

MODEL FORMS	SOURCE AND COMMENT
*Traffic Models	
1. $g_t=(p_0-p_t)/(p_0-p_r)=(N_t/\rho)^{\beta}$	AASHTO from 1959-60 Road Test, Illinois
2. $R_t=R_o+s(S)N_t$	RTIM2 Model from 1971-75 Kenya-TRRL Road Cost Study
3. $g_t=\exp[-(\rho/N_t)^{\beta}]$	USA (Lytton et al. 1982); S-shaped curve of slope ρ and curvature β
*Time Related Models	
4. $\Delta R_t=aR_t\Delta t-b$	Arizona, USA (Way and Eisenberg 1980).
5. $R_t=R_0+at^b$	Australia (Potter 1982).
6. $\Delta R_t/R\cong7\%$	Canada (Cheetham and Christison 1981).
20 -30% per year	Spain, Belgium (Lucas and Viano 1979)
*Interactive time, traffic or distress	
7. $R_t=a+bt+cf(S,\log N_t)$	Brazil (Queiroz 1981).
8. $\Delta R_t/R_t=\max(aCX^b,c)\Delta t$	Great Britain (Jordan et al. 1987).
9. $t=f[p_0, RD, RD^{2.5}, (C+P)^{0.5}]$	(Uzan and Lytton 1982).
Generalized Models	
10. $RI_t=e^{mt}[RI_0+a(1+SNC-F\ HS\ CRX)^{-5}NE_t]+cRDS_t+dCRX_t+ePAT_t$	(Paterson and Attoh-Okine 1993 (3)).
11. $RI_t=e^{mt}+[RI_0+a(1+SNC)^{-5}NE_t]+d\ CRX_t+ePAT_t$	(Paterson and Attoh-Okine 1993 (3)).
12. $RI_{noc}=e^{mt}[RI_0+a(1+SNC)^{-5}NE_t]$	(Paterson and Attoh-Okine 1993 (3)).
13. $RI_t=e^{mt}[RI_0+a(1+SNC-F_iHS\ CRX)^{-5}NE_t]$	(Paterson and Attoh-Okine 1993 (3)).
14. $RI_t=e^{mt}[RI_0+a(1+SNC)^{-5}NE_t]$	(Paterson and Attoh-Okine 1993 (3)).
15. $RI_t=e^{mt}[RI_0+a(1+SNC-F\ HS\ CRX)^{g}NE_t]$	(Paterson and Attoh-Okine 1993 (3)).
16. $RI_t=e^{mt}[RI_0+a(1+SNC)^{g}NE_t]$	(Paterson and Attoh-Okine 1993 (3)).
17. $RI_t=e^{mt}[RI_0+a(1+SNC)^{g}NE^{h}_t]$	(Paterson and Attoh-Okine 1993 (3)).

* Adapted from (2)

Note: g = damage function; p = serviceability index; N_t = cumulative number of ESAL's; R = roughness; S = pavement strength parameter; t = age of pavement since rehabilitation; CRX = area of cracking; RD = rut depth; C + P = area of cracking plus patching; β, ρ, are functions, and a, b, and h are constants estimated empirically through research; RI_t = roughness at pavement age t; m = environmental coefficients; NE_t = cumulative equivalent standard axle loads; SNCK = (1 + SNC − F HS CRX_t); SNC = structural number modified for subgrade strength; F − coefficient; HS = thickness of bound layers; CRX_t = area of indexed cracking at time t; RDS_t = standard deviation of rut depth; PHV_t = volume of potholing; PAT_t = area of patching.

models (2) and generalized models described by Paterson and Attoh-Okine (3) have been developed (Table 1). To date, the models developed for predicting roughness have concentrated primarily on the expected or average future performance of the pavement. The outcome is based on statistical prediction methods.

Artificial neural networks (ANNs) have been shown to offer a number of advantages over traditional statistical methods. They are capable of making generalizations and of offering real-time solutions to complex prediction problems because of their massive parallelism and strong interconnection. Because ANNs learn from pavement historical data, no human expert, specific knowledge, or developed models are needed.

The aim of this paper is to evaluate the capabilities of ANNs in predicting roughness progression in flexible pavement from structural deformation (modified structural number, incremental traffic loadings, extent of cracking and thickness of cracked layer, and incremental variation of rut depth), surface defects (changes in cracking, patching, and potholing), and environmental and non-traffic-related mechanisms (pavement environment and time). ANNs are particularly suited to such a task because they are "taught," that is, exposed to data, allowed to "learn," and "told" what are the appropriate responses to different inputs.

Artificial Neural Network Approach

ANNs, or simply neural networks, are computing systems made up of a number of simple and highly interconnected elements that process information by its dynamic-state response to external inputs, as described by Kamarthi et al. (*4*). ANNs have been studied for many years, but there has been a recent resurgence of interest in this rapidly growing area in artificial intelligence (AI). ANNs are a form of AI designed from a blueprint of the brain that simulates the brain's capability to think and learn through perception, reasoning, and interpretation. Important characteristics of a neural network are its ability to "learn" and "adapt" and its flexibility and parallelism.

Unlike expert systems, ANNs are capable of learning the interrelationship between the parameters of a problem by looking at some typical examples. ANNs are very flexible and can be thought of as black boxes that could be adapted for any problem. With today's advances in computer technology, the parallel structure of ANNs helps in the implementation and real-time applications. ANNs can operate simultaneously on both quantitative and qualitative data, and they naturally process many inputs and have many outputs that make them readily applicable to multivariate systems.

The basic unit of an ANN is a processing element (PE). It combines (typically sums) the inputs and produces an output in accordance with a transfer function (typically a threshold function). The output of one processing element is connected to the input paths of other processing elements through connecting weights. The PEs by themselves are not powerful in terms of computation or representation, but their interconnection allows analysts to encode relations between variables, giving different powerful processing capabilities. Figure 1 displays the anatomy of a single PE. The inputs' signals come from either the environment or outputs of other PEs and form an input vector $\mathbf{A} = (a_1, \ldots a_i \ldots a_n)$, where a_i is the activity level of the *i*th PE or input. Associated with each connected pair of PEs is an adjustable value called weight (also referred to as a connection strength). The collection of weight forms a vector $\mathbf{W}_j = (w_{1j}, \ldots w_{ij} \ldots w_{nj})$, where the weight w_{ij} represents the connection strength from PE a_i to the PE b_j. And finally the bias θ_j is used to compute the output value *b:*

$$b_j = f(AW_j - W_{0j}\theta_j) \tag{1}$$

$$b_j = f\left(\sum_{i=1}^{n} a_i W_i - W_{0j}\theta_j\right) \tag{1a}$$

Development of ANN Model

Data Generation

Roughness data were generated using the RODEMAN, a menu-driven PC version of the Road Deterioration and Maintenance Submodel of HDM-III. The approach utilizes a full empirical simulation model to generate roughness data. Table 2 is the example subset of data generated, and Table 3 shows the combination. There were 1,274 discrete data items.

Data Preparation

The phases of data preparation for the modeling were broadly classified into three distinct areas: data specification, data inspection, and data preprocessing. The data specification was determined during the generation of variables from the simulation. After the data were identified, box-and-whiskers plots were used to determine if there were outliers. An outlier is an extreme data point that may have undue influence on a model. Outliers are often (but not always) caused by erroneous data cases.

Box-and-whiskers plots are based on a "five-number summary," which consists of the median, the two quar-

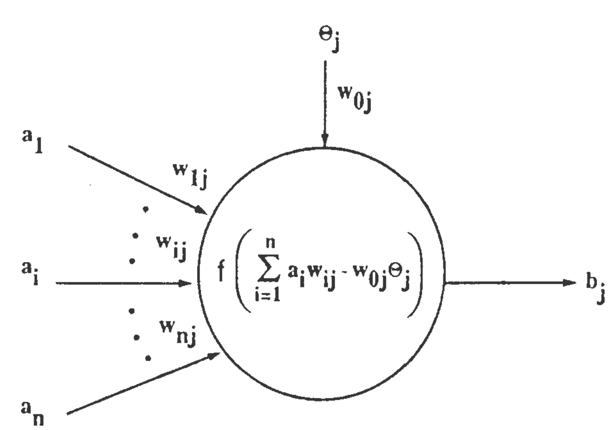

FIGURE 1 **Artificial neural system.**

TABLE 2 Example Subset of Data Generated by HDM-III Model

SNC	AADT veh/d	ESALY Million	AGE yr	CRA %	CRW %	CRX %	RAV %	PHA- %	RDM mm	RDS mm	RI IRI=	PAT %
3	1000	0.10	0	0	0	0	0	0	0	0	2.0	0.00
			1	0	0	0	0	0	3.0	1.3	2.21	0.00
			2	0	0	0	0	0	3.4	1.4	2.28	0.00
			3	0	0	0	0	0	3.8	1.5	2.36	0.00
			4	0	0	0	0	0	4.1	1.5	2.43	0.00
			5	0	0	0	0	0	4.3	1.6	2.51	0.00
			6	2	0	1	0	0	4.5	1.6	2.59	0.00
			7	6	0	4	0	0	4.7	1.7	2.69	0.00
			8	12	3	8	0	0	4.9	1.7	2.80	0.00
			9	20	9	16	0	0	5.1	1.7	2.94	0.00
			10	31	19	26	0	0	5.2	1.7	3.09	0.00
			11	44	31	39	0	0	5.4	1.8	3.27	0.00
			12	59	45	54	0	0.03	5.6	1.8	3.47	0.03
			13	72	61	68	0	0.04	5.8	1.9	3.68	0.07
			14	82	74	80	0	0.06	6.0	1.9	3.87	0.13
			15	90	85	89	0	0.07	6.2	2.0	4.06	0.20
			16	95	93	95	0	0.08	6.4	2.0	4.23	0.28

1. Potholing area data shown is prior to patching, and is reduced to zero annually by the patching.
2. 1 m/km IRI = 63.36 inch/mi IRI.

Note: SNC = Modified Structural Number

TABLE 3 Combinations and Ranges of Primary Parameter Used to Generate Condition Data

Environment	Surface Type	SNC	Surface Thickness	Traffic Loading (million ESAL/Lane-yr) 0.01	0.03	0.10	0.30	1.0	3.0
	AC	2	30	X		X			
		3	50	X		X		X	
		5	80		X		X		X
		8	100		X		X		X
DNF (0.005)	ST	2	12	X		X			
		3	12	X		X		X	
		4	15		X		X		X
		6	18		X		X		X
WNF (0.023)	AS FOR DNF ABOVE								
WF (0.100)	AS FOR DNF ABOVE								

Note: DNF = Dry, non-freeze; WNF = wet, non-freeze; WF = wet, freeze; ESAL = equivalent standard axle loadings (8,200 kg).

tiles, called "hinges," and the range (whiskers). Figure 2 is a box-and-whiskers plot of SNC (structural number modified for subgrade strength) without outliers, and Figure 3 is a box-and-whiskers plot of rut depth with an outlier. Although not all the outliers were erroneous, all were removed from the data before analysis because the data were only simulated, not from actual pavement conditions.

The Explorer software is a commercial ANN used in the modeling process. To use the software, the data inputs must be between 1 and 0. All the variables are divided by the maximum value in the generated data of the variable. Table 4 is a subset of data for a roughness prediction neural network. About 30 percent of generated data was used as an input, and about 10 percent was reserved for the set when networks were fully trained or had converged.

Training

The proposed scheme for roughness prediction involves the development of an ANN that could be trained to predict roughness of pavement, given pavement condition data. Initially three different architectures of the network were examined. The three had either one (48 PEs), two (24 PEs), or three layers (16 PEs), elements in keeping with a rule of thumb that requires a ratio of four hidden units for each input unit. The ANN training process depends mainly on the problem scale and the prediction accuracy required.

The back-propagation learning algorithm, also known as the generalized delta rule, was used in the learning process. In the back-propagation, each presentation of the data set and the input value (roughness) of the ANNs

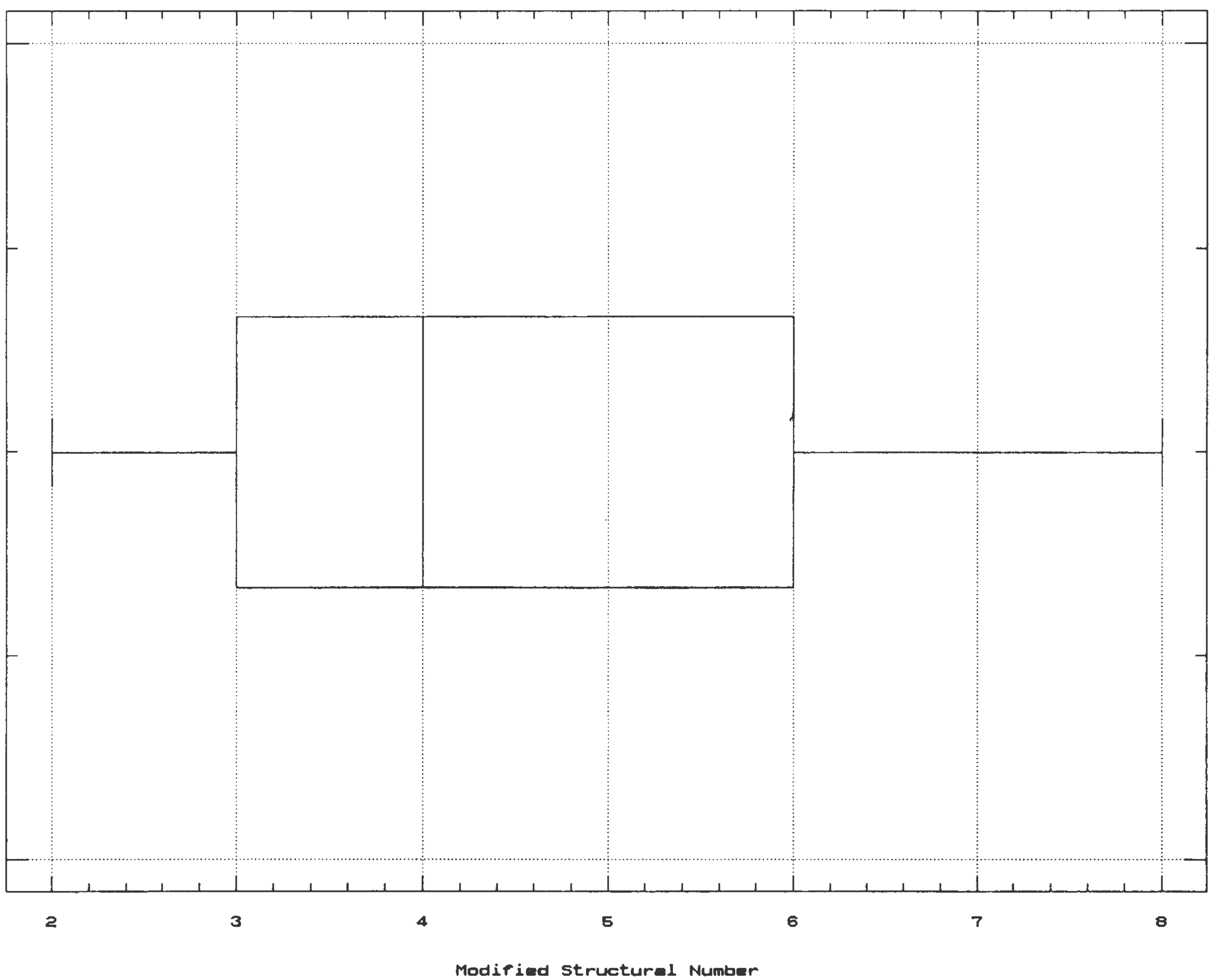

FIGURE 2 Box-and-whiskers plot of structural number modified for subgrade strength without outliers.

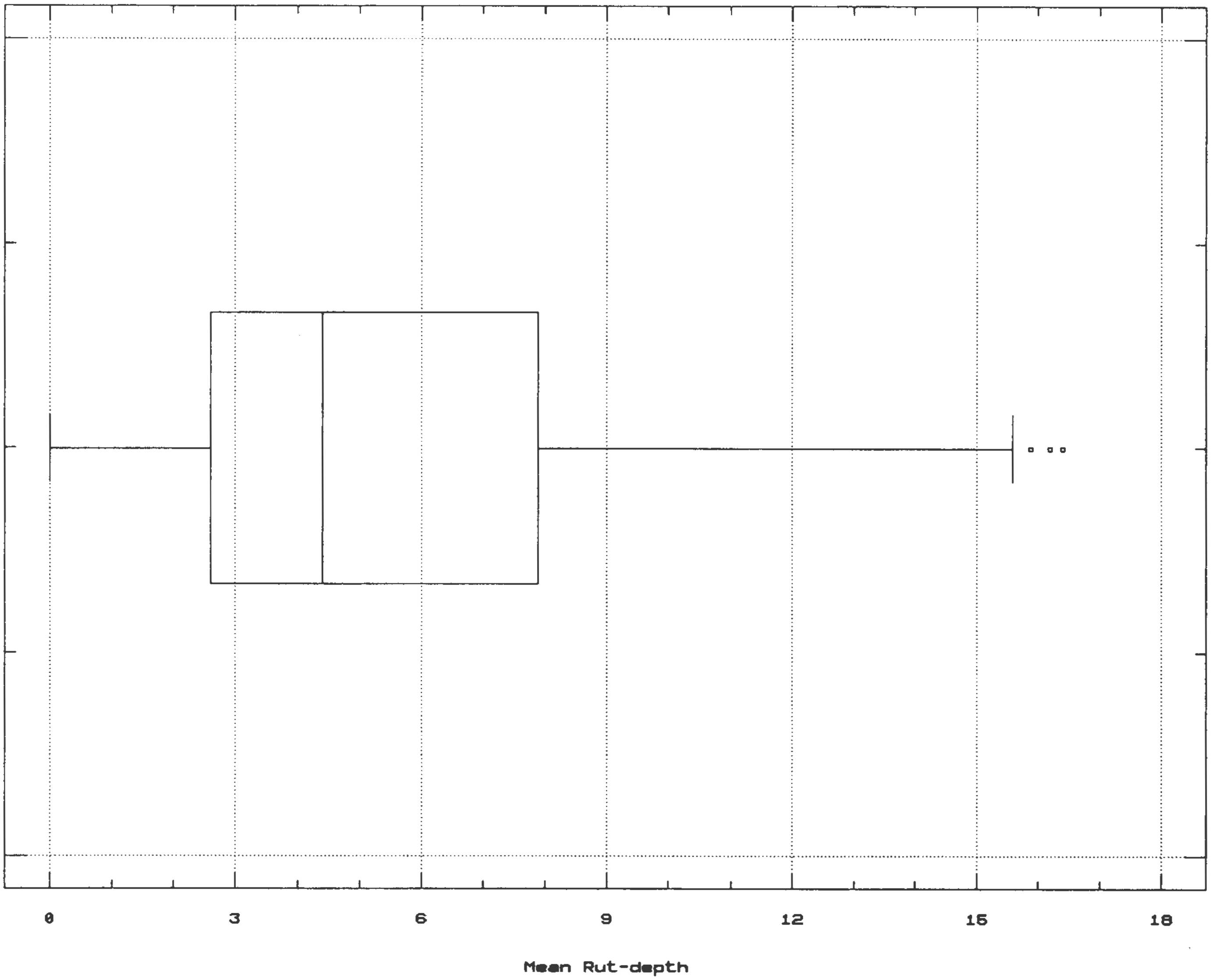

FIGURE 3 Box-and-whiskers plot of rut depth with an outlier.

are compared with desired output values and adaptive weights within the network and incrementally adjusted to minimize the output error. The sigmoid activation function was used. The inputs was compressed by the activation function into output values between 0 and 1. The back-propagation algorithm has demonstrated several advantages in addition to having the potential for determining networks with arbitrary mapping properties (5). Although the back-propagation learning method works, the learning process is very slow, even for fast computers (6).

The error function is expressed as

$$E = \frac{1}{2} \sum_{c} \sum_{j} \left[y_j(c) - d_j(c) \right]^2 \qquad (2)$$

where

c = input sample case,
j = output node index,
y = actual output, and
d = desired output.

The overall objective is to minimize the error function by adjusting the interconnection weights. The training algorithm using back-propagation is well presented elsewhere. The initial weights and biases are chosen randomly. The adjusted weights and biases are as follows:

$$w_{ij}^{\text{new}} = w_{ij}^{\text{current}} - \eta \frac{\delta^t E_t}{\delta w_{ij}} + \alpha \left(w_{ij}^{\text{current}} - w_{ij}^{\text{previous}}\right) \qquad (3)$$

$$\theta_i^{\text{new}} = \theta_i^{\text{current}} - \eta \frac{\delta^t E_t}{\delta \theta_i} + \alpha\left(\theta_i^{\text{current}} - \theta_i^{\text{previous}}\right) \qquad (4)$$

TABLE 4 Example of Subset Data Used as Input for ANN Modeling

SNC	AADT	ESAL	AGE	CRA	CRW	CRX	RAV	PHA	RDM	RDS	PAT	RI
0.25	0.003	0.003	0	0	0	0	0	0	0	0	0	0.14
0.25	0.003	0.003	0.45	0.14	0.09	0.16	0.09	0	0.14	0.46	0	0.18
0.375	0.003	0.003	0.1	0	0	0	0	0	0.15	0.23	0	0.15
0.375	0.03	0.03	0	0	0	0	0	0	0	0	0	0.14
0.375	0.03	0.03	0.25	0	0	0	0	0	0.26	0.31	0	0.16
1	0.01	0.01	0	0	0	0	0	0	0	0	0	0.14
0.375	0.03	0.33	0.1	0.03	0	0.02	0	0	0.29	0.31	0	0.18
0.375	0.33	0.33	0.6	0.94	0.94	0.95	0.02	0	0.79	0.83	0.19	0.5
0.75	0.01	0.01	0.25	0	0	0	0	0	0.17	0.23	0	0.20
0.75	0.01	0.01	0.8	0.17	0.05	0.13	0.88	0	0.15	0.17	0	0.69
0.75	0.1	0.1	0.25	0	0	0	0	0	0.14	0.17	0	0.24
0.25	0.003	0.003	0	0	0	0	0	0	0	0	0	0.14
0.375	0.03	0.03	0.55	0.01	0	0.9	0.14	0	0.33	0.35	0	0.18
0.5	0.1	1	0.35	0.77	0.77	0.78	0.17	0	0.50	0.63	0.06	0.15
0.5	0.1	0.1	0.8	0.8	0.86	0.87	0.13	0	0.42	0.46	0.02	0.24
0.5	0.10	0.1	0.6	0.17	0.1	0.15	0.83	0	0.28	0.29	0	0.18
0.5	0.01	0.001	0.75	0.1	0.02	0.07	0.9	0	0.22	0.25	0	0.16
0.375	0.33	0.33	0.55	0.93	0.93	0.94	0.03	0	0.77	0.79	0.15	0.39

where α and η are learning rates. Back-propagation is accomplished in four steps:

Step 1: Normalized condition data generated by simulation are presented to the input layer.

Step 2: One pair of corresponding inputs (condition data) and the output (roughness) are presented.

Step 3: Using the actual roughness (output), the error with respect to given roughness is determined.

Step 4: Error is used to adjust the connecting weight.

Step 5: Using the next data pair, the process is repeated until "correct" roughness is obtained for all inputs used for training.

Result

During training the network result is compared with the correct result, and the mean-square error (MSE) is computed as follows:

Network Size	*Training Data*	*Training Cycles*
12-48-1	0.2	30,000
12-24-24-1	0.001	30,000
12-16-16-16-1	0.002	30,000

The MSE improves significantly as the number of hidden layers increases. It is difficult to evaluate the reliability of a newly trained network; inputs could be removed, added, or altered and the network retrained until the reliability of the network is established, according to Pratt et al. (6).

Figure 4 shows the relationship between actual roughness (from simulated data) progression and roughness predicted by ANNs. Between 2 and 7 IRI there is a fairly good correlation between the desired roughness and the roughness output from the ANNs. Above 7 IRI the ANNs model overestimates the roughness predictions. The R^2 obtained was 39.54 percent and the standard error of 1.88 IRI; 56 data points were used for the testing.

Concluding Remarks

The application of ANNs in pavement deterioration modeling is feasible when a large data base on pavement condition is available. This could form the basis for developing a generic intelligent pavement deterioration process. In the present studies, it seems that the back-propagation method was not too successful in training the fully connected ANNs with sigmoid activation functions.

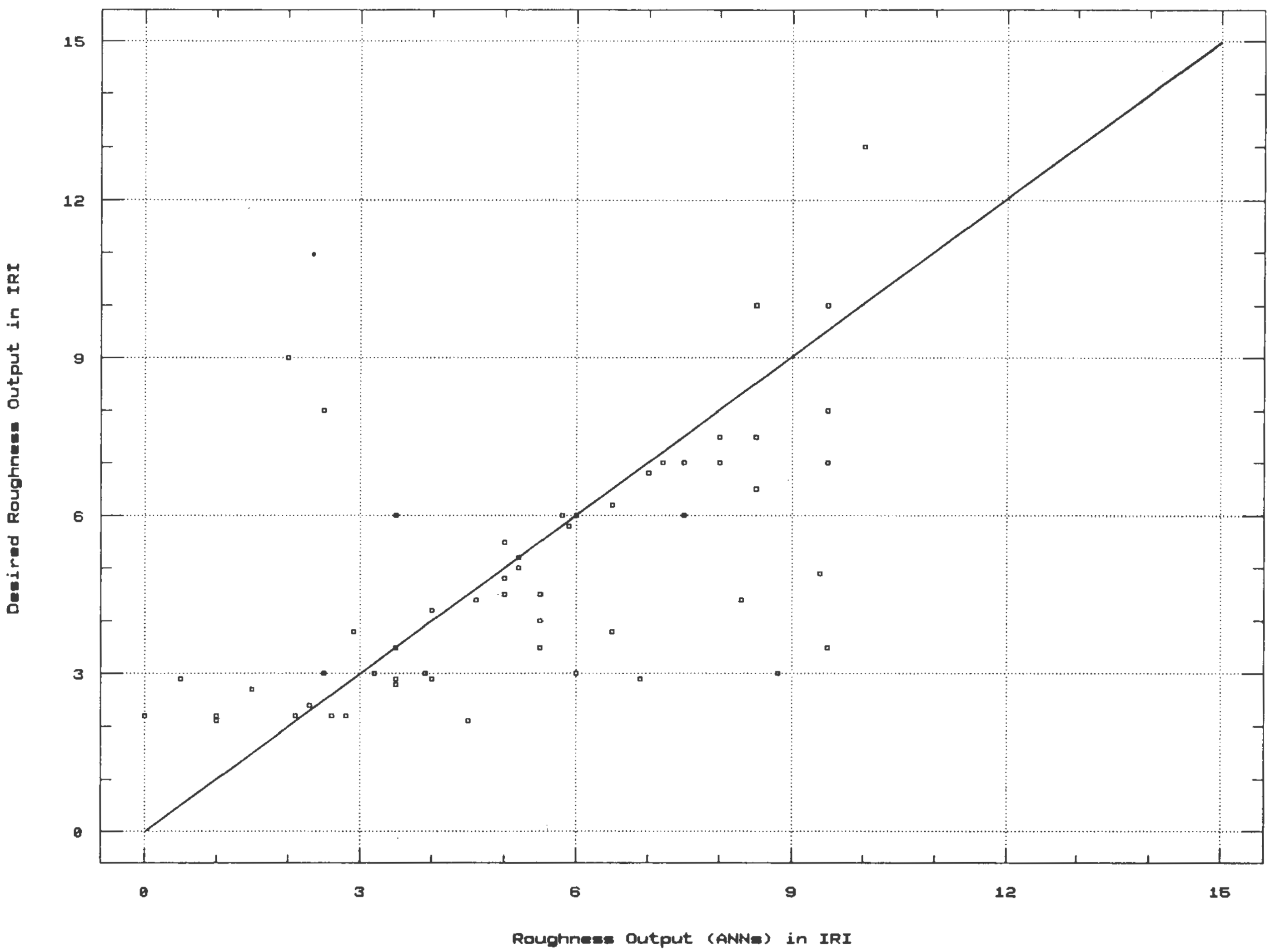

FIGURE 4 Plot of desired versus ANN roughness.

This might be because of the preprocessing of the input data. Furthermore, the commercial software used the applications has numerous in-build functions. Unfortunately, no rigorous method has been reported in the literature for selecting some of the in-build functions such as the learning rates. It will be important to explore whether different preprocessing of input data, learning rules, and transfer functions can perform more successfully. Testing was done using simulated data; it was recognized that this particular approach may not be general enough to perform well on other data sets, especially on in-service pavements. Furthermore, additional work is needed to identify which pavement condition variables can be used to accurately characterize roughness.

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Performance History and Prediction Modeling for Minnesota Pavements

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Issues and problems encountered in developing performance prediction models for pavements in Minnesota are discussed. The purpose of these models is to predict remaining life. The models are being incorporated into the Minnesota Department of Transportation pavement management system. The development of the models was centered on the prediction of future distress levels rather than the prediction of a composite index. The prediction models were based on about 13,000 surface condition data records collected on the entire pavement system between 1983 and 1991. The modeling was based on simple two variable models relating distress density to age. Additional variables such as surface type, traffic, and structure were handled by grouping the pavements by specific attributes. The project resulted in a set of performance prediction models for about 100 pavement groupings. The distresses modeled included transverse and longitudinal cracking at two severity levels, multiple cracking, alligator cracking, rutting, raveling, and patching for flexible pavements, and spalled joints, faulted joints, cracked panels, damaged panels, broken panels, faulted panels, overlaid panels, patched panels, and D-cracking. Roughness in terms of the present serviceability rating (PSR) was also modeled. The findings relate to the difficulties encountered in the process rather than traditional findings such as model coefficients. Examples of some of the difficulties follow: for specific sections, the data were variable; trends could be identified only by grouping the data from a number of sections together. Since pavement lives are longer than the window of time covered by the data, the grouping of sections combined older sections, "survivors," with new sections that included the poor performers. The poor performers would supply data only until they were rehabilitated, at which time they moved to a different group. Also explored was the increase in the PSR due to the overlay thickness. The results show virtually no correlation in the improved PSR to overlay thickness. A further analysis was performed including ride and surface conditions before overlay instead of thickness as independent variables. The better correlation exists. However, the satisfactory results in statistics could not be obtained. It appears that some factors that were not part of the data set had a significant effect on performance, such as maintenance policies, construction or material qualities, project priorities, and section lengths. Since the data were not available, one could only speculate as to the effects.

Pavement management is a generic term that describes the process of managing a wide variety of activities ranging from routine maintenance tasks such as crack sealing to major projects such as pavement reconstruction. A key element of any management system is forecasting needs and budgeting resources, which include people, equipment, and money. A principal mission of the Minnesota Department of Transportation (Mn/DOT) is managing a surface transportation network made up primarily of pavements. To manage the pavements, it is necessary to measure a variety of relevant attributes, including use, condition, and cost of operating the pavement network. Because planning and budgeting for pavement improvement projects require several years, it is necessary to forecast the future condition of the pavements or pavement performance.

Knowledge of pavement performance characteristics allows several activities to occur:

- Prediction of the future condition of the pavements;
- Prediction of the future funding requirement to keep the pavement network at a certain level of condition; and
- Comparison of the effects of various conditions or funding on pavement performance.

To incorporate forecasting of pavement needs into the Mn/DOT pavement management system, a means was developed in 1986 to predict the future condition of pavement sections. The predictions were made from pavement distress and ride prediction models developed at that time. The models take the form of mathematical equations that were developed to fit the growth curves for specific pavement distresses such as cracking, rutting, and roughness.

The modeling of specific distresses is relatively unique among agencies that have developed pavement management systems. Mn/DOT was able to do so because of its large pavement distress data base, which dates back to 1967. No other state had as extensive an archived data base on pavement performance.

Even though such an extensive data base existed, it was not without problems. Data on the pavement composition in terms of layered materials were not in a data base in 1984; these data had to be manually gathered. After a substantial effort of recording the as-built plan cross-section data, layer information now is available. Maintenance activities resulted in improvements in pavement condition, but those activities are not recorded and could not be accounted for. Quality control on much of the data collection was not formalized, resulting in changes in the rating process. The rating is visually obtained from a vehicle traveling at slow speed on the shoulder; the viewing perspective and varying light conditions along with normal rater subjectivity result in variations in the data collected from one time to the next, in addition to the normal change in the distresses.

With the data available in 1984, pavement performance prediction models were developed that modeled the growth of the pavement distress quantities and the present serviceability ratings (PSR), as described by Lukanen in 1986 (*1*). The models developed were considered interim at that time because of the problems, some of which were just briefly described, associated with the data.

Since the time of the Lukanen report (*1*), several significant data improvements have been made. One is the creation of a roadway history file, containing the as-built construction data on the layered materials in the pavement system. Improvements have also been made in the quality control processes for manual distress data collection; these include the provision of enhanced reference material for raters in the field and annual training sessions for raters. The PSR data collection has been improved with the procurement of new and better equipment such as the Mays ride meter, followed by the South Dakota profiler. The improvement in data collection activities began in 1983.

In 1991, it was felt that a large enough data base had been developed under the improved procedures to allow an updating of the pavement performance prediction models. The results of the updating are reported by Lukanen and Han (*2*).

In addition to developing mathematical models to predict or describe the growth of pavement distresses, the actual life of various pavement types was evaluated. At the same time a subsidiary issue, the amount of improvement to ride resulting from an overlay, was evaluated.

Data Used in Analysis

To establish a data base of in-service pavements in Minnesota, the selected data were downloaded from Transportation Information System (TIS) files by Mn/DOT. The downloaded files were created by Mn/DOT on a district-by-district basis to keep the size manageable. All of the files were condensed for transfer to the consultant's computers.

All of the trunk highways in Minnesota were selected for the model development. Within the Minnesota trunk highway system (approximately 14,500 miles of roadway), about 5,000 sections are identified as D-records (*4*). A D-record is established as a unique section for the purpose of performance measurements, including roughness and distresses; it represents the beginning point of a section of highway that has similar construction, traffic history, and surface type. Additionally, M-records (sampling sections) are added at each reference (mile) post between D-records, unless the reference post is located less than 0.3 mile from a D-record, to provide representation of the section. A total of 25,916 D-records and M-records were downloaded for the model development.

Since 1984, Mn/DOT has improved performance measurements by developing additional guidelines for the rating process and training the condition survey staff. Because the reliability of data obtained from 1983 to 1991 is expected to be much better than that for the data collected before 1983, this study was based on the condition data collected from 1983 to 1991.

Because the data collected after 1983 are specific to the individual D-record or M-record location, each D- or M-record was treated as a data record. The detailed data available on the composition of the pavement section made this possible. For each D- or M-record, data were gathered from a number of sources to characterize the pavement structure, surface condition, and use. The pavement structural information consists of the age, material type, and thickness of each of the layers, as well as subgrade soil information from deflection tests or from digitized soil survey maps. The surface condition information consists of data on pavement roughness and the amount of distress observed at each record location in a certain year. The use data consist of functional class information and traffic volume. The primary data sources used were these:

- Functional Class: The functional class was used to separate the pavements' usage for each of the roadways into one of four classes: Interstate, Principal Arterial, Minor Arterial, or Collector.
- Roadway History: The roadway history file contains detailed information on the pavement layers by material type, thickness, year placed, and offset from centerline.
- Condition: The condition file contains the distress data, surface condition ratings (SR), and present serviceability ratings (PSR) for each rating section.
- Traffic: Traffic data for the years 1983 to 1991 were used. The data consisted of the annual average daily traffic (AADT) and the heavy commercial average daily traffic (HCADT).
- Deflections: All of the deflection data were used to calculate the subgrade soil strength for the bituminous pavements. (Deflection testing is only conducted on bituminous pavements.)
- Soil Landscape Units: Soil classification data digitized from county agricultural maps were correlated to the subgrade strength as determined from the deflection data and were used to estimate the soil strength under concrete pavements.

Data Management Features

Data downloaded from different sources in Mn/DOT data bases have different static segmentation schemes, and they have not yet been integrated. However, a unique road number milepost system, which is a physical referencing system, was developed for all roads in the Mn/DOT network. Because of reconstruction activities, the mile markers in the system are reference points rather than physical mileposts. Moreover, realignment activities introduce new pavements with new mileposts. Therefore, there is an inherent relation among different data bases, that is, referencing mileposts.

Different data were segmented with different lengths depending on tests that are used to collect the data. Many attributes are included in the various types of data: functional classification, pavement type, roughness, distresses, traffic, and so forth. The values of the attributes vary along the road and over time. An overall segmentation is needed for the organization of the various attributes. With the help of a road number and referencing milepost, all relevant attributes are associated with a segment of pavement, and they stay uniform within the segment. The segment specified by a road number and beginning and ending mileposts can have variable (dynamic) length (*3*) or fixed (static) length depending on the availability of all attributes along the road and over time. In the Mn/DOT pavement management system, data on pavement condition were segmented in D-records and M-records representing a fixed-length segment of pavement (500 feet long). Because condition data are available only on these fixed-length segments, the overall segmentation is limited to those having condition data; this resulted in static segmentation. Each data file was then scanned block by block to generate a master file by meeting segmentation requirements of the condition data. The master file defines the analysis segment and remains in effect throughout the analyses and prediction modeling unless a major reconstruction activity takes place.

Figure 1 shows the number and distribution of all records or sections available in each of the functional classes. These records were constructed according to rating samples in D-records or M-records of the master files. A total of 28,833 records were available for analysis. A primary data analysis of all of the records resulted in 0.5 percent incomplete records. Incomplete records include the records that contain only aggregate layer or grading, no wearing surface, or no layer at all.

The complete records were further broken down by the four functional classes listed earlier: Interstate, Principal Arterial, Minor Arterial, and Collector and Local. They represent 7, 40, 42, and 11 percent of the total good or complete records, respectively. The further breakdown was based on the construction year of the original wearing course. Since 1953, the design procedures and specifications for bituminous pavements have been standardized, and their constructions are more controllable than they were before 1953. For each functional class, records containing the wearing course constructed before 1953 and after 1953 were separated into two major groups. As shown in the Figure 1, 100 percent of the records in the Interstate system are in the post-1953 category. About 49, 42, and 62 percent of the records in the Principal Arterial system, Minor Arterial system, and Collector and Local system belong in the post-1953 category, respectively. The emphasis of this study is on the post-1953 construction for each major rank group. Overall, post-1953 construction is 58 percent of the Trunk Highway system. A corollary to this is that 42 percent of the system in service was constructed before 1953 and is now older than 40 years.

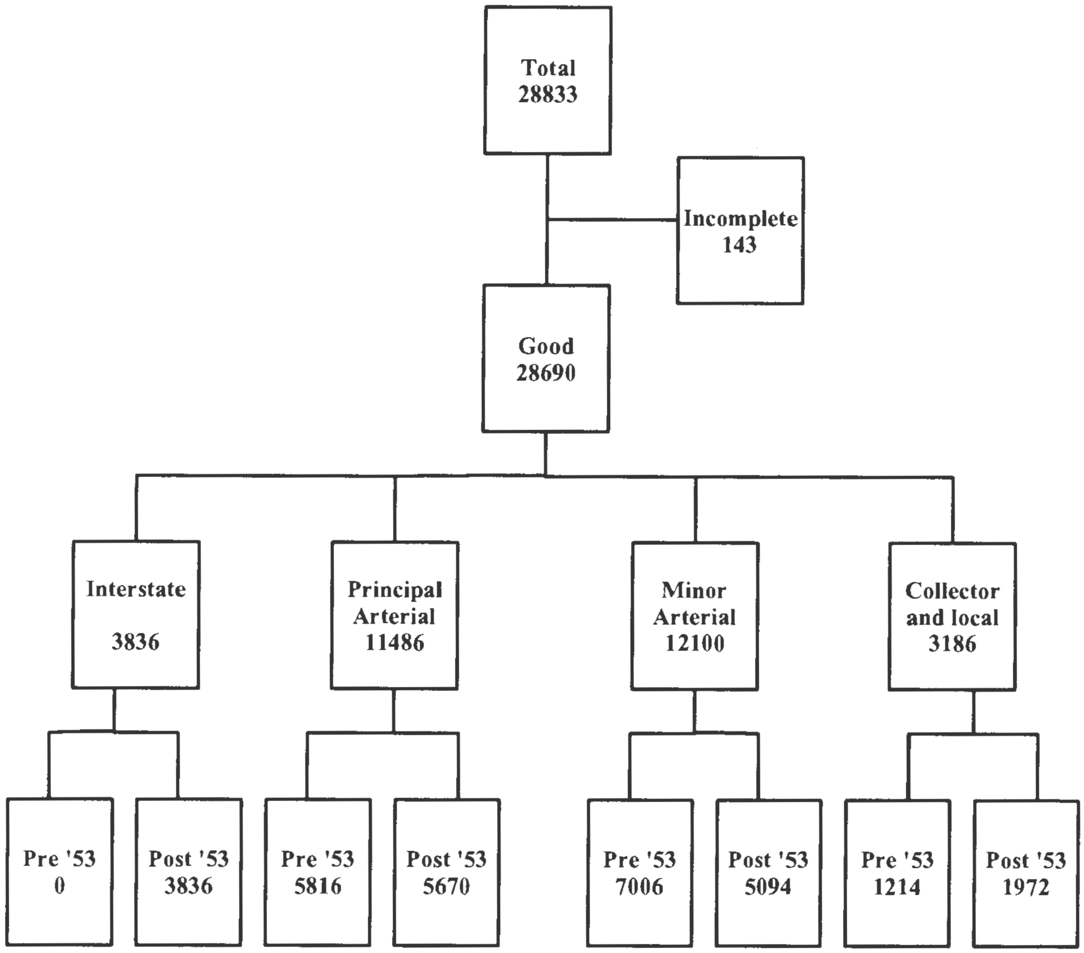


FIGURE 1 Distribution of available records.

Overall, the numbers of records available by general surface type and major rank group that have been constructed since 1953 are shown in Table 1. Three general surface types are defined: portland cement concrete (PCC), asphalt concrete (AC), and continuously reinforced concrete pavement (CRCP). PCC represents a road section composed of at least one portland cement concrete layer, thereby including bituminous over concrete (BOC) pavements. AC stands for a section without any PCC or CRCP layer. CRCP is a road segment with at least one continuously reinforced concrete layer. There are 16,572 records available in all. For performance modeling, further breakdown in grouping of pavement types was performed (see Table 2).

Pavement Life Analysis

One of the analysis tasks was to determine how long pavements were lasting by specific functional classification and pavement type. This information would be very helpful for cost-benefit analysis or life-cycle cost analysis

TABLE 1 Total Records Available for Analysis

MAJOR RANK GROUP	PCC	AC	CRCP
1. INTERSTATE	2874	506	456
2. PRINCIPAL ARTERIAL	2350	3312	8
3. MINOR ARTERIAL	704	4390	0
4. COLLECTOR	44	1928	0

TABLE 2 Life of Pavements

PAVEMENT TYPE	RANK GROUP	Interstate	Principal Arterial	Minor Arterial	Collector
CON	lane mile	633	590	285	1
	mean	22.2	23.6	27.9	13.0
	median	23.0	24.0	28.0	0.0
	std	4.1	5.8	6.2	0.0
BOC (1st OL.)	lane mile	20	156	43	-
	mean	6.2	9.1	12.7	-
	median	6.0	6.5	12.0	-
	std	1.0	4.3	6.7	-
BOC (2nd OL.)	lane mile	12	12	21	-
	mean	9.0	9.8	9.4	-
	median	9.0	9.5	8.0	-
	std	2.1	2.2	2.9	-
BAB	lane mile	324	1402	2447	1181
	mean	14.1	16.7	16.6	17.6
	median	17.0	16.0	17.0	17.0
	std	5.7	6.8	6.2	6.4
BFD	lane mile	67	211	306	226
	mean	16.9	14.6	15.3	10.5
	median	18.0	12.0	16.0	9.0
	std	4.2	6.4	4.5	5.0
BOB (1st OL.)	lane mile	186	557	1465	552
	mean	13.0	15.6	16.4	15.1
	median	12.0	14.0	16.0	15.0
	std	4.6	6.0	5.1	4.5
BOB (2nd OL.)	lane mile	48	61	116	65
	mean	9.3	7.1	10.8	15.0
	median	9.5	5.0	8.0	15.0
	std	2.8	3.1	5.7	3.0

for the various pavements used such as concrete, bituminous over aggregate base (BAB), bituminous full-depth BFD, concrete overlaid with bituminous, and several others.

Pavement life is typically thought to imply the length of time a pavement could last without losing bearing capacity, function, or safety. However, the life of a pavement can be extended by active maintenance or shortened by rehabilitation for reasons other than condition. Therefore, actual pavement life is not exclusively an indicator of structural or functional failure; it is, however, an indicator of overall management practice, as was found during the analyses for pavement life.

Pavement Life

The initial attempt at characterizing how long the pavement types in the analysis last was done by searching the data bases to determine how long a particular pavement was in service before it was overlaid or reconstructed. In the master file, statically segmented data blocks contain structural information that can be used for the analysis of pavement life. The master file was scanned and sorted according to functional classification and pavement type. As shown in Table 2, the number of lane miles (approximately by the number of segmented data blocks), the mean age, the median age, and the standard deviation of the age statistic is reported. Table 2 contains data from only those sections that have been rehabilitated, but it excludes sections rehabilitated in the first 4 years of life. This removes most "stage" construction from influencing the pavement life, but it also eliminates early failure.

Looking only at the pavements that have been overlaid or reconstructed did not take into account any of the pavements still in service (the survivors) (2). This skews the data to represent failures only. There were no outstanding trends in this respect from any of the pavement types.

Conditions at Rehabilitation

Another purpose of developing the pavement-life data was to provide information on how long a particular pavement type will typically last before it needs rehabilitation. In reality, however, it was found that many pavements are overlaid or reconstructed before this would have been needed on the basis of condition. To illustrate this point, several graphs were developed to show the last PSR, surface rating (SR), and pavement quality index (PQI) before rehabilitation. The PQI is a geometric average of the PSR and SR. It is indicated by the graphs in Figure 2 that some sections are rehabilitated long before or after they need rehabilitation based on condition. Figure 2 was constructed on the basis of data for the concrete pavements in the interstate system. Typical threshold values for rehabilitation, based on the PQI, are 2.6 to 3.0. Sections rehabilitated at a higher PQI cause the average pavement life statistic to be lower.

It was found that pavement was rehabilitated in a wide range of conditions, making it obvious that a particular pavement might be rehabilitated for reasons other than condition. This practice does not allow a fair evaluation of how long pavement life will last until the pavement has deteriorated to the point of needing rehabilitation. The data do, however, show that pavements are rehabilitated for reasons other than condition and that budgeting on the basis of pavement management needs to take into account the reasons for pavement rehabilitation not related to condition. In fact, different methods or models exist to set priorities for rehabilitation projects. Factors used to establish priorities for projects include pavement distress, ride, traffic, economy, functional classification, accidents, friction, geometric deficiencies, structural capacity, engineering judgment, age, and location (5). Pavement condition trends may more accurately or realistically describe the structural and functional life of a pavement. The condition data will show when pavements tend to reach a state of needing to be rehabilitated.

PSR Improvement Due to Bituminous Overlay

During the evaluation of pavement life, it was decided to evaluate how much pavement's PSR improved with an

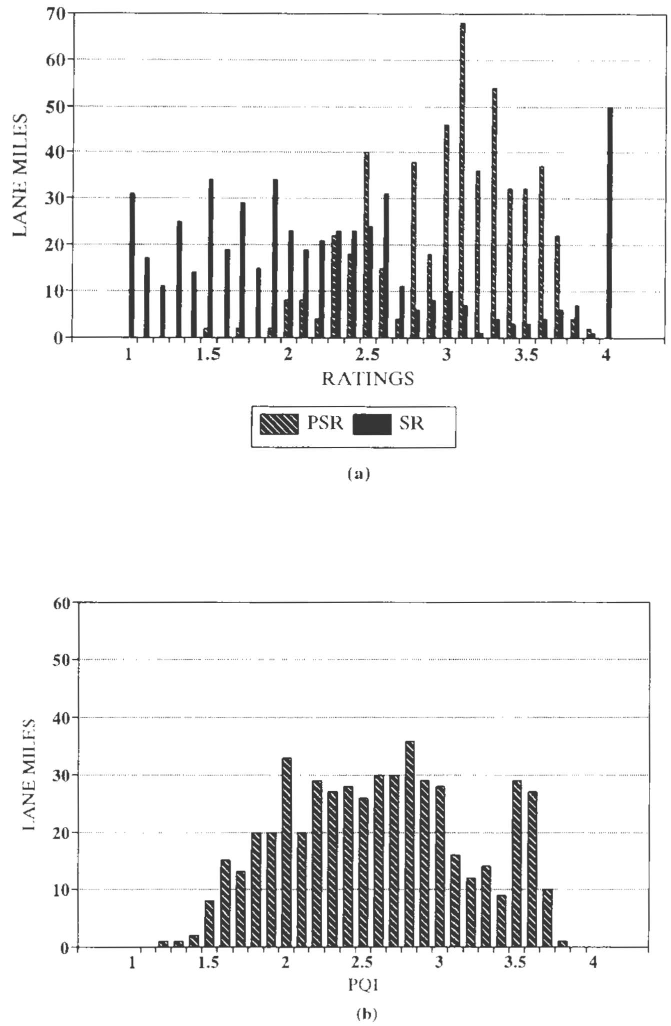
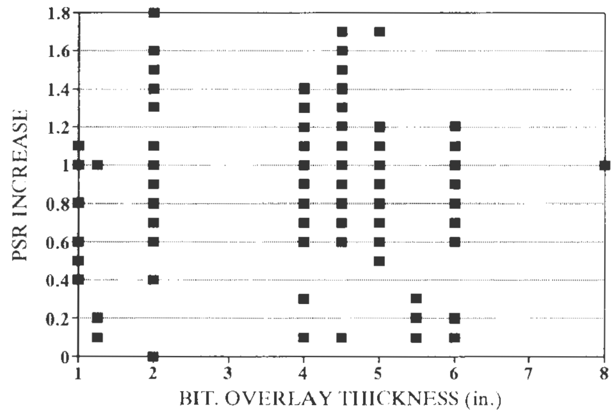


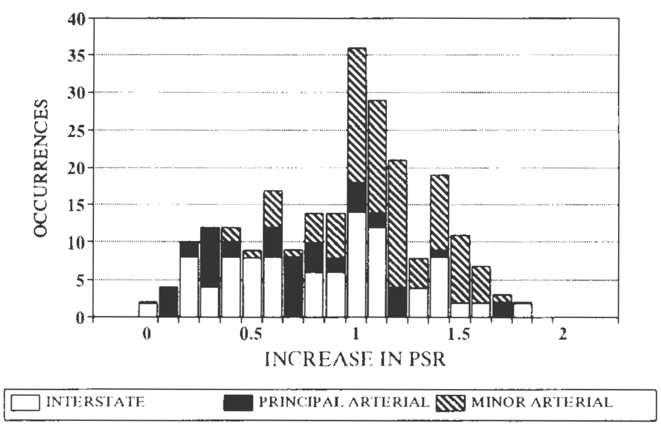
FIGURE 2 Performance levels before overlay: (*a*) PSR and SR; (*b*) PQI.

overlay. One particular factor that was evaluated was the effect the thickness of the overlay had on the improvement of the PSR. Thicker overlays should improve the PSR more than thin ones, because of the potential for improvement available from multiple lifts. The results of the analysis showed that the thickness of the overlay had nothing to do with the improvement in PSR. As shown in Figure 3(a) for the BOC pavements, no specific conclusions could be drawn as to the reasons the PSR improvement was not a function of overlay thickness.

To see what degree of improvement occurred in PSR as a result of the overlay and whether the thickness of overlay was a contributing factor, the master files from all major functional class groups were screened to create data sets for analysis. For example, on BFD pavements, multiple linear regressions were run with the SR before the overlay and the overlay thickness as the independent variables and the PSR increase as the dependent variable. An example of the resulting regression is as follows:



(a)



(b)

FIGURE 3 PSR increase due to overlay: (*a*) thickness; (*b*) FC.

$$\Delta PSR = 1.96 - 0.3\,6 * SR_{\text{before}} + 0.01 * OL \qquad R^2 = 0.18$$

where ΔPSR = PSR increase, SR_{before} = SR before overlay, and OL = thickness of overlay (in.).

The results of this example are consistent with the results obtained from other pavement types that generally show thickness of overlay is not a significant factor in predicting the improvement in the ride. By dropping variable OL and adding variable PSR_{before}, multiple linear regressions were rerun, resulting in the following:

$$\Delta PSR = 3.7 - 0.24 * SR_{\text{before}} - 0.79 * PSR_{\text{before}} \qquad R^2 = 0.47$$

where PSR_{before} is the PSR before overlay. The interpretation of the regression results indicates that the ride after the overlay is dependent on the ride and condition of the pavement section before the overlay is placed.

There were 239 data records available that had the PSR of the concrete before it was overlaid and the PSR of the BOC after the overlay. The thickness of the overlay varied between 1 and 8 in. A multiple linear regression was run between the PSR increase and the inches of overlay. The results of the regression are as follows:

$$\Delta PSR = 0.72 + 0.0783 * SR_{\text{before}} + 0.0103 * OL \qquad R^2 = 0.0206$$

An R^2 of 0.0206 shows there was no relationship between the thickness of overlay and the increase in PSR. The regression also shows the PSR went up about 0.9 regardless of the overlay thickness. As a result, multiple linear regressions were rerun using precondition factors and resulted in the following:

$$\Delta PSR = 2.86 + 0.184 * SR_{\text{before}} - 0.87 * PSR_{\text{before}} \qquad R^2 = 0.59$$

Within the data base several projects were available that provided PSR readings before and after the second overlay on concrete pavement. The relevant data again show virtually no correlation in the improved ride to overlay thickness. The best correlation exists among the before-PSR, before-SR, and the PSR increase. Based on the before ratings of PSR and SR, however, it appears that all of these sections might be overlaid for some reason other than ride or surface rating. The average PSR prior to overlay was 3.34, and the average SR was 3.72. After the overlay the average PSR increased to 3.8. However, the overlay thickness did not effect the amount of increase.

During the evaluation of the increase in PSR resulting from the overlay, it was observed that the improvement in PSR increased as the functional class (FC) decreased, as shown in Figure 3(b) for BOC pavements. That is, the PSR improvement was better on the Collector and Minor Arterial classes than on the Principal Arterial, and it was better on Principal Arterial than on Interstate roadways. No explanation for this can be found in the data, but it is an interesting finding. A possible explanation may be that an overlay on a Collector and Minor Arterial concrete pavement is considered to be a "permanent" rehabilitation, whereas an overlay on an Interstate concrete pavement is considered to be "temporary."

Performance Prediction Models

The available data base allowed the pavements to be grouped into smaller or more refined groupings than were practical during the interim study. The expectations were that the behavior patterns in smaller groups would be more similar than those in larger groups. Again, to limit the diversity that may be associated with older pavements, only data from pavements that were constructed after 1953 were included in the evaluations.

Data Processing

Once the data files were assembled, they were broken down by major pavement type as follows: concrete, concrete with first and second bituminous overlay, bituminous over aggregate base, bituminous over aggregate base overlaid, full-depth bituminous, and full-depth bituminous overlaid. Within each pavement type, the sections were further divided into groupings on the basis of functional class for all of the pavement types, by district for concrete pavements, and by thickness of bituminous, subgrade soil strength, and traffic on some of the larger bituminous groups. In all, 106 analysis groups were evaluated; many other combinations could still be evaluated and might provide improved results.

The data in each pavement grouping were consolidated by averaging the condition indices (PSR and SR) and distress quantities for each year of age. For example, if a pavement group had 50 condition observations of pavements when they were 10 years old, the data for all 50 ratings were averaged to establish the data point for age 10. Performance model development was then based on how the average condition of the pavement changed as the pavements in that group grew older. This process resulted in a set of equations for each pavement group that allowed the average condition of a pavement to be calculated based on its age.

Prediction Models

The equation forms that were used to fit the change in condition or distress were primarily a straight line (linear), polynomial, or an S-shaped curve (sigmoidal). All the models used are based on objective measurements. However, these empirical models imply the current management activity, including random variables and subjective decisions. The random variable and subjective decision could be analyzed using probability models and fuzzy set models, respectively. In the analysis presented, the straight-line equation was first used to model the change in the PSR and SR over time. The polynomial or sigmoidal model was tried if the linear fit was poor ($R^2 < 36$ percent). Finally, the linear model was used to characterize PSR versus age. The polynomial or sigmoidal model would often result in better correlation coefficients; however, the results were considered to be less effective for predicting pavement performance, because the slopes of many of the prediction curves would approach zero or become positive for older pavements. Predicting the loss of PSR based on such models would result in minimal or little change, which is not reasonable to expect for old pavements. The average PSR did show such a behavior for many of the groupings, but it likely was due to such factors as maintenance and rehabilitation of the pavements with low PSR. The sigmoidal equation was used to model the growth in the distresses, from which the SR could be calculated. The Mn/DOT pavement management system used decision trees that were dependent on the predicted distresses and the SR calculated from those distresses as well as the PSR. Therefore, there was no need to proceed any further with the models for the SR index itself.

The PSR shows very little change over a typical life span for most of the pavement groups. The loss in PSR per year is typically about one-half of the expected design loss rate, which is good; however, the PSR values do not start out very high. The data suggest that more emphasis be given to produce a better ride in new pavements and new overlays. Other observations with respect to ride are these:

- The rate of loss of PSR is greater for roadways in the Interstate and the higher-level functional classes. Interstate pavements generally lose their ride quality faster, and Collectors lose their ride quality the slowest.
- The loss of ride for concrete pavements is more dependent on the location in the state as defined by district than on traditional design factors of traffic and soil strength. This does not mean that the district staff are responsible for these differences. An argument that local materials dominate the performance of the concrete pavements, for example, could be investigated. For instance, D-cracking has been identified as a significant distress in several districts and nonexistent in others.
- New construction (first-generation) bituminous pavements retained their ride better than did overlaid bituminous pavements, and, in general, BAB did better than BFD. Bituminous overlaid concrete had the worst performance with respect to ride.

Distress-growth models were developed using the sigmoidal curve shape for all of the distresses that are part of the rating system. The S-shaped curve was fit through the data points of each of the distresses for each of the pavement groupings evaluated. With the modeled distress-growth rates, the SR could be calculated for each of the pavement groupings to describe the deterioration of surface condition with time. The model then could be used to estimate pavement life on the basis of condition.

The prediction models developed in this study were based on predefined pavement families. The pavement families are different from those of interim models. Therefore, comparison of the models in this study to the interim models was not performed.

Predicted Condition

Prediction models are used to forecast future conditions. Some of the results of the analysis regarding the SR are these:

• The higher functional class concrete pavement groups have a greater SR loss during their design lives. The average SR at the end of the design life are as follows:

Functional Class	*Average SR at 35 Years*
Interstate	2.08
Principal Arterial	2.52
Minor Arterial	2.54
Collectors	3.56

Bituminous pavements do not show as noticeable an effect due to functional class or traffic.

• Regional effects, as defined by districts, have as much of an effect on the performance of the SR for concrete pavements as other factors such as soil, dowels, or reinforcement. D-cracking seems to play a role in the regional effects but does not explain all of the differences between regions.

• The SR loss for bituminous surfaced pavements, by construction type, are as follows:

Pavement Type	*Average SR at 20 Years*
Bituminous, aggregate base	2.79
Bituminous, full-depth	2.60
Overlaid bituminous, aggregate base	2.28
Overlaid concrete	2.22
Overlaid bituminous, full-depth	1.83

It may be speculated that the poor showing for overlaid full-depth may be due to the stripping problem some of the earlier full-depth was subject to. It should be noted that the full-depth pavements are now constructed with designed bituminous mixtures for all layers and should not be as susceptible to stripping; therefore, the performance of the full-depth pavements constructed with designed mixes should improve.

Predicted Life

As a means of comparing the results from each of the groupings quickly, the year when the PQI (calculated from the model coefficients) reaches 2.8 was calculated as the predicted life based on structural and functional characteristics. The predicted PQI values were compared to the actual PQI for several pavement groups, and the results were found to be reasonable. It is recommended that, if the PQI is to be used to predict future pavement performance, it could be calculated from the predicted distresses and PSR.

Some general observations can be made from the results of the analysis. The higher functional classes (higher traffic) groups have shorter lives than the lower functional classes for concrete pavements. The predicted PQI of concrete pavements for each of the four functional classes evaluated at 35 years is as follows:

Functional Class	*PQI at 35 Years*	*Age at PQI of 2.8*
Interstate	2.48	27
Principal Arterial	2.65	29
Minor Arterial	2.35	30
Collectors	3.14	35

The functional class (traffic) does not have as noticeable an effect on the SR life of original construction bituminous pavements.

Findings, Conclusions, and Recommendations

Roadway History File

The addition of the roadway history data will be a significant aid for pavement management. It permits any of the pavement analysis procedures to be based on the actual section rather than on surface type alone. It is of particular value to the development and application of models to predict pavement performance. With these data, performance prediction models could be developed for much more refined pavement groupings. For this evaluation, 106 different pavement groupings were developed according to pavement type, use, and location. The roadway history file will allow additional groupings based on specific layer characteristics. The refinement in pavement groupings was considered to provide a significant advantage over the models that were developed for the interim models.

Pavement Life

The determination of typical pavement-life values for surface-type selection activities or other life-cycle cost analysis was found to be difficult. It was found that it was not reasonable just to use the number of years a pavement was in service before it was rehabilitated for the following reasons:

• The results reflect only the life of those that have been rehabilitated. Say, for instance, a pavement constructed 15 years ago was rehabilitated, and another pavement constructed at the same time is still in service and in good condition. A pavement-life estimate cannot be based only on the pavement that was rehabilitated, because that value does not take into account the surviving section.

• Many pavement sections are rehabilitated before their condition would warrant it. If a pavement was rehabilitated when its PQI was a 3.5, the data would not be representative of the number of years the pavement could be in service.

The typical number of years a pavement is in service is of importance to pavement management activities for overall planning and budgeting activities, but it is not valid to use for surface-type selection. An analysis of the number of years a particular pavement group lasts before it reaches some predetermined terminal-condition level is perhaps a better expression of the typical life of a pavement for surface-type selection activities.

Performance Prediction

For each of the 106 pavement groups evaluated, a typical annual loss rate for the PSR was developed, and a typical growth equation was developed for each of the pavement distresses for which were available. The results were reviewed, and a set of PSR loss coefficients and growth curves for each of the distresses was recommended for use in prediction of pavement performance for pavement management. The implementation would require some computer programming changes to take advantage of the data available in the roadway history file.

Recommendations for Future Activities

During the analysis, a number of instances were found in which pavements had substantial improvements in condition but no associated record of activities in the roadway history file. One of the possible reasons for these changes is maintenance activities that are not recorded into the pavement management system. It is recommended that a data-gathering process be developed to obtain information on maintenance activities that would affect a change in the condition ratings. Maintenance is a very important activity, and the maintenance activities and cost need to be a part of the pavement management data base to be fully effective. Cost analysis and cost comparisons are not possible until the data are collected and made available for analysis, and since maintenance can have a significant effect on performance, it is highly recommended that such a system be developed and implemented.

It is recommended that work be done to find ways to further improve the ride that results from pavement rehabilitation activities, particularly from overlays. Many of the current data indicate that the ride of new overlays often begins in the midthree PSR range. Improvement in the initial ride of a pavement may be able to add some life without large cost and will also improve the functional characteristics during the life of the pavement.

Efforts to improve the collection of data on condition should be continued. The current process is manual distress collection by visual inspection in the field. There may be variation in results because of lighting conditions and the subjectivity of the distress interpretation by the rater. Mn/DOT is presently proceeding with automating the distress data collection by using a video image data collection process and can limit the subjective distress interpretation effects in a controlled office environment.

It is recommended that there be continued work with the data available for model development. A wealth of available information currently is not utilized. The typical performance information available from the data can be used as another research data source for evaluating design, material, or construction parameters, and the effects they have on the pavement performance. The deflection data, for example, can be further analyzed to evaluate the structural characteristics of the bituminous pavements, which in turn can be compared with the data in the roadway history files. Differences in measured structural response to expected structural response may be useful in defining problem areas or as another input to predicting pavement life.

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Performance Models and Prediction of Increase in Overlay Need in the Danish State Highway Pavement Management System, BELMAN

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A primary requirement for a more reliable long-term analysis for maintenance management is to take into account the deterioration of pavement characteristics and the updating of pavement condition parameters after intervention. A significant effort has been invested in the general improvement of performance models in the Danish State Highway pavement management (PM) system, BELMAN, after discarding all recent models in the purchased, ready-made PM system. Models for performance of degradation and restoration of rough surfaces and for forecasting the need for increase in overlay within the analysis period have been successfully established. The roughness degradation and restoration model was developed by means of bump integrator measurements carried out on the Danish State Highway Network for several decades, including both routine and before-and-after measurements. The compound model was validated in EDP models simulating the development of roughness during 100 years of presumed rehabilitation. The forecasting model enables the PM system to forecast possible needs for future overlays and increases in calculated strengthening overlay thickness if strengthening is deferred. The model is based on the Danish analytical-empirical approach to pavement design. It uses the macroassumption, derived from extensive Danish experience in the variation of pavement E-modules, that referring the overall deterioration of the pavement to the asphalt concrete E-module is reasonable in a long-term view. Despite this rough assumption, the model has been verified and validated against an analysis of 2,000 back-analyzed, falling-weight deflectometer measurements from the State Highway Network with outstanding correlation. Implementing these and other models in BELMAN, it has been possible to use the PM system for its major purpose of forecasting and analyzing future perspectives under different budget constraints, giving explainable evolutions in main pavement characteristics.

The Danish pavement management (PM) system arose from pure ranking systems developed in the 1970s and early 1980s. The main shortcomings of these systems were their inability to optimize maintenance expenditures with limited budgets and to forecast future conditions and maintenance needs. To improve on this situation, a ready-made PM system was acquired, and the important task of verifying and validating (V&V) this system's models and output was begun.

It became clear that the major models had to be verified and validated separately and possibly replaced by more-correct models that were based on local conditions and research and also better-functioning models operating without artificially established limitations that were not justified by reality.

The three major groups of models engaged in the PM system procedure are these:

- Strategy models: These models indicate, on the basis of approved standards, when intervention ought to be considered and what maintenance solutions may be possible options.

• Performance models: These models show how economic and physical parameters will perform, taking deterioration and future intervention into account.

• Optimization models: From objective criteria, these models single out, from the list of possible options, the optimum plan of intervention that can be carried out within budget constraints.

The strategy models were verified against the Danish Road Standards. These models will now set limits indicating when functional and structural criteria have been exceeded and rehabilitation options may be possible. According to the Road Standards, these models would make rehabilitation a possible option according to the following criteria:

• The cost of repair exceeds the annual depreciation of a wearing course renewal;

• Routine measurements show that roughness is below the threshold value in the Road Standards;

• The structural residual lifetime is less than the standard design period; or

• The functional residual lifetime, based on a visual judgment, is less than 2 years.

The V&V of the strategy models was done easily, but output from the PM system's "what-if" analysis could not be validated against actual experience. Supposedly this was caused by inadequate performance models, because the analysis results depend heavily on the quality of the performance models.

The performance models extrapolate the present condition of structural and functional pavement parameters according to deterioration models and describe how parameter values are changed when intervention is carried out. Inadequate performance models were identified as the main cause for misleading and inconsistent analysis results. In 1989, a 3-year development project was undertaken to correct this situation. The preliminary results of this project are discussed in the following sections.

BELMAN Performance Models

To establish performance models for pavement behavior, testing accelerated many times is carried out if historical data are not available. The test models are adjusted later as real data become available. However, developing performance models from long-term performance data gives the optimum conditions for modeling with no error in the time scale.

In BELMAN the future functional condition is calculated by means of a model and with reference to actual conditions. The model is established on the basis of a regression analysis on historical data from measurements of roughness versus age of the pavement and from before-and-after roughness measurements when the pavement is rehabilitated. The future condition is calculated following the established model for deterioration and the model for increase in roughness, when overlaid, both referring to present roughness and age of pavement.

Assessment of the future structural condition in BELMAN is made by actual assessment of pavement E-modules using the falling-weight deflectometer (FWD) and by an analytical-empirical design procedure. The present need for overlay and the structural residual life are calculated. In the future condition the residual life is reduced by 1 year every year, and, subsequently, the need for strengthening overlay is increased according to the number of years since the last assessment of present structural adequacy. When pavement is overlaid, the structural residual life is upgraded equal to the calculated effect of strengthening the pavement.

Apart from the previously mentioned structural and functional performance models, the BELMAN system, of course, also contains economic performance models explaining the evolution in repair expenditure with age and users' vehicle operating cost in proportion to the roughness of the pavement surface. These models are not described in this paper, which deals only with the performance models for pavement behavior.

Functional Condition Performance

The primary parameter of functional condition considered for maintenance intervention is the surface roughness of pavement. However, with time the roughness of the surface changes as a result of traffic impact as well as maintenance intervention. To describe this phenomenon, two models are used, one to describe the degradation of the roughness and another to describe the restoration of the rough surface when the pavement is rehabilitated.

To verify and validate the models in the original, purchased PM system, a data analysis was launched. It was based on stored roughness data from the previous 7 years of bump integrator routine measurements in Denmark. All valid data were analyzed in relation to the age of the actual wearing course, together with a substantial number of before-and-after measurements on pavements that had been rehabilitated.

Typical results of this analysis are shown in Figure 1, giving the measured bump integrator measurements, BI, in relation to the years since the last rehabilitation, and in Figure 2, giving the increase in BI after rehabilitation. On

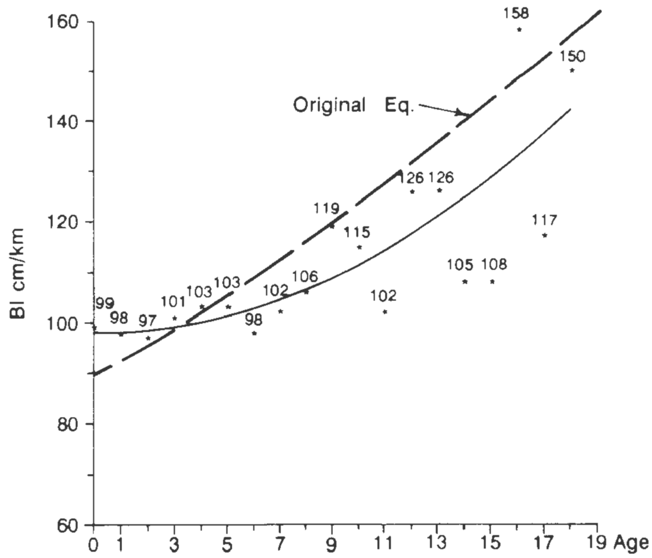


FIGURE 1 Roughness of AC wearing course versus age.

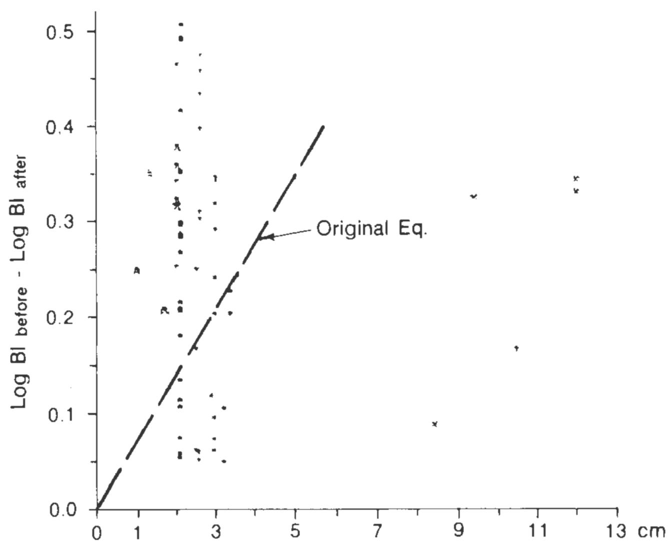


FIGURE 2 Roughness improvement versus applied thickness.

both plots the original models for degradation and restoration are also plotted. The two model equations are the following:

Degradation:

$$PSI_{\text{new}} = .06 * PSI_{\text{old}}$$

Restoration:

$$\Delta PSI = \frac{\Delta h}{35}$$

where Δh is the thickness of new overlay and PSI is correlated to BI with the equation

$$PSI = 12.5 - 4.25 * \log(BI)$$

It was immediately recognized that the fit of these two models to virtual data was very poor, especially for the restoration model, and hence they were both discarded.

Roughness-Degradation Model

To establish a new degradation model, data from the annual routine measurements were retrieved for 1982 through 1988, encompassing 1,400 section samples for which the average BI was evaluated for each 100 m. All sections were reviewed for invalid and misleading data. A total length of 2600 km of roads, or half of the road network, was included in the analysis.

All sections were sorted according to type of wearing course and proportioned according to length to give them equal weight before the relation between measured roughness and age of wearing course was analyzed. For the prevailing types of wearing courses in Denmark, populations large enough for a statistical analysis were obtained.

The prevailing types of wearing courses in Denmark are AC—asphalt concrete, DBM—dense bituminous macadam, and SD—surface dressing, 8/11 mm. Typical plots of the BI measurements for a 20-year range are shown in Figures 1, 3, and 4. For AC and DBM there is a clear tendency toward a more uneven surface with age, whereas for SD there seems to be a stable level of roughness independent of age.

Both AC and DBM were analyzed with a regression equation of the following composition, as recommended by Stevenson (*1*):

$$BI(AGE) = a * AGE^2 + b * AGE + c$$

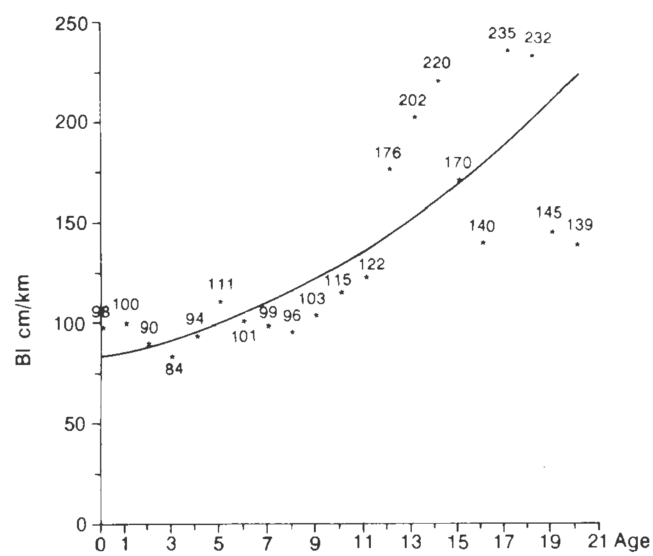


FIGURE 3 Roughness of DBM wearing course versus age.

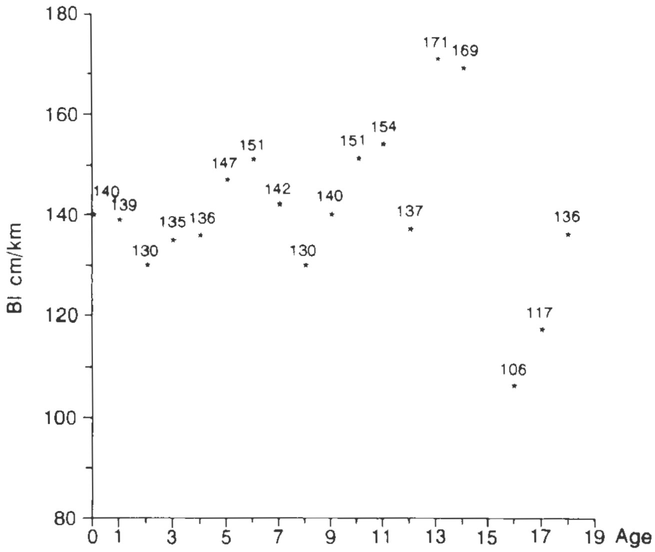


FIGURE 4 Roughness of SD wearing course versus age.

For AC, DBM, and AC + DBM, the following values were found for the constants in the equation and the corresponding R^2 value of the regression:

	a	*b*	*c*	R^2
AC	.141	.092	98.3	0.61
DBM	.242	2.100	83.6	0.61
AC + DBM	.270	−.140	93.5	0.51

For the time being, only the equation for AC + DBM was chosen as a practical application in the PM system. The analysis of SD data showed no clear correlation, but for political reasons the same relation as that established for AC + DBM was chosen to be used for SD. A plot of the combined results of AC and DBM is shown in Figure 5, which also shows the regression curve for the degradation model.

When BELMAN uses the model, it is vertically staggered to encompass the virtual measured value for the pavement section in question before future performance is determined.

Roughness Restoration Model

The set of data compiled for the degradation model also contained a substantial amount of before-and-after measurements of roughness. These were investigated for trends in improvements of the rough surface resulting from rehabilitation.

The first attempt was to verify whether all resurfacings fulfilling the Road Standards specifications would reach the same level of roughness after completion, independent of the roughness level before application. But this relation showed a very scattered tendency at that point, and no clear trend.

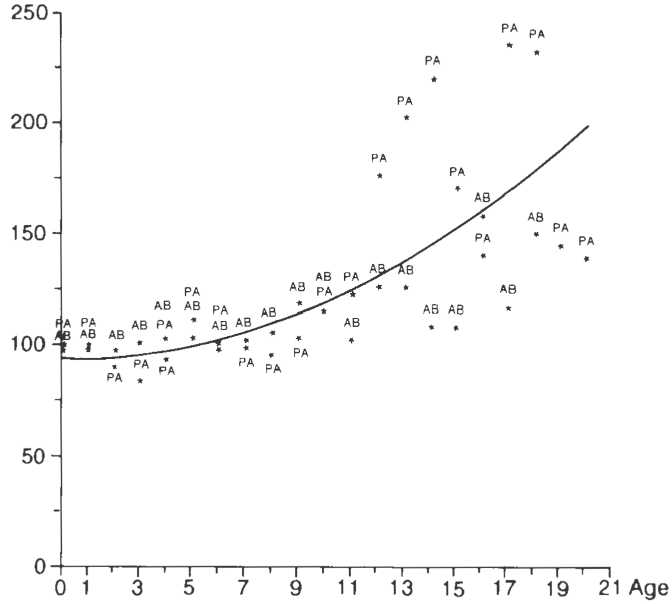


FIGURE 5 Roughness of AC and DBM versus age, with plot of the degradation model curve.

The second attempt was to investigate whether a relationship existed between the roughness level before and the relative improvement in the rough surface that can be obtained after application of a surface layer. For this purpose the percentage improvement of the current BI, which can be measured at any time, was chosen to reach the estimated BI after resurfacing. This approach showed an explainable trend for mixed asphalt concrete materials, but for SD the investigation showed that in the best case the percentage would be negative and in the political case the improvement would be nil.

Hence, it was decided that the improvement model for SD was fixed at 0 percent, which means that application of SD alone would not reduce the roughness of the road surface. However, for all mixed asphalt concrete materials, the trend was the same. For surfaces that were already smooth, the obtained percentage of improvement was small, but it grew with the increasing roughness of the existing road surface until the roughness reached a level that enabled full restoration with one only application. This approach was chosen for the further establishment of a roughness restoration model, to be tested in a V&V trail in which the model might be discarded.

Again, it was decided that only one model covering all types of asphalt concrete mix applications would be established. The regression curve representing the model should fall between two asymptotes representing the upper and lower limits of the percentage improvements expected; a regression analysis with an equation containing an arc-tangent function, which holds this significance, was chosen. The plot of the measured values and the restoration model curve is shown in Figure 6.

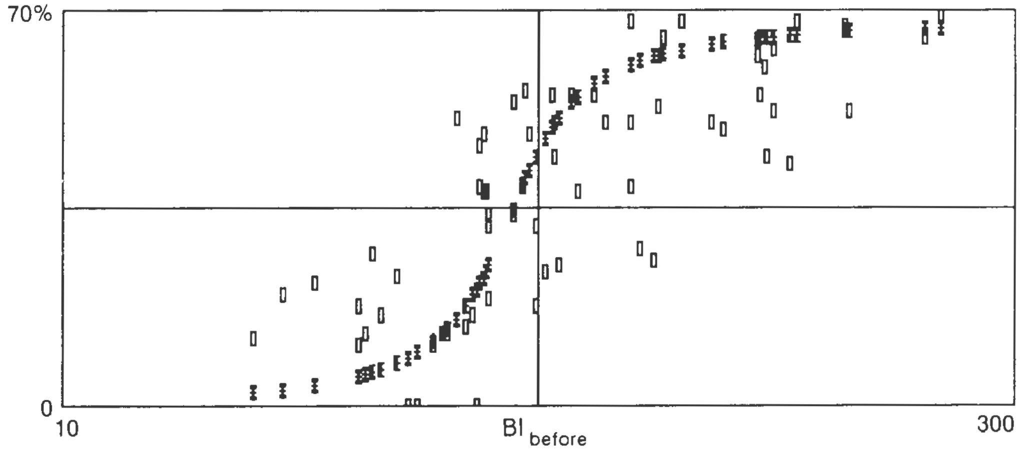


FIGURE 6 Percentage improvement versus roughness before application, with plot of the restoration model curve.

The final equation for the model, which has a correlation factor of 0.8, is stated as follows:

$$BI_{\text{after}} = BI_{\text{before}} * (1 - \%_{\text{BI}})$$

$$\%_{\text{BI}} = 33.77 + 22.88 * \text{atan}\,(.063 * BI_{\text{before}} - 9.214)$$

The model also fulfills the secondary demand that the estimated improvement in the rough surface after resurfacing give values in compliance with roughness criteria in the Road Standards specifications for asphalt concrete mixes. Following are the specifications' values for renewal of wearing courses:

	Percent Improvement	
BI_{before}	*Model*	*Road Standards*
100	5	—
150	40	20
200	63	40
250	66	52
300	66	60

The values indicate that the model gives higher estimates in the medium range than are demanded in the Road Standards. This may be because the model is based on actual values (which also show the greatest variance in this area) and because the Road Standards values are the criteria for acceptance, which contractors normally exceed to avoid failures. Therefore, this discrepancy is almost to be expected.

The shape of the model curve is explained as follows: very smooth road surfaces can be improved little in practice and will remain smooth after resurfacing, less-smooth road surfaces can be restored because of the leveling effect of the asphalt finisher and the experience of the crew, but very uneven road surfaces will need more than one application to eliminate the roughness completely.

Verification and Validation

To verify the combined degradation and restoration model, a computer simulation was performed; various normal and abnormal procedures for recurrent rehabilitation were simulated. The test was intended to show the stability of the model against exceeding the natural range of roughness levels and to investigate how the model behaved under abnormal circumstances.

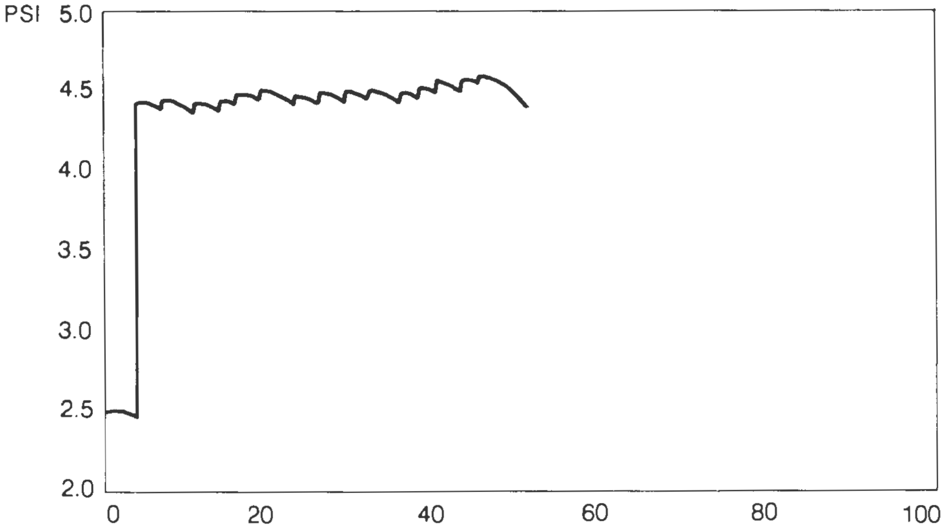
The test was made with repeated rehabilitation taking place either very frequently, as shown in Figure 7, or at the normally expected frequency, as shown in Figure 8. The frequency was selected randomly by the program and gave a simulation period of 50 to 130 years.

The results of these tests showed that the model behaved very well. It never dropped out of the scale, and the average roughness value of the surface throughout the tests was very close to the verified value from real road maintenance. Regardless of how roughly the model was treated, it remained stable.

Compared with the original model, the enhancement is significant. The original model exposed to the same tests fell or grew out of the scale and therefore had to be boundup in restrictive limitations that for the new model were completely unnecessary.

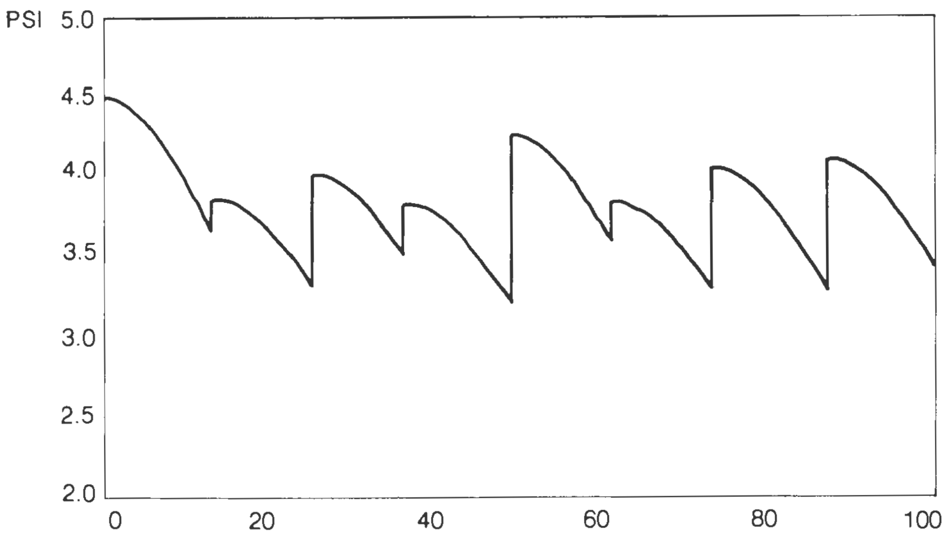
Evaluation of Roughness Models

Replacing the original model with the new one produced a very positive effect, changing the quality and reliability of the BELMAN output completely. Forecasts of residual



Year	Before	After
4	2.4	4.4
7	4.3	4.4
11	4.3	4.4
14	4.3	4.4
16	4.4	4.4
19	4.4	4.4
23	4.4	4.4
26	4.4	4.4
29	4.4	4.4
32	4.4	4.5
36	4.4	4.4
38	4.4	4.5
40	4.5	4.5
43	4.5	4.5
45	4.5	4.5

FIGURE 7 Model simulation with rehabilitation occurring frequently.



Year	Before	After
13	3.6	3.8
25	3.3	4.0
36	3.5	3.8
49	3.2	4.2
61	3.6	3.8
73	3.2	4.0
87	3.2	4.1
101	3.3	4.0
115	3.2	4.1
130	3.2	4.2

FIGURE 8 Model simulation with normal rehabilitation frequency.

functional life in "what-if" analysis declined and increased with a change in budget, as expected. An example of this can be seen in Figure 9, taken from the Danish Road Institute *Annual Pavement Condition Report* for the Danish State Highway Network.

Structural Condition Performance

Design procedures for the assessment of the need for strengthening overlays are well known and exercised in many ways. Some use empirically based methods with diagrams, and others use analytical calculations; common to all, however, is that the result of the design is only valid for the actual state of the structural condition for which it is calculated. When such models are introduced in PM systems to analyze future maintenance intervention needs, the effects of structural deterioration and deferred strengthening often are not taken into account. This was the case with the purchased PM system under discussion in this paper.

To improve this facility in BELMAN, the decision was made to develop a theoretical model based on the analytical-empirical model that has been used in Denmark for many years for the structural design of roads with flexible pavements. It was decided that deterioration of the pavement parameters would not be investigated at this stage of the BELMAN improvement project as long as the developed model could be verified and validated against the extensive experience of numerous FWD tests carried out on the Danish State Highway Network over many years.

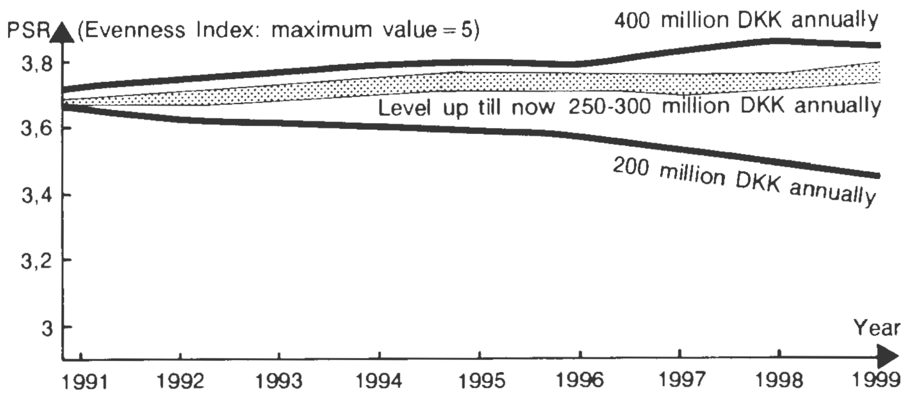


FIGURE 9 Example from "what-if" analysis of the evolution of roughness for different budgets.

Forecasting Strengthening Need

For all design procedures, the design period is established by technical, economic, and possibly political criteria that determine when bearing capacity is inadequate and calculation of strengthening need is necessary.

If calculated years to pavement failure are fewer than this accepted design period, normally a strengthening overlay design is executed to calculate actual strengthening need. However, in a management system such as BELMAN, future strengthening needs must also be forecast within the analysis period for pavements that today exceed the structural design period or for which the application of the strengthening overlay will be deferred.

To forecast future strengthening needs for pavements that have deteriorated beyond the present condition, a description is needed of how the pavement material properties will perform with time considering the effects of climate and traffic. However, to assess both the horizontal and the vertical scale for this structural performance model, the performance curve for each of the material parameters of each pavement layer must be known, as well as the time scale, which is dependent on the variation in daily climate during the lifetime of the pavement. Cold winters or very rainy seasons will cause faster deterioration than average conditions, and so forth. Although the Danish Road Institute has worked with the problem of long-term performance of material parameters for many years, the full description of the deterioration curves still seems far off, and more field investigations must be carried out before a more detailed description of pavement performance over time becomes available. Therefore, the decision was made to establish a simpler model that could be validated and implemented in the present version of BELMAN in operation.

Precondition for Prediction Model

The prediction model should describe the augmented need in strengthening overlay thickness in case reinforcement becomes necessary or is deferred. It should not necessarily describe the state of deterioration of the pavement. It was decided to base the model on the Danish design model and validate it against routine FWD tests from the State Highway Network. Previous experience led to the choice of degrading only the asphalt concrete E-module in the model calculations.

The Danish design model is based on an analytical-empirical model. By means of this model, the actual vertical stress in each layer interface and the horizontal strain at the bottom of the asphalt concrete layer are calculated under a standard wheel load. They are then compared with established criteria for permissible levels of stresses and strains in the structure interfaces.

The analytical part of the design model is primarily based on the fundamental equations of Boussinesq [Ullidtz (*2*)], developed for the description of the distribution of stress and strain in infinite isotropic half-space. These equations were made applicable by Kirk and Odemark (*3*) for use in a layered half-space by introducing the method of equivalent thicknesses. The method was later improved with the concept of stress-dependent subgrade material properties (*2*).

Criteria for permissible stress for materials in proportion to their actual Young's modulus and criteria for permissible strain for asphalt concrete materials in proportion to their binder content are derived empirically. The work was based on laboratory tests by Kirk (*4*) and full-scale investigations in STINA 2 (*5*) to assess the number of accumulated load repetitions that will cause pavement failure at a given level of stress or strain in the pavement structure. The formulated relationships are as follows:

$$\log(\sigma_{crit}) = .978 * \log(E) - .307 * \log(N_0) - 1.234 \qquad (E > 160\text{ MPa})$$

$$\log(\sigma_{crit}) = 1.161 * \log(E) - .307 * \log(N_0) - 1.638 \qquad (E < 160\text{ MPa})$$

$$\log(\epsilon_{crit}) = \log(BF) - .176 * \log(N_0) + 2.533$$

where

σ_{crit} = critical stress,
ϵ_{crit} = critical strain,
E = E-module of the material,
N_0 = standard axle load repetitions, and
BF = bitumen factor, reflecting the type and content of binder (4).

In the design procedure the calculated stresses and strains in the proposed pavement structure are compared with the critical values, and if these values are exceeded, the structure is adjusted and recalculated until consistency with the criteria is obtained, as described by Ertman and Stubstad (6).

The analytical-empirical model is also a deterioration model for the structural adequacy of pavement bearing capacity. By calculating the actual stresses and strains in an existing pavement structure, solving equations for σ_{crit} and ϵ_{crit} with respect to the traffic load, and using calculated stresses and strains as present critical values, the residual structural lifetime will be calculated and expressed in number of load repetitions, which, with known annual daily traffic (ADT), can be recalculated to number of years to pavement failure. When calculated stresses and strains are based on E-modules for each layer in the pavement assessed from back-analysis of FWD measurements, the residual structural life will represent the present structural condition of the pavement and hence be used in the forecasting model.

The entire Danish State Highway Network has been surveyed for bearing capacity on a routine basis since 1988 by means of FWD tests [Schmidt (7)] followed by back-analysis calculations [Jensen and Leerskov (8)]. All calculated E-modules from the asphalt concrete, subbase, and subgrade left a clear picture that only the E-module of the asphalt concrete layer significantly changed the level of magnitude in proportion to the calculated structural residual lifetime of the pavement. Therefore, it was decided from the beginning only to change the magnitude of the asphalt concrete E-module with time, unless the V&V test discarded that decision.

Model Design

The algorithm in the model should, by use of the design procedure, calculate the residual structural life of the existing pavement structure. The layer thicknesses and E-module of each layer in the structure were known from the FWD measurements, and the critical number of standard axle load repetitions was derived and expressed in number of years to pavement failure. This calculated residual life should be reduced by 1 year every year. Each time the residual lifetime was reduced, the equivalent reduction in the asphalt concrete E-module was calculated as the reduced asphalt concrete E-module that gave the degraded pavement 1 year less residual lifetime, and the need of overlay thickness giving the degraded pavement a residual lifetime equal to the design period was calculated. When the model reached a residual lifetime of less than 1 year, the procedure was stopped and the need for strengthening was not increased further.

For an initial test of the assumption in the model, FWD test points with a back-analyzed and temperature-corrected E-module and derived structural residual lifetime were selected, with different numbers of years to pavement failure representing different stages of pavement degradation. The tests were made by successively reducing the asphalt concrete E-module and calculating the reduced residual lifetime. The plot of the results from one of the calculated test roads is shown in Figure 10, where each data point represents the sequential results of calculations for test data having different initial residual lifetimes. The plot shows that the results are spread continuously within the band, with increasing strengthening need in proportion to the reduction in residual lifetime caused by reduction in the asphalt concrete E-module. The median curve within the band can be drawn as representative for the prediction model, but the model implemented operates as the algorithm and makes individual calculations for each FWD-tested point on the section.

Because of the smooth evolution in overlay thickness required as the calculated bearing capacity deteriorates, as well as the similar plots from calculations on other types of pavement structures showing the same picture, the model concept was approved for the V&V test.

Verification and Validation

For verification and validation of the model, the median curve was compared with the result from another analysis made on the distribution of assessed overlay needs from more than 2,000 FWD tests carried out on the entire Danish State Highway Network. The plot in Figure 11 shows the parallel set of curves representing different traffic load levels, giving for each curve the correlation between overlay need and structural residual lifetime. The median curve from the prediction model follows the parallel curves, which is taken as validation of the prediction

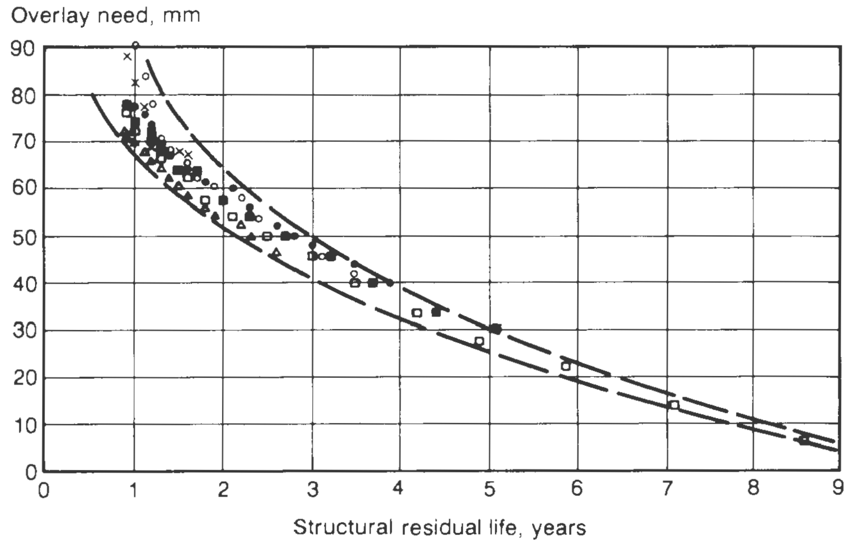


FIGURE 10 Strengthening need in proportion to residual lifetime.

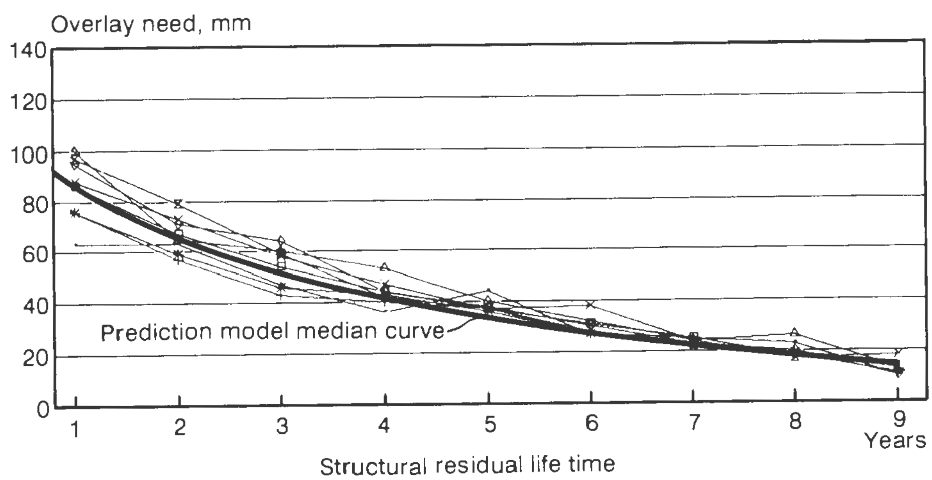
model because it follows the same average degradation curve as those for evaluated existing pavements in the State Highway Network. The curve is shown corresponding to a design period of 9 years, which was used in the overlay need analysis, and it is not drawn below 1 year, because existing pavements normally have at least some residual lifetime left.

Evaluation of Structural Forecasting Model

With implementation of the previously described prediction model in BELMAN, the PM system now updates the assessment of actual need of overlay thickness in proportion to time and according to the present stage of degradation of the pavement's bearing capacity.

As can be seen from Figure 12, with the model it should be possible to follow the actual structural performance curve of the pavement. Of course, seasonal variations in climate and road wear change from year to year, and thus the model may not be absolutely correct. However, the prediction will be much more accurate than making no reassessment of the overlay thickness needed.

Furthermore, in the Danish PM system's procedure for data acquisition, the strengthening need is recalculated from actual FWD tests, which are made as routine surveys



Traffic load levels:

0-19 ESA — 20-49 ESA — 50-99 ESA — 100-199 ESA

200-299 ESA — 300-399 ESA — 400-499 ESA — 500-599 ESA

FIGURE 11 Correlation between actual overlay need and prediction model curve.

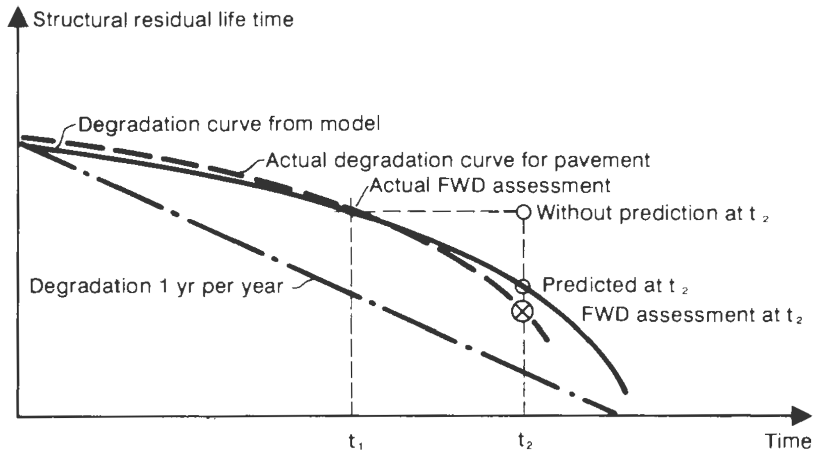


FIGURE 12 The prediction model acting on a presumed degradation curve.

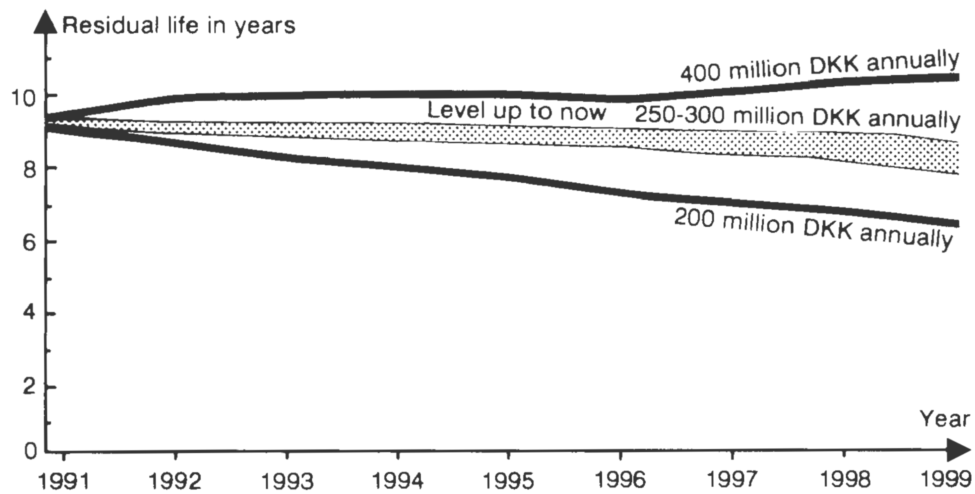


FIGURE 13 Influence of budget level on development of residual life.

the last 4 years of the structural residual lifetime of the pavement. Therefore, the model becomes very precise in the most critical part of the degradation curve.

Figure 13, taken from the Danish Road Institute *Annual Pavement Condition Report,* indicates the results of the analysis of the influence of budget level on structural residual lifetime in the highway network achieved by means of BELMAN after implementation of the model.

Conclusion

Performance models are very important in PM systems for adjusting measured conditions to presumed future conditions when the intervention option is executed in the planning stage, especially with a PM system that optimizes among several maintenance options for each subsection.

Without performance models, deferring maintenance would have no technical or economic consequences in planning. Technically, it would be impossible to follow the development of the residual lifetime of the road network at different funding levels, and economically, infinite deferring of maintenance would have the highest benefit in planning—which of course is completely unrealistic.

However, development of the performance models also revealed that models cannot just be borrowed from another environment but that with repeated measurement data, it is worthwhile to develop performance models. Throughout the work it was highlighted that good performance in the verification and validation test and after implementation in the BELMAN pavement management system is of the greatest importance for the credibility of the output.

The models made it possible to analyze the relationship between funding levels and the development of the functional and structural residual lifetime of the road network, which was the main objective.

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Mechanistic Performance Model for Pavement Management

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A framework for a pavement management system employing mechanistic performance submodels for pavement behavior is presented. These performance submodels explain the development of the physical distresses in fundamental terms. This approach enables the individual distress modes to be addressed in pavement management strategies. It also forms the basis for a dynamic programming optimization scheme. The performance submodels are based on a reliability formulation incorporating full-distribution uncertainty information of the variables. They provide the transition probabilities for the optimization that determines the optimal strategy for rehabilitation from a set of alternatives subjected to management and operational constraints. The optimization also yields the expected annual performance in terms of the distresses and the expected capital outlay required to implement the strategy.

One essential element in an effective pavement management system (PMS) is an adequate characterization of the existing pavement condition of a pavement section. This usually takes the form of a composite index such as the pavement condition index (PCI) as used in PAVER (*1*), the PSC used in RAMS (*2*), or the PCR used in WSPMS (*3*). However, if the individual distress modes are not masked by such composite indexes, such as the PMS implemented by the California Department of Transportation (Caltrans)(*4*), the correct rehabilitative remedy can be prescribed to address the individual deficiencies.

A framework for a PMS using mechanistic distress submodels for predicting pavement performance is presented. These submodels are formulated within a probabilistic framework that allows for stochastic consideration of pavement performance so that a "dynamic" or "closed loop" decision process can be used. An optimal rehabilitation policy is determined in which only the present decision needs to be implemented and future decisions are conditional on the actual performance of the pavement.

Since pavement condition is characterized in terms of the individual distress modes, the deterioration in pavement performance for each attribute can be individually appraised and rehabilitation alternatives can be prescribed according to some rehabilitation-condition policy that specifies the appropriate measure to correct the deficiency. The level of pavement performance can then be managed by establishing minimum acceptable levels and specifying the minimum level of reliability for a rehabilitation alternative for each mode of distress. The latter is the maximum tolerable probability that the pavement condition will fall below acceptable levels in the respective distress modes during the minimum life of the rehabilitation.

Overview of Stochastic Mechanistic PMS

An overview of the proposed stochastic mechanistic Pavement Management System (StoMe) (*5*) is shown in Figure 1. It is composed of three distinctive features:

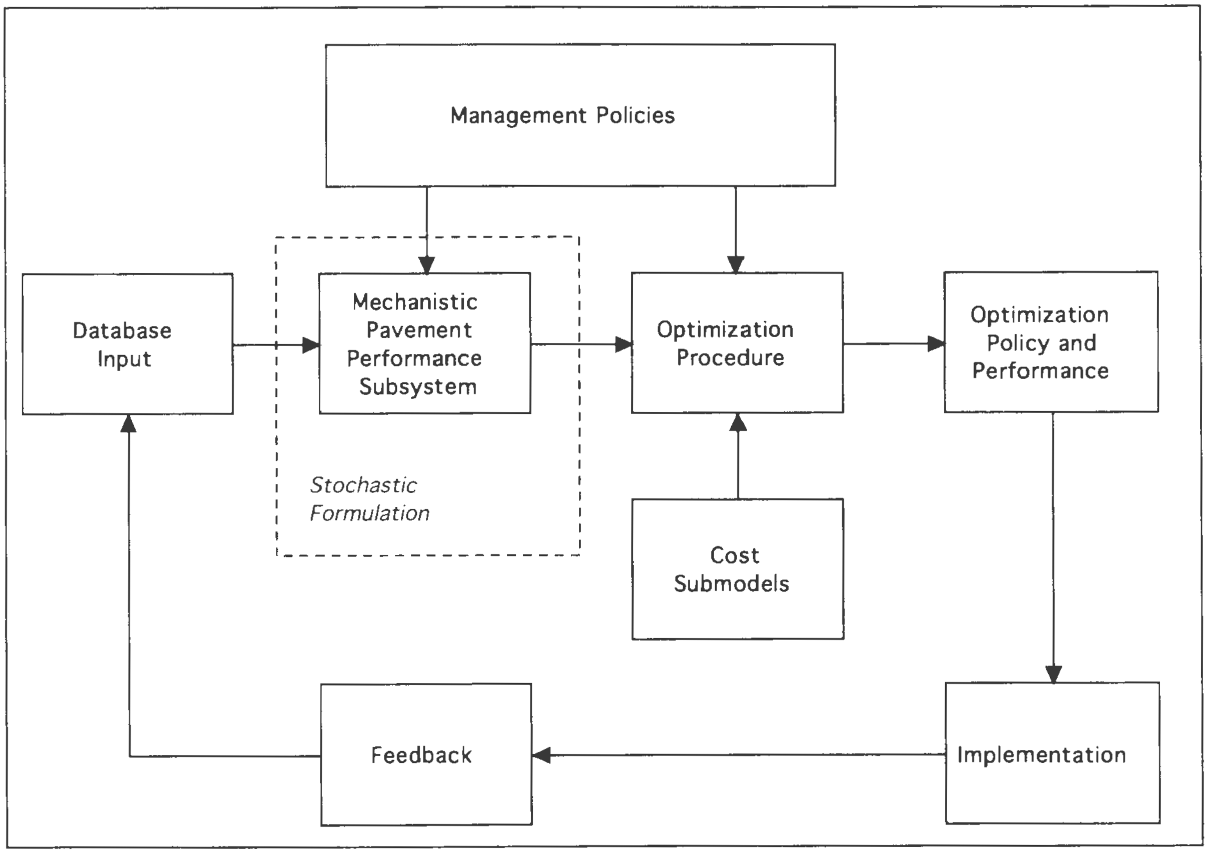


FIGURE 1 Overview of stochastic mechanistic PMS.

1. Mechanistic pavement performance subsystem,
2. Stochastic analysis formulation, and
3. Optimization procedure.

This system recognizes that the input variables are stochastic in nature. Accordingly, the mechanistic models for the individual distress modes are formulated in a probabilistic framework, incorporating state-of-the-art structural reliability methods. Given the uncertainty in the input variables, a probability distribution for the level of distresses is obtained instead of a single deterministic level of distress for pavement deterioration. The probabilities of transition from one condition state of the pavement section to another can then be derived, providing one set of inputs to the optimization subsystem.

The dynamic programming technique is employed in the optimization component, by means of which an optimal rehabilitation policy in terms of discounted net life-cycle costs over the planning horizon for the pavement section is derived, subject to specified management operational constraints. These constraints can be aggregated for each pavement section to obtain the network optimal policy.

Mechanistic Pavement Performance Subsystem

For the purpose of setting up the framework for the mechanistic PMS, only the fatigue cracking mode of distress from repeated traffic loading is now modeled here. The implementation is representative of other modes of distress, differing only in the exact details of the mechanistic model representation.

Invariably, the mechanistic modeling is achieved in two stages as shown in Figure 2. The level of the controlling structural response, the stress or strain in the pavement section causing the initiation and propagation of the distress, is first determined through some structural analysis of the pavement. The level of distress in the individual modes is then determined as a function of the structural response via the mechanistic distress submodels.

Structural Analysis Component

At present, since target strategies only are required at the network management level, and because of its simplicity

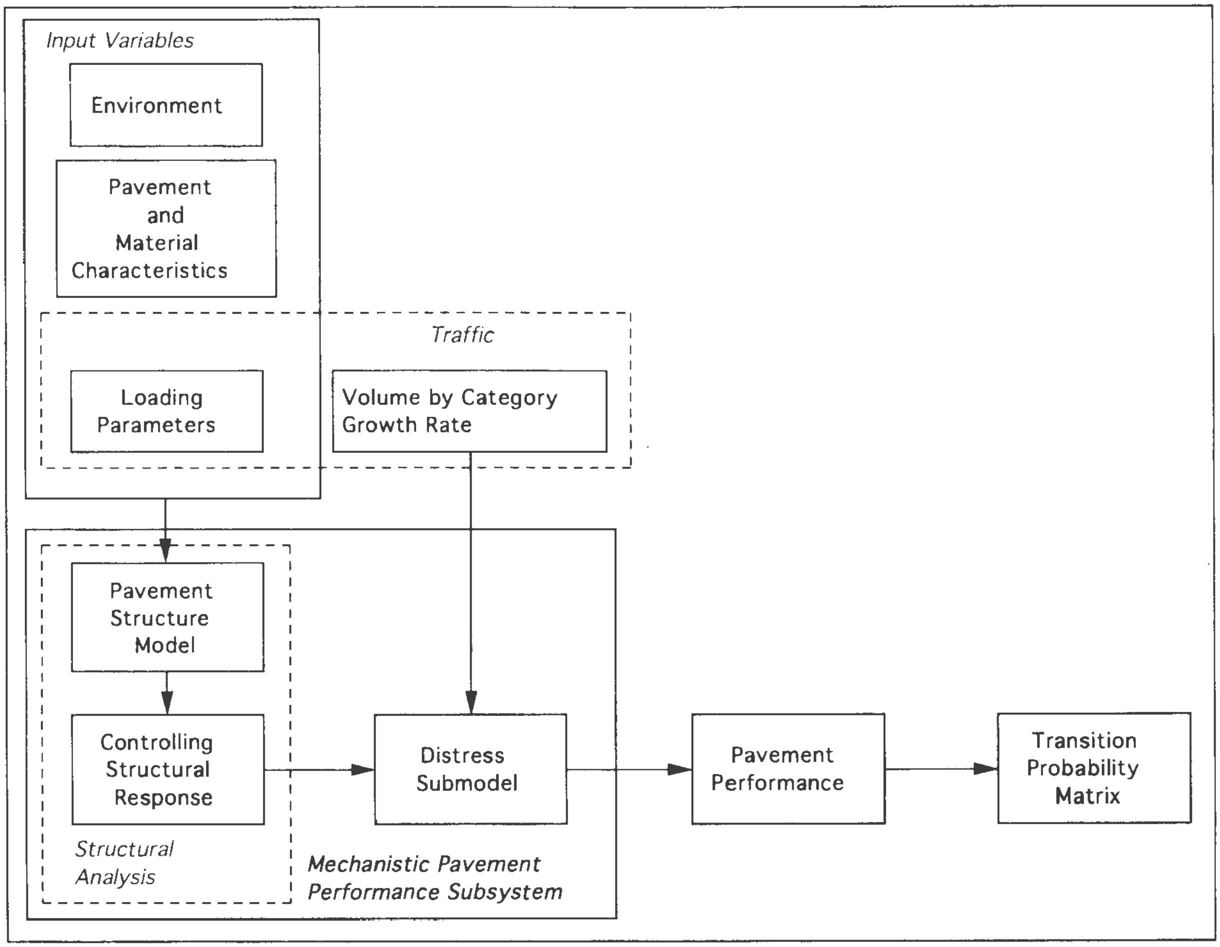


FIGURE 2 Mechanistic pavement performance subsystem.

and economy, the multilayered model—in particular, the ELSYM program (6) developed at the University of California, Berkeley—is incorporated into StoMe for the structural analysis module. This does not, however, preclude the use of more accurate methods such as the finite-element method.

In any case, several modifications to existing analysis programs would be necessary for successful implementation. Figure 2 shows the relations between the structural analysis and distress submodels, and the input associated with each component. The input data set must be enlarged to include traffic, environmental, material, and condition characterization. In addition, the input data set is no longer deterministic, as would be the case in existing structural analysis programs, but must be stochastic, so each random variable is specified by its mean, standard deviation, and distribution type. Furthermore, the program must be modified for the interface with the distress submodels, by which the controlling structural response for each distress mode is passed on to the distress submodel component.

Distress Submodel Component

Each distress submodel defines a performance function in which the level of distress may be determined as a function of the controlling structural response according to some damage criterion. A commonly accepted damage criterion for fatigue cracking derived from AASHO Road Test results (7) is adopted here:

$$N_f = 18.4C\left(4.325 \times 10^{-3}\epsilon_t^{-3.291}\left|\frac{E^*}{6.89}\right|^{-0.854}\right) \tag{1}$$

where

N_f = allowable number of repetitions for 45 percent cracking at maximum tensile strain ϵ_t in the asphalt-bound layer,
E^* = dynamic asphalt mixture modulus (kPa), and
C = the factor accounting for asphalt content and degree of compaction suggested by Pell and Cooper (8).

The cumulative damage hypothesis of the linear sum of cycle ratios may be applied to determine total fatigue distress caused by a range of strain levels (*9,10*). In this manner the performance function for fatigue cracking may be expressed as

$$g_{wT}(\mathbf{x}) = L_w - \sum_{t=1}^{T} \sum_{i} \left\{ \frac{n_{it}}{N_i} \right\} - L_u \tag{2}$$

where

$\mathbf{x}$ = vector of input variables in the mechanistic model,
N_i = allowable number of load applications at strain level ϵ_i according to Equation 1,
n_{it} = actual number of load applications in the tth year at the same strain level ϵ_i,
L_w = damage index corresponding to w percent cracking, and
L_u = damage index of the initial condition of the pavement, so that $(L_w - L_u)$ is the "remaining life" of the pavement with respect to w percent cracking, assessed by the sum of cycle ratios.

The damage index is defined so that a value of unity denotes the extent of damage given by the failure criterion (e.g., 45 percent cracking). Correspondingly, the damage index Lw is given by the ratio Nw/Nf, where Nw is the number of load cycles to w percent cracking at the same strain level. For example, the damage index for 10 percent cracking (L10) is 0.72 (or 13.3/18.4), since N10 has the same form as Nf in Equation 1, except that the coefficient is 13.3, from the AASHO Road Test findings (7).

Stochastic Formulation

The condition of the pavement at any time can then be characterized by the limit-state surface $\mathcal{L}_x = [\mathbf{x}:g_{wT}(\mathbf{x}) = 0]$ according to

$$F = [\mathbf{x}:g_{wT}(\mathbf{x}) \leq 0] \tag{3}$$

$$S = [\mathbf{x}:g_{wT}(\mathbf{x}) \geq 0] \tag{4}$$

where F and S are the fail and safe sets, respectively, with respect to w percent cracking and $\mathbf{x}$ is the vector of input variables in the mechanistic model as shown in Figure 2. When the sum of cycle ratios exceeds the "remaining life" of the pavement $(L_w - L_u)$, $g_{wT}(\mathbf{x}) \leq 0$ and the pavement would be deemed to be in the fail set, that is, exceeding w percent cracking. This then forms the framework for the probabilistic formulation of the mechanistic performance submodel.

In general, the condition of a pavement in a particular distress mode may be characterized by two damage indexes, L_{w_j} and L_{w_k}, representing the lower and upper bounds, respectively. Thus, for a pavement section with initial state S_1 of damage index L_u, the probability of finding the pavement section in the distress state S_2 bounded by L_{w_j} and L_{w_k} after another T years of traffic operations is given by

$$P_F = P[g_{w_jT}(\mathbf{x}) < 0] - P[g_{w_kT}(\mathbf{x}) < 0] \tag{5}$$

This is the transition probability from state S_1 to S_2. A matrix of these probabilities from states S_i to all possible states S_j forms the transition probability matrix for the optimization module of the PMS.

Each term on the right-hand side of Equation 5 is evaluated as

$$P[g_{wT}(\mathbf{x}) \leq 0] = \int_{g_{wT}(\mathbf{x}) \leq 0} f_x(\mathbf{x})\, dx \tag{6}$$

where $f_x(\mathbf{x})$ is the joint probability density of variables x_1, $x_2, \ldots, x_n$.

The exact solution of Equation 6 would require an n-fold integration of the joint probability density $f_x(\mathbf{x})$ of the n basic variables, which would become computationally intractable if the number of variables exceeded just a few, except in special cases, when the integral may be obtained in closed form. Instead, an approximate but reasonably accurate solution is determined using the first-order reliability method (FORM) (*11,12*). FORM incorporates the full-distribution probabilistic information of the variables in determining the solution, unlike the MVFOSM method adopted in existing probabilistic design approaches (*13*), which uses only the first and second moments' information and lacks the invariance to the formulation of the performance function of the distress mode (*14*). The proposed methodology may be easily extended to the case of multiple distress modes using the principle of cut-sets (*15*), which is the crucial point for such a mechanistic PMS.

Optimization Procedure

When growth in traffic volume is considered, the transition probabilities are expected to change with time (*12*). The assumption of a homogeneous Markovian process employed in some systems (*16,17*) then would not be valid. Furthermore, because of the overlays that may be placed on the pavement section, the pavement strength and corresponding transition probabilities change. The process is nonstationary, and the set of feasible pavement states expands with time. In this case, the dynamic programming approach (*18*) is appropriate for determining a rehabilitation policy that minimizes some objective value over the planning period.

Pavement Condition State

In view of the mechanistic modeling of pavement behavior, the pavement condition state will also have to be characterized in mechanistic terms. Accordingly, two pavement features are important in this characterization—pavement distress condition and pavement structure.

The pavement distress condition may be denoted by a vector $(\mathbf{d}_1, \mathbf{d}_2, \ldots, \mathbf{d}_m)$ where $\mathbf{d}_m$ is the distress level for the mth distress mode. The level of distress for each distress mode is discretized into a set of collectively exhaustive, mutually exclusive bounds corresponding to varying extent of damage, represented by the damage index. This may be expressed in a damage-level table such as Table 1 for the case of fatigue cracking. The greater the number of levels, the finer is the discretization and the more accurate, but computationally longer, is the optimization model.

The pavement structure may be denoted by a vector $(\mathbf{n}_0, \mathbf{n}_1, \ldots, \mathbf{n}_q)$. The first element in the vector, $\mathbf{n}_0$, denotes the number of underlying cracked asphalt layers. The other terms record the sequence of q modifications to the original structure. If overlays and routine maintenance alternatives are considered, only overlay alternatives will modify the pavement structurally, and only these decisions are recorded in the vector. A number of routine maintenance activities may be performed between these overlays. These do not modify the pavement structurally, so the transition probabilities do not change; hence they are not recorded in the vector. For example, a pavement structure described by $(1, \lambda_{\upsilon 2}, \lambda_{\upsilon 1})$ is composed of two overlays, namely, $\lambda_{\upsilon 2}$ on the original pavement followed by $\lambda_{\upsilon 1}$, each belonging to a set of overlay alternatives, and one cracked layer (i.e., the original asphalt layer). Together with the distress condition vector, these two vectors uniquely define the state of the pavement section at any point in time.

Optimality Equation and Optimal Policy

The objective function of the problem may then be formally defined as $V_k(\mathbf{i},\mathbf{j})$ = minimum expected net present cost from the start of year k to the end of the planning period, given that the distress condition vector is $\mathbf{i}$ and the pavement structure vector is $\mathbf{j}$. By this definition, the aim of the optimization is to determine a policy of rehabilitation treatment that will achieve the objective function at the start of the planning, namely, $V_0(\mathbf{i}_0, \mathbf{j}_0)$, where $\mathbf{i}_0$ and $\mathbf{j}_0$ are the initial distress condition and pavement structure vectors, respectively.

On the basis of this objective function, the optimality equation for obtaining the objective function at every year k, formally called a stage, may be expressed as follows, where y is the number of stages for the transition defined by

$$V_k(\mathbf{i},\mathbf{j}) = \min \begin{cases} \lambda_{\upsilon 1}:\ r_1 \cdot C_a(\mathbf{i},\lambda_{\upsilon 1}) + r_2 \cdot C_u(\mathbf{i},\lambda_{\upsilon 1}) + \\ \sum_{\mathbf{i}_2} \left\{ P(\mathbf{ij},\mathbf{i}_2\mathbf{j}_2,\lambda_{\upsilon 1},k,y) \cdot \left[\frac{r_3 \cdot y \cdot U(\mathbf{i},\mathbf{i}_2)}{(1+r)^{y/2}} + \frac{V_{k+y}(\mathbf{i}_2,\mathbf{j}_2)}{(1+r)^y} \right] \right\} \\ \vdots \\ \lambda_{\upsilon p}:\ r_1 \cdot C_a(\mathbf{i},\lambda_{\upsilon p}) + r_2 \cdot C_u(\mathbf{i},\lambda_{\upsilon p}) + \\ \sum_{\mathbf{i}_2} \left\{ P(\mathbf{ij},\mathbf{i}_2\mathbf{j}_2,\lambda_{\upsilon p},k,y) \cdot \left[\frac{r_3 \cdot y \cdot U(\mathbf{i},\mathbf{i}_2)}{(1+r)^{y/2}} + \frac{V_{k+y}(\mathbf{i}_2,\mathbf{j}_2)}{(1+r)^y} \right] \right\} \\ \lambda_{O1}:\ r_1 \cdot C_a(\mathbf{i},\lambda_{O1}) + r_2 \cdot C_u(\mathbf{i},\lambda_{O1}) + \\ \sum_{\mathbf{i}_2} \left\{ P(\mathbf{ij},\mathbf{i}_2\mathbf{j}_2,\lambda_{O1},k,y) \cdot \left[\frac{r_3 \cdot y \cdot U(\mathbf{i},\mathbf{i}_2)}{(1+r)^{y/2}} + \frac{V_{k+y}(\mathbf{i}_2,\mathbf{j}_2)}{(1+r)^y} \right] \right\} \\ \vdots \\ \lambda_{Oq}:\ r_1 \cdot C_a(\mathbf{i},\lambda_{Oq}) + r_2 \cdot C_u(\mathbf{i},\lambda_{Oq}) + \\ \sum_{\mathbf{i}_2} \left\{ P(\mathbf{ij},\mathbf{i}_2\mathbf{j}_2,\lambda_{Oq},k,y) \cdot \left[\frac{r_3 \cdot y \cdot U(\mathbf{i},\mathbf{j}_2)}{(1+r)^{y/2}} + \frac{V_{k+y}(\mathbf{i}_2,\mathbf{j}_2)}{(1+r)^y} \right] \right\} \\ \qquad \text{for} \quad k = 0, 1, \ldots, H-1 \end{cases} \quad (7)$$

$$y = \begin{cases} y_\lambda & \text{if} \quad k + y_\lambda \le H \\ H-k & \text{if} \quad k + y_\lambda > H \end{cases} \quad (8)$$

where

H = number of stages (years) in the planning period;

y_λ = minimum life of rehabilitation activity λ, during which nothing should be done to the pavement section;

$\lambda_{\upsilon 1},\lambda_{\upsilon 2}, \ldots, \lambda_{\upsilon p}$ = elements of Λ_υ, the set of overlay alternatives considered;

$\lambda_{O1},\lambda_{O2}, \ldots, \lambda_{Oq}$ = elements of Λ_O, the set of routine maintenance alternatives considered;

$\mathbf{i}_2,\mathbf{j}_2$ = new condition and pavement structure states as a result of the rehabilitation;

$C_a(\mathbf{i},\lambda)$ = agency cost for implementing alternative λ at distress condition $\mathbf{i}$;

$C_u(\mathbf{i},\lambda)$ = cost to users as a result of the ongoing rehabilitation activity at distress condition $\mathbf{i}$;

TABLE 1 Damage Levels for Fatigue Cracking

Damage Level	Description	Damage Index
D1	>45% cracking (severe)	>1.0
D2	10–45% cracking (intermediate)	0.72–1.0
D3	<10% cracking (minimal)	0.0–0.72

$U(\mathbf{i,i_2})$ = average annual excess cost to users as a result of the pavement condition's transition from **i** to $\mathbf{i_2}$;
r = discount rate;
r_1, r_2, r_3 = parametric weightings of costs to agency and users; and
$P(\mathbf{ij,i_2j_2},\lambda,k,y)$ = transition probability for rehabilitation activity λ, from pavement state **ij** at stage k to pavement state $\mathbf{i_2j_2}$ at y stages ahead, obtained via Equation 5.

$V_H(\mathbf{i,j})$ is the objective function at the boundary of Equation 7 (i.e., at the end of the planning period). Formally, it is the long-term expected costs obtained by following an optimal rehabilitation policy from that time on. In the economic analysis of pavement life-cycles, it is usual to characterize the value of the pavement section at the end of the cycle by a salvage value (*19*). In this way, $V_H(\mathbf{i,j})$ may be assessed as negative costs, by simple proportion of the cost of the last overlay E_k, according to

$$V_H(\mathbf{i,j}) = -\left(\frac{L_R}{L_O}\right)E_k \quad (9)$$

where L_R and L_O are the remaining and expected lives of the last overlay, respectively.

The optimality equation provides the mechanism for recursively determining the value of the objective function at the start of the planning period $V_0(\mathbf{i_0,j_0})$ beginning with the values $V_H(\mathbf{i,j})$ at the boundary. Thus, the objective value at stage $k = n - 1$, $V_{n-1}(\mathbf{i,j})$ is found according to Equation 7. The corresponding rehabilitation alternative that minimizes the objective function at each state forms the optimal rehabilitation policy for this stage. Then with $k + 1 = n - 1$ in the equation, the objective value at stage $k = n - 2$, $V_{n-2}(\mathbf{i,j})$, is derived from $V_{n-1}(\mathbf{i_2,j_2})$ and $V_H(\mathbf{i_2,j_2})$ determined from the previous step. In this recursive fashion, the objective value at the start of the planning period $V_0(\mathbf{i,j})$ is eventually determined with $k = 0$. Furthermore, the set of optimal rehabilitation alternatives for each state at every stage forms the optimal rehabilitation policy for the problem.

The problem defined by Equations 7 and 8 may be represented by a path diagram. An example is shown in Figure 3 for the case of a 5-year planning period with two condition states: cracked denoted by 1 and uncracked denoted by 2. Only two alternatives are considered: "do

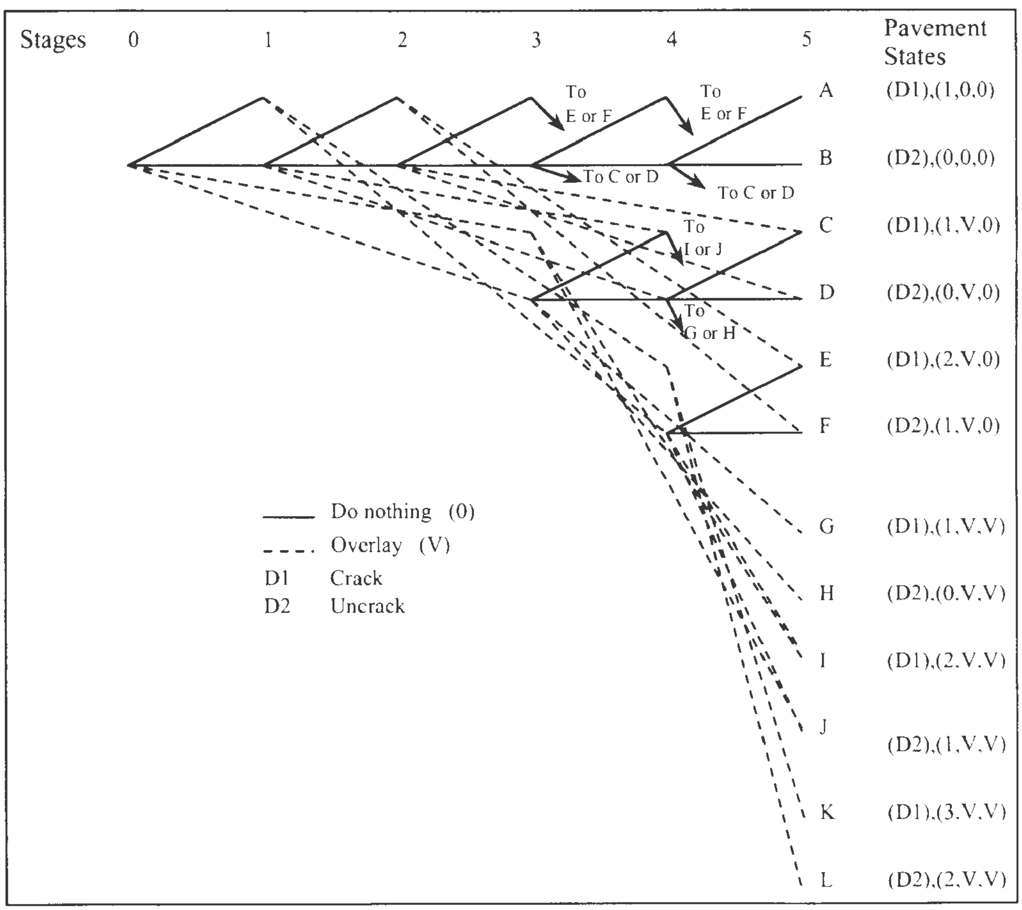


FIGURE 3 Path diagram for dynamic programming optimization.

nothing" (0) or an overlay (V). In the example, a minimum life of 3 years has been assumed for an overlay. In general, a computer program is required. A transition mapping in terms of a computer code describes the possible paths in the path diagram.

From the optimal policy, two other results of value to management can be determined, expected performance and expected capital outlay. The expected performance gives the probability that the pavement section will be found in the various states at the beginning of each year in the planning horizon when the optimal rehabilitation policy is implemented. On the other hand, the expected capital outlay gives the expected cost of rehabilitation to be expended by the agency at the start of each year, expressed in current dollars. Depending on the actual performance of the pavement section, the true capital expenditure can be higher or lower than that expected.

If all costs are computed in dollars per lane-mile, the sum of the expected annual capital outlay weighted by the lane-miles of the section yields the expected annual budget required to implement the optimal policy for the network. Similarly, the sum of the expected performance of each pavement section weighted by the lane-miles yields the fraction of the network that can be expected in the various pavement states at the beginning of each year.

Management Policy

A set of management policies serve as input to the optimization module. These policies include the range of rehabilitation alternatives and their corresponding minimum lives, the cost weightings r_1, r_2, and r_3 of Equation 7, and the discount rate. Management can also control the performance of the pavement section by specifying a performance criterion that defines the minimum reliability of the rehabilitation activity or, conversely, the maximum probability of transition to failure.

Furthermore, in view of the mechanistic distress modeling of pavement performance, the appropriate rehabilitation treatment is specified via a rehabilitation-condition policy. This is a matrix of rules for determining which rehabilitation treatment should be considered for implementation after the pavement condition has been surveyed. In the alternatives are overlays or routine maintenance, one reasonable rehabilitation-condition policy for the condition states considered in Table 1 is presented in Table 2. Under this policy, pavement sections considered failed with severe cracking are overlaid. In this case, only overlay alternatives are considered in the optimality equation of Equation 7. When the pavement is in other conditions, all treatment options are available for consideration.

The consideration should be based purely on technical feasibility. For example, routine maintenance should not

TABLE 2 Rehabilitation-Condition Policy

	Rehabilitation Alternatives			
		Overlay Thickness Alternatives		
Damage Level	Routine Maintenance	Thin	Medium	Thick
D1		X	X	X
D2	X	X	X	X
D3	X	X	X	X

NOTE: Crosses indicate alternatives to be considered in optimization.

be considered for a severely cracked pavement section. Otherwise, the rules should be as flexible as possible, since any unnecessary restrictions may eliminate better solutions from the optimization, such as reservation of overlays for pavement conditions with evident cracking. If, however, an overlay is laid even when cracking has not become evident, performance in the future could be improved so significantly that the costs for future rehabilitation would be reduced to the extent that such an option became economically viable. Furthermore, the thickness of the overlay should be determined by the optimization procedure and not preselected by some general rule of thumb.

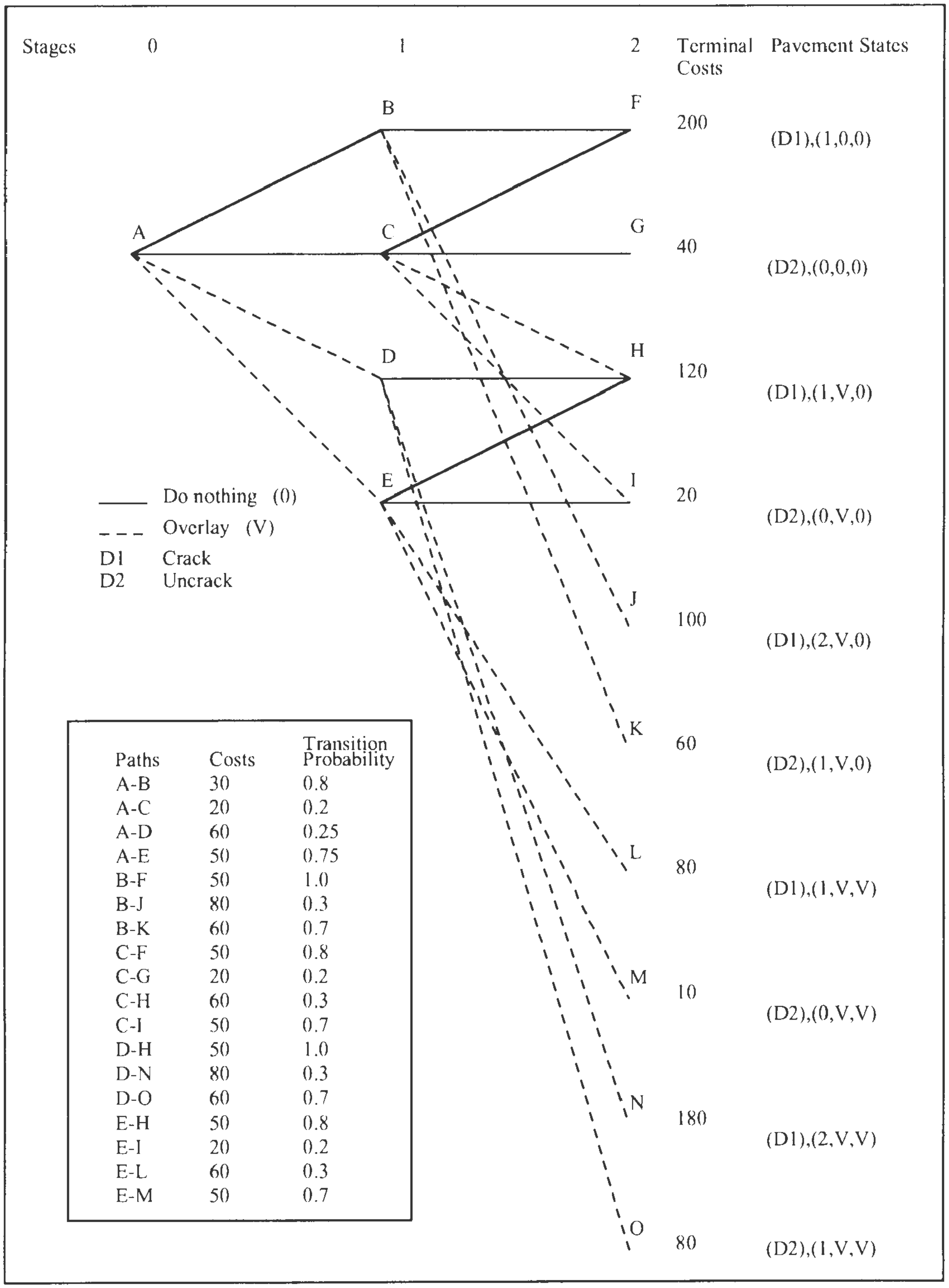
COMPUTATIONAL EXAMPLE

The dynamic programming approach is a closed-loop decision process yielding an optimal rehabilitation policy for the pavement section for the entire planning period. The significance of such a policy is illustrated by the simple two-stage problem shown in Figure 4. Points A through O denote the possible pavement states for the two stages, where A is the condition of the pavement at present. Only two condition states and two alternatives are considered. The minimum life in this case is 1 year for both alternatives. The costs and probabilities of transition for each path are tabulated in Figure 4. The numbers at the terminal states are the boundary values representing the long-term expected costs. All the costs and probabilities are arbitrarily assigned for demonstration purposes only.

The minimum expected costs starting from Point B to the end is $V_B = 138$ by an overlay (V) decision at B, determined as follows:

$$V_B = \min \begin{cases} (0)\text{: } (1) \cdot (50 + 200) = 250 \\ (V)\text{: } (0.3) \cdot (80 + 100) + (0.7) \cdot (60 + 60) = 138 \end{cases}$$

Thus, the optimal policy at B is V. Similarly, the optimal rehabilitation policy and corresponding objective function for the other states are recursively computed and shown in Table 3.



Paths	Costs	Transition Probability
A-B	30	0.8
A-C	20	0.2
A-D	60	0.25
A-E	50	0.75
B-F	50	1.0
B-J	80	0.3
B-K	60	0.7
C-F	50	0.8
C-G	20	0.2
C-H	60	0.3
C-I	50	0.7
D-H	50	1.0
D-N	80	0.3
D-O	60	0.7
E-H	50	0.8
E-I	20	0.2
E-L	60	0.3
E-M	50	0.7

FIGURE 4 Two-stage computational example.

The optimal policy yields a minimum expected cost of 158. This is achieved with an overlay *V* at *A*. By this decision, the pavement can go into states *D* or *E*. If the pavement actually goes to *D* at stage 1, then nothing is done (0), or if it actually goes to *E*, another overlay *V* is laid. The decision at stage 1 will take the pavement to the end of the 2-year planning horizon.

The optimal policy for a larger problem with more rehabilitation alternatives and distress conditions can be interpreted in a similar way. The optimal decision at every stage is made conditional on the actual pavement condition. This closed-loop decision process, provided by the feedback on pavement condition, makes the optimal policy cost-effective.

TABLE 3 **Optimal Rehabilitation Policy and Objective Function**

Pavement State	Costs of Alternatives: Do Nothing	Costs of Alternatives: Overlay	Objective Function	Optimal Policy
A	159	158	158	V
B	250	138	138	V
C	212	103	103	V
D	170	176	170	0
E	144	84	84	V

NOTE: *V* denotes overlay; 0 denotes do nothing.

In the case of the open-loop decision process, a sequence of rehabilitation activities is found that minimizes the expected present cost. For instance, consider sequence 0–0 (i.e., "do nothing" at stage 0 followed by "do nothing" at stage 1). Altogether in this sequence there are three possible paths that the pavement can take to arrive at the end: *ABF, ACF,* and *ACG* with probabilities $(0.8) \cdot (1)$, $(0.2) \cdot (0.8)$, and $(0.2) \cdot (0.2)$, respectively. This yields an expected cost of 270.4, computed as follows:

$$\begin{aligned}\text{Expected cost } (0-0) &= (0.8)\cdot(1)\cdot(30+50+200)\\ &\quad + (0.2)\cdot(0.8)\cdot(20+50+200)\\ &\quad + (0.2)\cdot(0.2)\cdot(20+20+40)\\ &= 270.4\end{aligned}$$

The possible paths and expected cost for the other sequences are included in Table 4. By this approach, the minimum expected cost is 159 obtained by the sequence 0–*V;* "do nothing" at *A* followed by an overlay no matter where the pavement actually ends, whether at *B* or *C.*

By the open-loop decision process, the sequence is determined based on the projected performance derived from current situation without incorporating any feedback on pavement condition. Consequently, it never yields a strategy that has lower cost than the optimal policy obtained in the closed-loop decision process.

TABLE 4 **Expected Costs for Sequence of Rehabilitation Activities**

Sequence of Rehabilitation	Possible Paths	Expected Costs
(0)–(0)	ABF, ACF, ACG	270.4
(0)–(V)	ABJ, ABK, ACH, ACI	159
(V)–(V)	ADN, ADO, AEL, AEM	159.5
(V)–(0)	ADH, AEH, AEI	203

NOTE: *V* denotes overlay; (0) denotes do nothing.

CONCLUSIONS

A framework for a pavement management system incorporating mechanistic distress submodels for predicting pavement performance is presented. In this way, the distress modes of pavement deterioration may be individually evaluated and the appropriate rehabilitation measures prescribed to address each deficiency. The distress submodels are formulated as performance functions using FORM to provide the stochastic basis for obtaining the transition probabilities for the dynamic programming optimization procedure. The optimization approach provides a closed-loop decision process that finds an optimal rehabilitation policy during a planning period conditioned on how the pavement actually performs at each stage.

Although these mechanistic distress models are sometimes simplistic and predict only individual modes while ignoring the interaction effects, which can be significant, the approach is an important first step, providing the possibility of integrating the PMS with existing mechanistic pavement and overlay design procedures. As data are being gathered into the master data file, these models can be further refined and improved. Furthermore, with adequate structural modeling, at least in principle, this approach can also evaluate the effectiveness of the use of new materials and construction methods for rehabilitation.

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LOCATION REFERENCING AND GPS/GIS FOR THE INFORMATION TECHNOLOGY AGE: TO HARMONIZE, STANDARDIZE, OR MODIFY?

Improvements to Utah's Location Referencing System To Allow Data Integration

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A location reference *system* and a location reference *method* are distinguished by listing options available for location reference methods and explaining the importance of a standardized system to facilitate integrating data from more than one source. The conclusion describes necessary changes to Utah's method and the implementation procedures necessary to stabilize and improve Utah's system to meet the objective of data integration. Both linear and spatial approaches to location referencing are discussed. However, the focus is on explaining the details of the four basic linear methods, including advantages and disadvantages of each. Issues the Utah Department of Transportation needed to address when it selected its approach to location referencing are presented, including balance between system and method, stability of addresses, procedures to accommodate address changes, ability to replace one unit of measure with another, institutional issues, and training requirements.

The question most often asked in a highway agency is, "Where is it?" Keeping track of where events and objects are on roads is called *location referencing.* Since terminology is important in location referencing, Table 1 gives definitions of the terms used.

Location Referencing

The most important issue regarding location referencing is to make a clear distinction between a location reference system and a location reference method. National Cooperative Highway Research Program (NCHRP) *Synthesis of Highway Practice 21* (*1*) defines the difference between system and method:

> There is a definite distinction between a highway location reference system and a highway location reference method, the former being a larger set of office and field procedures that includes the latter. The method is seen by the user in the field as a way to identify a single location; i.e., to reference a specific position with respect to a known point. The system is seen as the procedures that relate all locations to each other. It includes techniques for storing, maintaining, and retrieving location information.

Location Reference Systems

To manage location referencing a highway agency must have one, and only one, location reference system. A location reference system, like all information systems, requires separate components to acquire, store, manipulate, retrieve, and distribute information. Typical location reference systems are a mixture of manual procedures for data acquisition and distribution and computerized procedures for data storage, manipulation, and retrieval.

Unlike other information systems, location reference systems depend on the manual components of acquisition and distribution. The manual functions are carried out by employees in the agency who communicate the

TABLE 1 Definitions

Term	Definition
Address	Sequence of numbers and characters to represent the location of a point, specific to a location reference method
Offset	Linear distance along the route to relate a point to a known point
Location	Particular position on a route, identified by address(es) [a]
Primary direction	The direction in which a route is said to "run"
Positive direction	Undivided highways: the primary direction Divided highways: the direction of travel on each side
Negative direction	Opposite to the positive direction
Mile point	Distance in miles from the beginning of the road in the primary direction
Mile post	Post placed along the road, with a number representing the mile point of the post
Reference post	Post placed along the road, with an identification number
Reference point	Point on the road which can be easily identified and whose identification number and location is known
Location reference method	Set of procedures used in the field to identify the address of any point
Location reference system	Set of procedures used in an agency to manage all aspects of location referencing

[a] A point location is identified with one address, a section location with two addresses

addresses of points among one another and with the system. Since consistency in this communication is paramount to success, managing the manual component is a large part of managing the entire system. One way to ease this burden is to enforce a well-conceived location reference method.

Unfortunately, many agencies regard the location reference system as unnecessary. Hence, training courses to show people how the system and the method works are often neglected. Today, few highway agencies make location reference training a requirement for all employees. In fact, few states even publish a location reference users' manual. An example of such a manual is the *Roadway Reference System Users Manual* of the Indiana Department of Transportation (DOT) (*2*).

Location Reference Methods

A location reference method consists of a mechanism to find and state the address of a point by referencing it to a known point. Its purpose is to communicate the location of a point through an address.

The method must be viewed as part of a larger system and should be developed within that context. The method must be easy to use in the field. It must also have characteristics that support the system. The balance between these two requirements provides the key to success for any location reference system. The NCHRP Synthesis (*1*) states that the objectives for a location reference method are to provide a means for

1. Designating and recording the geographic position of specific locations on a highway,
2. Using the designations as a key to stored information about locations, and
3. Uniformity in application of procedures through which various highway-related data observations are located.

Listing "uniformity" as an objective explicitly highlights the desirability for an agency to either use only one location reference method or provide a location reference system that can accommodate many methods at once. This also shows that designating a location should be independent of the viewpoint of various organizational units making observations.

There are two quite different approaches to location reference methods, commonly classified as either "linear" or "spatial." Linear location reference methods express the address in terms of a linear displacement along a highway. Spatial location reference methods express the address in terms of three-dimensional coordinates.

Although much work is being done in the field of spatial methods, the authors are unaware of any highway agency that has abandoned a linear method in favor of a spatial method.

Spatial Methods

Spatial methods use a set of coordinates to identify the location of a point. These "geocoordinates," as they are often called, are commonly expressed either in longitude, latitude, and elevation or in state plane coordinates and elevation. The driving force behind using geocoordinates seems to be a desire to use Geographic Information System (GIS) technology.

Advantages

The advantages of spatial methods are as follows:

- No physical marking is required in the field,
- Coordinates can be obtained electronically with a Global Positioning System (GPS) receiver,
- Any address given in terms of coordinates is permanent since the location in a three-dimensional space never changes,
- Any point can be automatically displayed on an electronic map, and
- Addresses can be given for data that are outside the right-of-way using the same method.

Disadvantages

The following are disadvantages of spatial methods:

- It is difficult to assign the topological relationships between highway segments in a three-dimensional manner,
- It is difficult to detect measurement errors in the field,
- Communicating the location of a point is impossible without a map or without a linear location reference method,
- The motoring public will not be able to use location referencing to chart their progress along a route,
- Calculating a distance between two points requires complicated three-dimensional geometry,
- Users in the field must have a GPS receiver,
- GPS receivers do not work when there is overhead cover such as trees and bridges, and
- Accuracy requirements are significantly greater than for any linear method, because small errors can result in the identification of a point on an entirely different facility.

Linear Methods

The manner of identifying a known point, generally called a reference point, usually distinguishes one linear location reference method from another. Existing implementations of linear location reference methods can be described using one or more of the following fundamental methods:

- Mile point,
- Mile post,
- Reference point, and
- Reference post.

Even though there are many different names, all linear location reference methods are fundamentally the same. The NCHRP Synthesis (*1*) addresses this issue in its conclusion:

> To the casual user of a highway location reference method, there appear to be many widely different methods in use today. There is a tendency to "see" significant differences between methods on the basis of different names. To make matters more confusing, terms such as "straight-line diagram", "route log", "coordinates", "milepoint", and even "milepost" and "reference post", are used rather loosely in connection with location reference methods. . . . There really is not a great deal of difference between the several most commonly used methods.

Mile Points

The mile (or kilometer) point method is the most fundamental method. Most location reference systems employ the mile point method in some manner. The more successful systems use the mile point method internally to relate locations to one another.

This method assumes that each road has one reference point located at its beginning. The address of any point along the road is the numerical value of the distance of the point from the beginning of the road. Mile points are not physically identified in the field.

Mile point addresses are communicated with a format of "NNNN 999.999", where NNNN is the route number and 999.999 is the mile point. Figure 1 shows a typical road that is 8.7 mi long and has five "incidents": a start, a bridge, a T-intersection, a culvert, and an end.

Advantages

The advantages of the mile point method are as follows:

- The distance between any two points on the same road is equal to the difference between the "to" and the "from" addresses,
- Special posts are not required, and
- Mile point systems are easy to understand.

Disadvantages

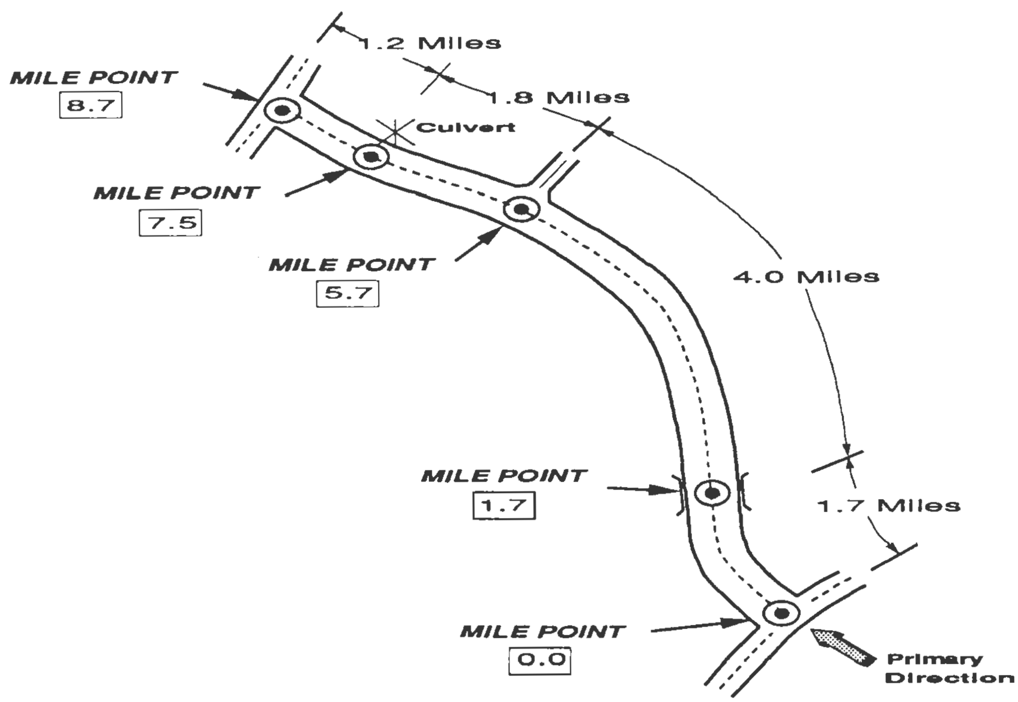
The disadvantages of the mile point method are as follows:

- A user in the field must start to measure at the beginning of the road each time to get an address,
- Addresses are unstable because mile points change whenever the length of the road changes, and
- Whenever mile points change on a road, the location reference system must go to all files, including historical records, and renumber the addresses for all points on the road.

Mile Posts

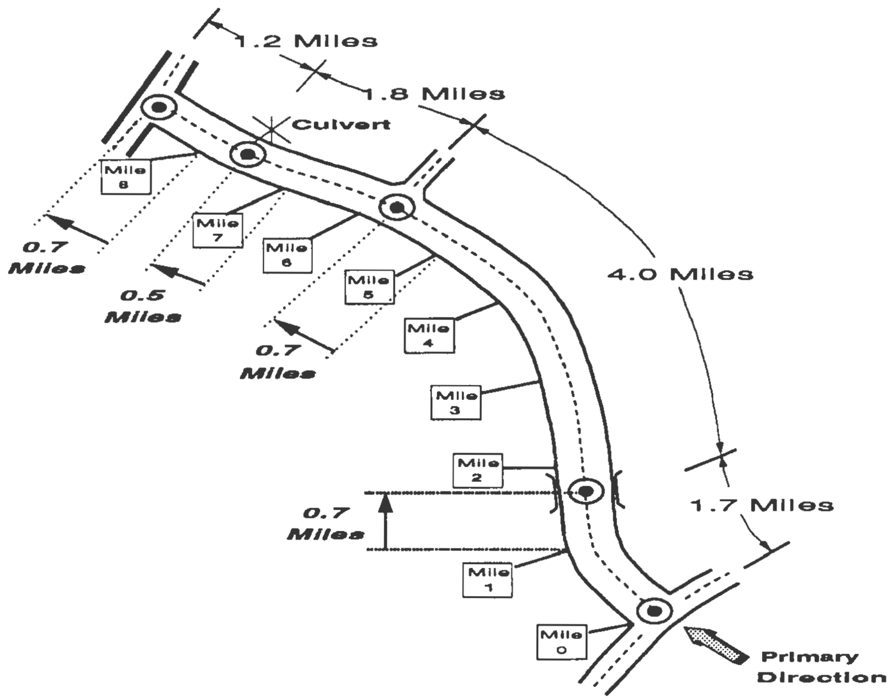
The theoretical difference between the mile post and the mile point methods is in the physical placement of posts at even mile points along a road. Each mile post must be labeled with a number that represents the true mile point at the post. The address of any point, then, is given by adding or subtracting the distance traveled from any post to the point in question.

The format for communicating the address of a point is "NNNN 999.999," as for the mile point. Figure 2



DESCRIPTION	ADDRESS
Start of road	000.000
Bridge	001.700
"T" Intersection	005.700
Culvert	007.500
End of road	008.700

FIGURE 1 Mile point location reference method.



DESCRIPTION	ADDRESS
Start of road	000.000
Bridge	001.700
"T" intersection	005.700
Culvert	007.500
End of road	008.700

FIGURE 2 Mile post location reference method.

shows the same road as that in Figure 1, this time with the mile posts.

Advantages

The mile post method has these advantages:

- It is easy to use in the field,
- Motorists can use the posts to chart their progress along the road,
- A user has to travel at most 0.5 mi to find the nearest post,
- Numerical sequencing of the signs provides users with easy orientation, and
- A user can calculate the distance between any two points by subtracting the "from" address from the "to" address.

Disadvantages

The mile post method has these disadvantages:

- Maintenance forces must place, maintain, and work around posts;
- Posts must be replaced whenever the length of a road or the unit of measure changes;
- If the posts ever become out of date, the method can no longer be a mile post method; it becomes a reference post method and all the requirements of using a reference post method must be practiced; and
- Mile posts can be confusing on concurrent routes (the numbers on the posts represent the mile point for only one route, or there is a set of posts for each route).

Reference Posts

The reference post method uses posts physically placed at various increments along the road. Each post has a reference number. In this method the reference point is identified by the number on the post. The address of any point is stated by giving the route number, the distance traveled from any reference post to the point in question, and the direction.

To calculate the distance between any two points, all reference numbers must be related to a mile point. Although a reference post number never changes, the mile point associated with a reference post number may change. Maintaining the relationship between reference post number and mile point is the key to success. The distance between any two consecutive posts is maintained in a file. Any user or information system that wants to calculate the distance between any two points must use this file.

The format for communicating the address of a point using the reference post method is "NNNN XXX ± 99.999", where NNNN is the route number; XXX is the reference number on the post; + or − indicates a positive or negative direction, respectively; and 99.999 is the distance from that post.

Figure 3 shows the same road as that in Figures 1 and 2, this time, with reference posts added.

Advantages

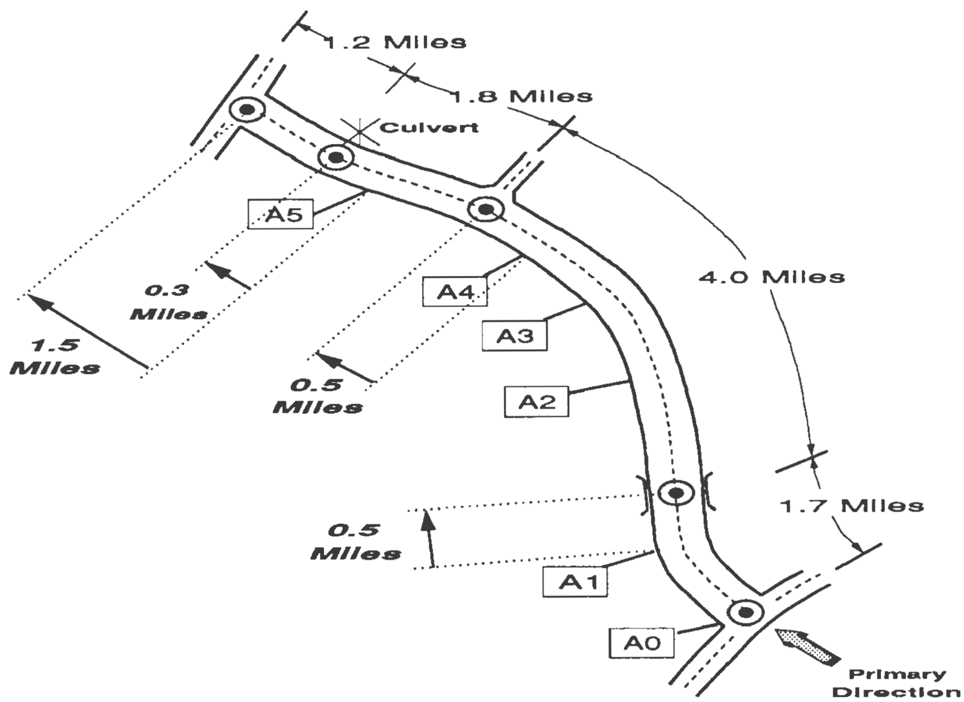
The reference post method has these advantages:

- It is easy to use in the field,
- Addresses are stable and changes in route lengths or in the unit of measure for distances do not affect the physical location of the posts or the validity of the post reference numbers,
- On concurrent routes a single set of posts applies to all routes, and
- The distance between posts is usually small enough so users need not travel a long distance to find one.

Disadvantages

The reference post method has these disadvantages:

- Motorists may not be able to chart their progress along a route,
- Maintenance forces must place and maintain the posts and work around them,
- Users and information systems must use a list to calculate distance between any two points, and
- It is difficult to maintain and distribute the list of mile points for all reference posts.



DESCRIPTION	ADDRESS
Start of road	A0 + 00.000
Bridge	A1 + 00.500
"T" intersection	A4 + 00.500
Culvert	A5 + 00.300
End of road	A5 + 01.500

FIGURE 3 Reference post location method.

Reference Points

The difference between the reference post and the reference point methods is the physical placement of the posts in the field. The reference point method relies on assigning reference numbers to easily identifiable physical features such as bridges and intersections. The reference point is identified by a number on a list. Distance between any two consecutive points is given on the same list. The list is required in the field to find the number for any reference point.

The format to communicate the address of a point using the reference point method is identical to that in the reference post method: "NNNN XXX ± 99.999."

Figure 4 shows the same road as that in Figures 1–3, this time with reference points.

Advantages

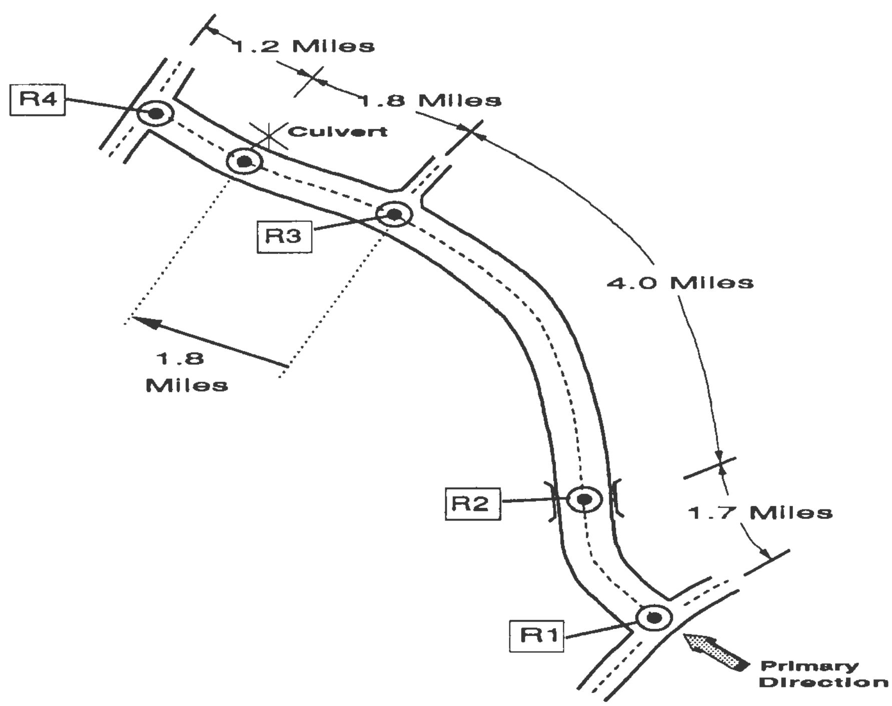
The reference point method has these advantages:

- Special posts are not needed,
- Addresses are stable and changes in route lengths or in the unit of measure for distances do not affect the validity of the numbers for the reference points, and
- On concurrent routes the reference points apply to all routes.

Disadvantages

The following are disadvantages of the reference point method:

- It is cumbersome to use in the field,
- Reference points can often be located only at impractical distances apart on rural roadways,
- Motorists are not able to chart their progress along the route,
- User and information systems must employ a list to calculate distance between any two points, and
- Maintaining and distributing the list of mile points for all reference points is difficult.



DESCRIPTION	ADDRESS
Start of road	R1 + 00.000
Bridge	R2 + 00.000
"T" Intersection	R3 + 00.000
Culvert	R3 + 01.800
End of road	R4 + 00.000

FIGURE 4 Reference point location method.

Issues in Selecting a Method

In presenting issues that an agency should address in the selection of an approach to location referencing, the relationship between system and method is discussed from five different perspectives: balance between method and system, experience of some DOTs, stability of addresses, institutional issues, and the act of replacing one unit of measure with another.

Balancing Method Against System

In general, two aspects must be balanced when the appropriate method for an agency is selected. The method must be easy to use in the field, and the supporting system must provide a mechanism to accommodate changes in addresses. It is desirable to reduce the impact of address changes so that separate files, including historical files, can be easily integrated. Creating an appropriate balance between these two aspects is confusing because one is only achieved at the expense of the other. This is why mile point and mile post methods are unattractive; ease of use comes at the expense of address stability.

Three principles have been observed by the authors. First, systems based on a single method are generally more successful than those involving many methods. Second, systems based on post methods are generally easiest to use in the field. Finally, systems that require a list to be used in the field are generally more difficult to use and maintain.

Experience of Some DOTs

A true mile post system must have a procedure in place to ensure that the posts are always located at exact mile points. All posts beyond an affected point must be removed and replaced whenever a realignment activity occurs. Since this removal and replacement is seldom done, many agencies that started with a mile post method ended up with a reference post method. Yet, these agencies still called their method a mile post method and did not have a system in place to manage either. Mislabeling the method and lack of system procedures have resulted in much confusion.

Agencies still using these mislabeled mile post systems are trying to force some procedures of a mile post system to perform like those of a reference post system while still employing the main characteristics of a mile post method. When a road's length changes, an "adjustment equation" is introduced in the system. Because of post placement errors, some agencies have "short miles" and "long miles," also accounted for by adjustment equations in the list.

Stability of Addresses

The impact of address changes is also a system issue. The system must have procedures to accommodate changes in addresses swiftly and thoroughly. Since few agencies have integrated data bases in place, it is difficult to communicate address changes to all existing information systems automatically. Usually these matters are left to manual procedures, and manual procedures are notorious for not being applied properly, especially without documentation or formal training in their application.

Therefore, an agency has two choices: automate procedures or minimize address changes. Since providing the system with automated procedures requires an expensive integrated data base, it is usually better to focus on education and address stability. Minimizing address changes is a methods issue.

Institutional Issues

Location referencing has a tremendous influence on virtually all areas of business in a DOT. Anyone involved with DOT data must be familiar with various parts of the location reference system, and all must be familiar with the method.

Whenever any change is recommended, it is most often greeted with resistance. People, particularly those intimately familiar with the nuances of the current method, tend to resist change. If an agency wants to change its method, this resistance must be considered, planned for, and accommodated. In the Utah Department of Transportation (UDOT), this was accomplished through education seminars and by forming a joint task force consisting of all major players, including the police.

Changing Units

Changing the unit of measure for distances to the International System of Units (SI) will definitely have an impact on the location reference system. The size of this impact can be linked to how easily the location reference method can handle the change.

The conversion can be simple. In the reference post method, for example, all distances in all files can be converted from miles to kilometers through a simple program. Then those in the field must start reporting all distances in kilometers instead of miles.

However, the conversion can be complicated. For example, agencies using any form of the mile post method, mislabeled or not, must either remove and replace all posts or convert their method to a reference post method. The agency must then make the same modifications in reporting distances mentioned above for the reference post method.

UDOT Location Reference System

System Review and Recommendations

The key to sharing information gathered and maintained by different divisions within the department was to relate all information pertaining to a specific location to a common address on the highway system. For 15 years UDOT had used a Highway Reference System (HRS) to establish and report common addresses for points along the highways. In 1992, UDOT requested proposals for an engineering data base to develop a capability to provide complete and easily usable information to district field personnel and department decision makers. As part of this request, UDOT specified that the data base provide an automated capability to store, maintain, retrieve, and report information by location, using the HRS. UDOT also requested a review of HRS to determine what adjustments would be needed to make the system compatible with the automated system.

The consultant review and evaluation of HRS revealed major discrepancies between the desired capability and what was actually provided by the present system. HRS did not have documented procedures, and the operating methods were unclear. Over the 15 years since system implementation, changes in data collection and reporting procedures and individual, informal changes to meet individual user's needs had rendered the system ineffective.

UDOT's selected engineering data base provided the capability for the automated portion of a usable location reference system. It could concurrently support several reference methods. In addition to the automated capabilities of the engineering data base, the consultant made several recommendations for actions to implement an adequate location reference system, calling for UDOT to develop

- A manual explaining UDOT's location reference system and giving examples of its use,
- A formal location referencing training course for all employees who are involved with the HRS,
- A policy designating one office as responsible to maintain all aspects of the HRS including effective distribution of the address list,
- A procedure by which the location reference office annually freezes address data for a period of 1 year so all data collected during that year are referenced to the same addresses,
- A formal computerized and manual system to cover all aspects of location referencing,
- A procedure to make cascading changes to addresses in all current and historical files to allow comparison of data collected when other addresses were used,
- A procedure to make the location reference method as easy to use in the field as possible, and
- A strategy to implement metric measurement notation.

Necessary location reference method changes basically combined the best features of the reference post method with the reference point method. Recommended changes were as follows:

1. Leave existing posts in the field where they are. Costs to remove and replace the posts would be high, and the posts can be used as reference posts in the upgraded referencing system after "freezing" their locations to provide consistency.
2. The fact that mile points are fundamentally different from existing mile posts must be communicated effectively. The best place to start would be to officially change the name "mile post" to "reference post." This would help eliminate the mistaken belief that posts are always 1 mi apart and would also help in the transition from miles to kilometers when none of the posts will be 1 km apart.
3. Change the format of the address used by the HRS to the format shown below. This format must be used by all systems in the agency.

NNNND FFF + 9.99 TTT + 9.99

where

NNNN = route number designator with leading zeros;
D = direction of roadway lanes, for example, P, primary direction, used on the set of lanes that runs in the primary direction on divided highways; B, primary direction, used to indicate an undivided highway; N, opposite direction for the set of lanes on divided highways that runs opposite to the primary direction; R, ramp in the primary direction; and S, ramp in the negative direction;
FFF = identifier on the closest reference post in the negative direction from the address;
9.99 = distance from FFF to the address in the positive direction;
TTT = identifier on the closest reference post in the negative direction from the address of the "to" point (only for sections); and
9.99 = distance from TTT to the address in the positive direction (only for sections).

4. Change all existing systems in UDOT to accommodate the new address. If data from existing systems are to be integrated with new data, all must use the same addresses.
5. Maintain and distribute the following four lists to users in both paper and electronic format.

- Route list, showing route identifier, positive direction, and a description of each route in the location reference system;

- Reference post list, showing route identifier, reference post identifier, mile (kilometer) point, distance from the next preceding reference post, and unit of measure for distance;
- Reference point list, showing address and a description of major physical features along each route; and
- Concurrent highway list, showing the addresses of concurrent highway sections

6. Change the method used to acquire addresses.

Institutional Issues

A Highway Location Reference System Group was formed to deal with the multitude of institutional issues that arose. Group membership included representatives from all UDOT users and a representative from the Utah Highway Patrol to represent the views of law enforcement users, both state and local, who report accidents and other information using location references. Identification of all of the varied user requirements and providing a capability to satisfy them was key to implementing both the system and method. In some cases this dictated compromises, which led to some users' functions not being optimized. Thanks to the Location Reference System Group's expertise and professionalism, these areas were identified and accommodated.

Pros and cons regarding extensive modification of UDOT's existing system were considered. Major points in favor of the new system were that it would provide

- Easily communicated, exact location information from a wide variety of inputs and to any connected users;
- Unification and integration of data from diverse data collection systems; and
- Increased location referencing accuracy.

However, the new system would require

- A major effort to implement, and
- Extensive computer program changes for all data-gathering activities.

Several major departmental decisions were made affecting UDOT's location referencing system. A single, departmentwide location referencing system is essential to allow multiple users to share data. The automated portion of the system will be provided by the engineering data base program. Finding locations and identifying relationships among various combinations of data at and between specific locations is a repeated requirement, essential to ensure that information and analyses from diverse data areas reflect true conditions in the field.

For example, investigating police officers usually drive from the scene of an accident to the next reference post to establish the reference post location and the distance from it. However, data collection is usually conducted in a primary direction along a route over an area spanning several reference posts.

To accommodate the varied needs of data collectors, the system allows locations to be identified using any valid address. However, to ensure easy communication with all users and uniformity, the system converts input addresses to a standard address that is stored, retrieved, manipulated, and used for all reporting. This leads to two types of addresses:

1. To identify an address where data are collected, a "UDOT address" may be used. This address is expressed by a route number, direction indicator, reference post number, and an offset, which may be any distance (e.g., 0015P 321 + 4.63).
2. To provide the most stable and predictable way to identify a location for a wide variety of users over time, it was decided to establish a "UDOT standard address." A standard address ensures one, and only one, address for each location or event. The UDOT standard address uses route number, direction indicator, the number of the reference post immediately preceding the location, and an offset in the positive direction, which is less than the distance to the next reference post (e.g., 0015P 325 + 0.63). This address is the one under which all data pertaining to a particular location are stored, retrieved, manipulated, and reported.

Data will be gathered and stored as separate roadways for each direction of travel on divided highways.

Address reporting formats will be multiple and varied to meet the needs of individual users. For example, one user may need a report on all routes within a single UDOT district, and another may need to use standard addresses to locate individual pavement sections or points along a route or routes. Other users will have their own unique requirements.

To provide stability, accuracy, and repeatability, a unit within the Transportation Planning Division was designated to manage, operate, and maintain the location referencing system. Maintenance Division and district maintenance personnel were designated as responsible to replace missing or damaged posts in locations designated by the system manager.

Within UDOT's system a single reference method was desirable to communicate location more easily and to provide more consistent data for use. A single method throughout UDOT will allow easier, more accurate data communication and integration. To meet these requirements UDOT selected the reference post method for location referencing. Several decisions were required to implement this method:

• Existing mileposts were redesignated "reference posts" and remained in their original locations. Missing or damaged posts were replaced and maintained at their original locations.
• Each route had a zero reference post placed at its point of beginning and an ending reference post marking the end of the route.
• Route designations and cardinal direction signs were placed on every fifth reference post, along with the post number.

As currently constituted, the system provides several essential capabilities:

• To accept any reported address, convert it to a UDOT standard address, and store, retrieve, manipulate, and report it in UDOT standard address format;
• To identify linear segments in a standard manner by converting beginning and ending addresses to UDOT standard addresses;
• To recover the distance attribute between two addresses and to report the UDOT standard address of a point from any address when provided with a distance and a direction;
• To provide standard addresses for selected data elements without displaying addresses for any other undesired items;
• To be easily convertible to metric measurement units; and
• To treat divided highways as separate roadways.

Within the system the method

• Contains minimum perceived changes for field personnel,
• Uses existing mileposts as they were previously installed,
• Is easy to learn and use in the field,
• Has flexibility to meet varied user needs for location identification, and
• Provides stable addresses over time

Implementation

There were several implementation impacts. Full implementation of the revised UDOT location reference system and method required about 1 calendar year and 3 to 5 person-years of effort. Implementation required

• Complete inventory of mileposts along the highway system to establish precedence, succession, distance, and condition of existing mileposts for their conversion to reference posts;
• Full inventory on opposing roadways for divided highways;
• Modification of all existing data collection systems to use the new location reference method and format; and
• A manual interface for each data area to translate between old and new method addresses.

Finally, all potential users must be educated in using the system and to realize that optimizing the system is not the same as optimizing each individual area. Users in the UDOT Central Office must be aware of the reference method used in the field and know system capabilities for data retrieval, manipulation, and report generation. In the field, personnel must be familiar with the method used to report and find locations and be aware of the system capabilities. In all areas, individual users must understand that they may be required to give up some desirable features to allow the system to best serve overall department needs.

Summary

UDOT adopted the reference post method of location referencing. This method allows data gathered by various department divisions to be related to specific locations along the highway system. Used with the management system provided by the engineering data base, this method provides the key to sharing information among UDOT's many separate activities.

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Establishing a Link/Node Referencing System in North Carolina

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The state of North Carolina has historically managed highway-related data on a county/route/mile post system. Route changes due to new construction or redesignation of a route cause the mileposting of the route to change; therefore, tracking historical information over time is virtually impossible. A link/node referencing system was proposed to solve this problem by providing a stable designation over time. A node is assigned to each permanent physical feature on the road with links established as the distance between adjacent nodes. This system solved the problem because all data will be associated with a link or node and will not be dependent on the route designation and the mile post.

The development of the link/node system required coordination between various branches of the North Carolina Department of Transportation (NCDOT). Each branch had a different method of maintaining data. The operation of a relational database requires a single reference system to be used throughout NCDOT. Many compromises were necessary for each branch to adapt to the new reference system.

The development of the system also had to allow for computerized data conversion. Many computer data files are stored in flat file form. NCDOT is in the process of converting flat files into a relational database. The link/node system is the primary key for the relational database. Several modifications had to be made to the link/node system to aid in the computer conversion.

History

North Carolina maintains a highway system of over 260 800 lane-km (162,000 lane-mi). A county/route/milepost system for referencing information to the highway system has been used. The mileposting of each route begins at the county line and follows the route through the county. New construction or reconstruction can affect the total length of the route in the county, resulting in a change of milepost designation for the section of the route. Therefore, a section of highway that has been referred to at one mile post will from that time forward be referred to by another mile post. No record of changes has been maintained, thereby making tracking historical information across time almost impossible.

The NCDOT is in the process of developing a relational database to contain departmentwide data. For this database to be successful, a common primary index was needed to link tables from different branches within NCDOT together. A committee was formed with representatives from all branches of NCDOT to develop a unified reference system. Extensive coordination effort was required to bring all parties into agreement on a single system. For instance, there are five conventions of numbering counties in the state. Most branches did not want to compromise and wanted to continue using their existing numbering system. The process of coming to an agreement was painful, but without a standardized coding and reference system there cannot be a departmentwide relational database.

The department is also in the process of digitizing the highway network for a Geographical Information System (GIS). It is anticipated that it will be several years before the mapping and attributed tables for GIS are complete. The need for a unified reference system before the GIS completion date was recognized. Also, data stored in the attribute tables would not be stable over time if the primary index was a county/route/mile post system.

Alternative Reference Systems Considered

Three different referencing systems were considered: updating the county/route/mile post system, a link/node system, and a station post system. The link/node system was chosen as the most suitable for North Carolina's highway system.

As discussed earlier, it is almost impossible to track any information across time with the current county/route/mile post system. Because North Carolina's highway system is constantly changing, the logistics of updating all historical files to reflect changes was determined to be too complicated. In meetings with the Management Information Systems (MIS) section of NCDOT on developing the new reference system, a method of keeping track of all changes was studied. It was felt that programming to encompass the changes to all files using the reference system would be very time-consuming and, since changes would be occurring frequently, the cost of computer time to update all files daily or weekly was prohibitive.

A station post reference system was considered. It was determined that the cost of installing station posts along both sides of all 125 580 centerline km (78,000 mi) of highway would be prohibitive. In addition to the initial cost, the cost of monitoring and replacing posts destroyed due to accidents, mowing, and vandalism would be an annual maintenance problem. Therefore, the station post system was not determined to be economically feasible.

With a link/node system, all data would be stored associated with links and nodes which would not change over time. Any route changes would take place in one file, and with a relational database all appropriate historical data could be retrieved for any section of road. Also, all data points can be tied to a readily identified location so someone in an office could determine the link/node location from a physical description.

Recently the FHWA has required data for the Highway Performance Monitoring System (HPMS) be reported in a link/node referencing system. Data reported in HPMS is obtained from other databases and a common reference system will simplify assembling of the report.

Link/Node System

A link/node system was selected as the method to isolate data from changes in designation over time. Each permanent physical feature is assigned a node number. These features include intersections, bridges, railroad crossings, county lines, and other features that will not change over time. Features such as city limits, changes in pavement type, etc. were not used because these features are subject to change. Permanent features other than intersections were used because these features are used to describe locations on accident and other reports. Personnel located in various offices must be able to convert a written description to the link/node reference system. Therefore, designating nodes at all permanent physical features used to describe locations in these reports will increase the accuracy of the database.

Links are established as the highway between adjacent nodes. Any point along a link can be designated as the offset from one node toward the adjacent nodes. Routes then become an accumulation of adjacent links. This system solves the problem of tracking historical data because all data are associated with a link or node and are not be dependent on the route designation or to mileposting which is subject to change.

Three tables are required to manage the system. Highway link data, which include county, route, begin node, end node, and link length (see Table 1), are the basis of the system. The first table built from this data is the link table. The link table consists of the beginning node, the end node, and the highway distance between the two nodes (see Table 2). A route table is then compiled by connecting the links throughout a route (see Table 3). A table describing each node (routes intersecting at the node) is computer-generated from the above two tables. This table

TABLE 1 Data Entry

COUNTY	BEGIN NODE	END NODE	LENGTH	ROUTE
32	00683	00786	1.28	US 64
32	00787	00788	1.01	US 64
32	00786	00787	0.24	US 64
32	00788	00795	2.34	US 64
32	00788	01432	1.61	NC 574

TABLE 2 Link Table

COUNTY	BEGIN NODE	END NODE	LENGTH
32	00683	00786	1.28
32	00787	00788	1.01
32	00786	00787	0.24
32	00788	00795	2.34

TABLE 3 Route Table

ROUTE	COUNTY	BEGIN NODE	END NODE	LENGTH	MILEPOST
US 64	32	00000	00683	0.00	0.00
US 64	32	00683	00786	1.28	1.28
US 64	32	00786	00787	0.24	1.52
US 64	32	00787	00788	1.01	2.53
US 64	32	00788	00795	2.34	4.87

must be amended to include other physical features at the node not described in the route table such as bridges, railroads, county lines, etc. (see Table 4).

All data stored in the database will be referenced to the link/node system. Point data will be stored by the offset distance from a node. Other data will be assigned to links or portions of links, again described by the offset distance. The node numbers will always remain stable; therefore, when a route is changed, only the route table will be updated to reflect that change. The change will automatically be reflected in the node description table. However, all data such as pavement type and condition, accidents, traffic history, etc. will remain on the section of highway to which such data pertain.

The link/node system is also compatible with GIS. The nodes can be located on the digitized maps. From this, the *xy*-coordinates can be assigned to each node. In the future, when GIS is operational, the *xy*-coordinates can be used to locate data. This will be beneficial because handheld Global Positioning System (GPS) units can determine exact position in the field from satellites, increasing the accuracy of data location. Eventually much data, such as accident data, will be located by this method.

A flat file called the universe file is being maintained to contain data required for the Highway Performance Monitoring System (HPMS). Data in this file include roadway characteristics, average daily traffic, city limits, and mileposting of highway characteristic changes. Other files maintained by various units of NCDOT using a mile post designation include accident, pavement condition data, construction history, and the location and inventory file. Only the universe file has been updated annually to reflect the changes in the highway system because of requirements of the FHWA. Therefore, this file is the most

TABLE 4 Node Locator Table

COUNTY	NODE	DESCRIPTION	DESCRIPTION	DESCRIPTION
32	00683	US 64	NC 224	SR 1618
32	00786	US 64	BR. 12363	
32	00787	US 64	RR 54347	
32	00788	US 64	NC 574	
32	00795	US 64	SR 2042	BR 98876
32	00789	US 64	US 301	
32	00790	US 64	CL 73	

US-US Route, NC-NC Route, SR-Secondary Road, BR - Bridge, RR-Railroad, CL-County Line

up to date and hence was used as the basis for the conversion.

The MIS section of NCDOT developed a computer program to assign nodes to intersections and other features and to compute link length between nodes based on the universe file and the feature and location file. The universe file contains all roads, including entire length and intermediate points where road inventory items change. It does not include all intersections of roads. The feature and location file contains a list of intersections and corresponding mile posts along each road. However, the feature and location file was only approximately 50 percent complete and did not include all roads or all intersections along a given road. Therefore, only approximately 70 percent of nodes were included in the computer-generated information. Students were employed to locate nodes on county maps from this information, identify missing nodes and assign node numbers, and determine link length between inserted nodes. There are also discrepancies in section lengths between the two tables. Since information in the universe file takes precedence over all other files, corrections had to be made to a small portion of the link lengths generated from the feature file.

Node numbers were assigned on a county-by-county basis, with each county starting with node 00001. To accommodate large urbanized counties, the node numbers consist of five digits. At this point, our largest county consists of over 6,000 nodes. This includes noding intersections of state-maintained roads, bridges, railroads, and county lines. Once the link/node system is completed for the state highway system, the Traffic Engineering Branch wants to expand the system to include local streets to locate accidents. It is anticipated that a five-digit number will be necessary to accommodate this expansion. There are 100 counties in North Carolina, and the two-digit county code will become part of the node number, thereby resulting in a statewide seven-digit number for node identification.

DATA CONVERSION

Once the manual location of nodes and determination of link length was accomplished, a computer update of the files generated by MIS was necessary. MIS set up a system where links were entered with their corresponding routes. The program then assembles routes from the various links by going from the end node of the first link to the beginning node of the second link, etc. To do this, a beginning link of each route had to be designated so the system could determine the start of a route. Therefore, the initial link of each route was entered with a beginning node of 00000, with the second node being the actual first node on the route. The computer can then compile the route from start to finish.

Occasionally people who have worked in the field of data collection for many years have trouble thinking in terms other than county/route/mile post and have difficulty conceptualizing the link/node system. Therefore a cross-reference table from link/node to mile post will be maintained to facilitate data collection for reporting purposes and to help make the transition from one system to the other. This table will calculate mile post data from the link lengths and provide a window for users who want to continue using the county/route/mile post system to access the database. All data will be stored in association with the link/node and not by mile post. Those people who are used to using the mile post convention can continue to access data by mile post with the link/node system operating internally.

After the link/node tables have been completed, a computer conversion of the universe file will take place. Since the length between points on the universe file is consistent with those used in the link/node system, this conversion will only require minor programming. However, the mileposting of other files that require conversion is not consistent with the new link/node system. For instance, mileposting in the pavement condition database has not been revised in 10 years. Any changes in routes during that period have not been incorporated into the database. Also, some of the mileposting was done in the opposite direction from the universe file. Factors such as these make a computer conversion infeasible without verifying accuracy of the tables being converted. Therefore, manual review of these tables will be necessary to ensure correct mile posting before conversion takes place so that the associated data will be designated to the appropriate links.

At this time, conversion from county/route/mile post to link/node on 80 of the 100 counties in North Carolina has been completed. The next step of converting the existing flat files to the new referencing system will be a major undertaking. It will be impossible to convert any files to the link/node system until the entire state has been completed. One county was selected and used to develop and test software for data conversion. Pitt County was selected because it is one of the few counties that is complete on the GIS. When the reference system is complete for this county, MIS can develop software and use this county for testing. Using a pilot county will allow software for the conversion to be completed so that when the statewide link/node system is finished, all flat files can be converted and the databases can be operational in a very short time span.

Once the conversion has been completed a process to modify the database for changes to the highway system will be necessary. MIS is developing an update procedure that will accommodate the addition or deletion of nodes. This procedure will include checks to prevent breaks or overlaps of links along a route. All related databases will automatically be updated when a change occurs.

Cooperation Effort

Much resistance has been encountered by other branches that cannot see past the additional work of the conversion to the benefits to be derived from the new reference system. Due to staff reductions, they do not want to invest the human resources required to prepare their databases for conversion. However, for the system to be a success, all branches must participate and use the link/node reference system. Therefore, a directive from upper management is imperative for department-wide conversion to take place.

Conclusion

The benefits of a statewide uniform referencing system far outweighs the efforts required to accomplish the task of conversion. The ease of handling data will allow greater in-depth analysis for required information and reports. Management will be able to assess information more readily to make better-informed decisions.

Major changes usually encounter resistance from those who are accustomed to the status quo. However, data standardization is essential for the development of a departmentwide relational database. The development of the link/node system will provide a foundation on which to base future database tables and modeling.

A unified referencing system will provide the following benefits:

1. Data can be shared throughout NCDOT, and each branch will not have to maintain duplicate data files.
2. Historical data can be accurately tracked over time for each section of highway.
3. HPMS reports can be generated from the database with updated information.
4. Operation of GIS requires a standardized reference system.
5. Activities such as performance prediction modeling that require information from various data tables can be accomplished.
6. This system will allow computerized updating of all related data tables for modifications when nodes are added or deleted.

For successful implementation of the link/node system, all branches must make a commitment to convert to the standardized system. Upper management must support the concept and require all branches to convert to the same referencing system to accomplish this goal.

Integration of a Pavement Management System and a Geographic Information System in South Carolina

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With the increasing use of Geographic Information Systems (GIS) in public agencies, there is a growing trend toward integrating the Pavement Management System (PMS) data into the GIS. With the technological advances in computer hardware and software, this integration is becoming more practical. The advantages for the PMS engineer include the ability to visually display the results of database queries and pavement management analyses on a map of the highway network, view network conditions through dynamic color-coding of highway sections, and access sectional data through the graphical map interface. The alternative approaches to PMS/GIS integration in general are discussed, along with a detailed evaluation of the alternatives in South Carolina. The integration can be achieved through total integration so that the PMS is part of the GIS, through export of PMS data to match the GIS, or through export of the map into a PMS map display/query module. The advantages and disadvantages of each approach to system integration are discussed. The issues of highway referencing and data/map connection are presented. Finally, there is an examination of PMS/GIS integration as implemented in South Carolina.

With the increasing use of Geographic Information Systems (GIS) in public agencies, there is a growing trend toward integrating Pavement Management System (PMS) data into the GIS. With the technological advances of computer hardware and software, the integration of these two types of systems is becoming more practical.

Great effort is often expended by an agency in the implementation of a GIS because of the labor involved in the following operations:

1. Digitizing or cleaning detailed maps, or both, and
2. Attaching the data referencing information to the graphic elements.

Map digitization is the first major step in a GIS implementation and can often require a couple of years to complete. The second major step is to attach reference information (usually mileage for state highway agencies) for attaching existing data to the graphics. As a result of the level of effort required, a GIS implementation often takes several years to complete and the integration of other systems is sometimes adversely affected by this time lag.

The advantages of the GIS/PMS system integration for the PMS engineer include the following abilities:

- To visually display the results of database queries and pavement management analyses on a map of the highway network;
- To view network conditions and projected work programs through dynamic color-coding of highway sections; and
- To access sectional data through the graphical map interface.

The South Carolina Department of Highways and Public Transportation (SCDHPT) Office of Planning has been implementing a GIS using the Intergraph MGE software (utilizing the Informix database software) on Unix workstations. A PMS development project was conducted simultaneously. As part of the PMS implementation, the PMS/GIS integration options were assessed to determine the best solution to meet the users' needs. This paper focuses on the GIS/PMS implementation from the PMS engineer's perspective as a system user.

Two state maps are being developed by the Office of Planning in SCDHPT: a detailed map based on 7.5-min quads (referred to as the quad map in subsequent discussion), and a 1:100,000 map with less detail (referred to as the state map in subsequent discussion). The state map was originally digitized for publication annually. At present the state map is completely digitized, whereas the quad map is still under development.

When maps are initially digitized, it is often done on a random basis (especially if the map was not created originally for a GIS, but for another purpose, such as map publishing). In a randomly digitized map, the graphic elements look like the map when displayed; however, the line strings do not correspond to pavement sections. In fact, if the map was not digitized initially for a GIS, the line strings would have no identifiers attached such as highway number, mile post, and so on. This is the case with the SCDHPT state map.

Since the state map was at a scale sufficient for network pavement management and the map was completely digitized and cleaned, it was selected for use in the PMS/GIS integration. This map utilizes state plane coordinates on the MGE software.

Alternative Approaches for PMS/GIS Integration

Three general approaches are available for PMS/GIS integration:

1. *Total integration:* The PMS is implemented within the GIS software and thus becomes part of the GIS;
2. *PMS data export:* The PMS data are exported and then imported into the GIS for display or querying; and
3. *Map export:* The map is exported from the GIS and then imported into the PMS for use in a map display/query module.

Total Integration

Total integration involves the implementation of the PMS within the GIS software system. A disadvantage with this approach is that the choice of software for system implementation is very limited, since any given GIS package will operate with only a specific database management system (or sometimes more than one). In the case of South Carolina, this is Intergraph/Informix, because this software was already being used for the GIS development.

The total integration approach often results in a system that is more difficult to use and less flexible from the PMS engineer's perspective. This approach greatly limits the options available for the PMS implementation since the limits of the GIS software become the limits for the PMS software as well.

Unless the GIS has dynamic segmentation available to match the PMS analysis sections to the map lines, the map has to be statically segmented to have the line strings match the PMS sections. This can result in a system that is either much less flexible or a lot more work to maintain.

This approach is best suited to an agency in which the PMS user is already familiar and comfortable with using the GIS software and wants the PMS to be totally integrated within that system, otherwise the other two approaches have the major advantage of greater software flexibility. In addition, the other two approaches allow the mixing of hardware/operating system environments for the GIS and PMS software. For example, many installations utilize a GIS on a Unix network and a PMS on a personal computer (PC) network. The networks' common area allows file transfer between the hardware and operating systems.

PMS Data Export

The PMS data export approach requires an output utility in the PMS that will export the sectional data in a form that can be imported into the GIS for attachment to the line strings. This approach also entails the problem of making the line strings match the PMS analysis sections as in the total integration approach. Dynamic segmentation in the GIS can be used to overcome this limitation.

This approach has the advantage of not placing restrictions on the development environment used for the PMS, since the PMS and GIS communicate through file transfer and can use different software or reside on different platforms. This approach has the major disadvantage of requiring the user to use two separate systems—creating data on the PMS, but then having to perform data transfer to do graphical querying each time the PMS data are modified.

The PMS data export approach is generally preferable to the total integration approach because of the flexibility in software combinations available. The authors have implemented systems that use this approach in several cities, using FoxPro-based PMS, ARC/Info GIS software for map maintenance, and ARCVIEW for map display or queries.

Map Export

The map export approach requires an input utility in the PMS that can import the map file for use in a map display/query module that is a part of the PMS. The utility needs to have the capability for dynamic segmentation of the line strings to match the analysis sections.

This approach has the advantage of being easiest to operate for the PMS engineer. In addition, there are no restrictions on the development environment used for the PMS or the GIS. Data display screens, querying functions, and so forth, can be identical whether invoked in the map display module or in the text-based database functions.

In many situations, this approach offers fewer disadvantages. However, more complex PMS software is required to provide the map import and display or query capabilities. In addition, this approach may not be suitable if other GIS users require access to PMS data through the map. Table 1 summarizes the major advantages and disadvantages of each approach.

For the SCDHPT, the map export approach was selected since it provides the easiest-to-use solution for the PMS engineer and because the PMS software was then not restricted to using Intergraph/Informix. The selected approach required the capability for dynamic segmentation since the PMS allows dynamic sectioning to produce analysis sections from a detailed database. With this approach all map maintenance is still done on the Intergraph MGE system. The updated map is imported to the PMS on an annual or semiannual basis.

Highway Referencing and Map Data Connection

In all approaches to the PMS/GIS integration, a fundamental requirement is to achieve the connection between the data and the map graphics (line strings representing

TABLE 1 Summary of PMS/GIS Integration Approaches

	Total Integration	PMS Data Export	Map Export
Approach	PMS and GIS integrated in common software	PMS data exported to GIS for linking to map	Map exported from GIS to PMS for linking to data
Map Maintenance	GIS	GIS	GIS
Data Export / Import	No export / import	**Disadvantage**: PMS data requires export whenever data or analysis results change	Map requires export / import annually
Hardware platform	**Disadvantage**: GIS and PMS restricted to common platform	Data transfer allows PMS and GIS to exist on different platforms	Map transfer allows PMS and GIS to exist on different platforms
PMS Software Flexibility	**Disadvantage**: Limited by GIS software speed and capabilities	No limitations on PMS software	No limitations on PMS software
Consistency of User Interface	Consistent interface between PMS and GIS portions of system	**Disadvantage**: PMS and GIS have different user interfaces	Consistent interface between PMS and GIS (PMS map display) portions of system
Ease of Use for PMS Engineer	PMS engineer required to use GIS software -- generally a more complex approach	**Disadvantage**: Data transfer and required knowledge of two systems adds complexity	Greatest ease of use for PMS engineer
Segmentation	Dynamic segmentation required in GIS	Dynamic segmentation required in GIS	Dynamic segmentation required in PMS
Divided Highways	Generally only single lines are maintained in a map	Generally only single lines are maintained in a map	Lines duplicated in PMS
GIS Access to PMS Data	All GIS users could access PMS data	All GIS users could access PMS data	**Disadvantage**: GIS users cannot access PMS data

highways). Highway agencies use various referencing schemes to relate data to the highways, the most common forms of which are true mileage and mile posting with equations. In a true mileage system, all references to highway location are based on the true distance from the start of the highway. In mile posting with equations, all references are made to mile post markers that originally match true mileage but later do not, because of highway realignments, and so on. A series of mileage equations relates the mile post marker to the true mileage from the start of the highway.

True mileage referencing is easier to relate to the map line strings since the intermediate step of mileage equations is eliminated. A true mileage system is used in South Carolina.

Since the state map was digitized before the need to attach data, the information necessary to attach data to the map was nonexistent. Thus a manual step was required involving the entry of highway identification data and known mile points into an Informix database attached to the Intergraph map. Mile log sheets were produced from the Road Inventory System listing the mile points at each highway intersection. Line strings in the state map terminate at highway intersections (although there are often multiple line strings between intersections). Each line string in the map was manually selected in the GIS software and the associated highway identification data were entered. Unknown mile posts were entered as −1.0 to be replaced later by an interpolation routine. This provides the connection information to allow data to be connected to the map.

PMS Map Import Module

The SCDHPT PMS was implemented on a PC using FoxPro as the development environment since it provides the fastest database access available and very user-friendly interfaces can easily be implemented. Data are imported to the PMS from a variety of sources, including

1. Highway definitions and attribute data from the mainframe Road Inventory System,
2. Traffic data from the PC network Traffic Database System,
3. Structure history data from the Construction History Database, and
4. State map from the Intergraph system.

The PMS system concept overview is shown in Figure 1. The PMS/GIS interface is achieved through a map import module that includes the following functions:

1. Intergraph file conversion,
2. Highway mile post interpolation,

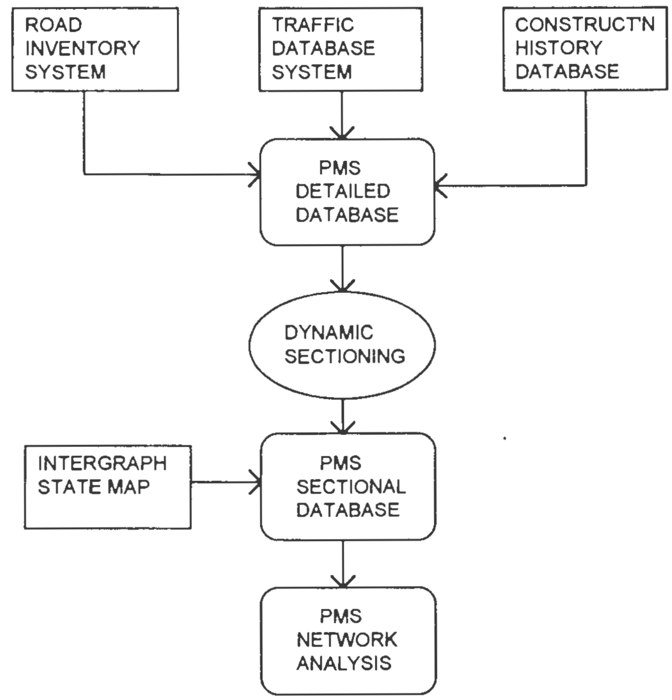

FIGURE 1 PMS system overview.

3. Divided highway duplication, and
4. Sectional database linkage.

Figure 2 shows the steps involved in achieving the GIS/PMS system interface through the map import and conversion.

Intergraph Map File Conversion

The Intergraph map file conversion function is used to import the Intergraph EDG file(s) into a FoxPro database. The EDG file is an Intergraph export file format produced by the MGE software and transferred to the PC for import. The individual map layers can be processed or updated individually. These layers include

1. Primary highways (including Interstate highways),
2. Secondary highways,
3. County and state lines,
4. City boundary lines,
5. Water (lakes and rivers),
6. County names,
7. City names, and
8. Maintenance district boundary lines.

Only the primary highway layer has PMS data attached in the system.

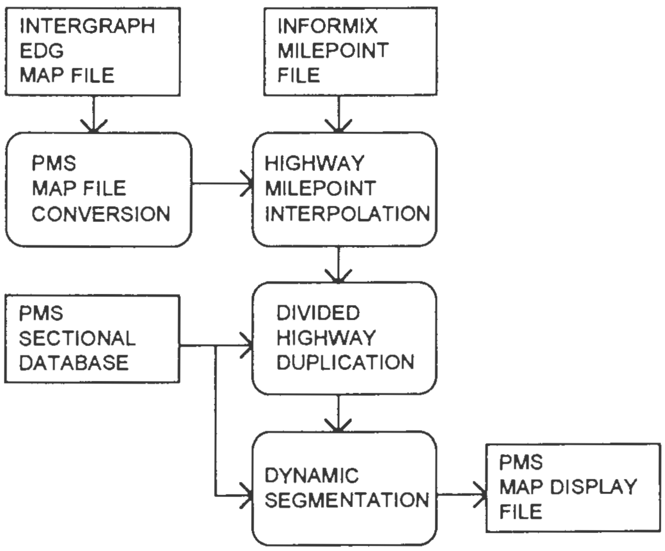

FIGURE 2 PMS map import and conversion process.

Highway Mile Point Interpolation

The highway mile point interpolation function is used to import the Informix milepoint file into a FoxPro file. Mile post interpolation is performed to fill in the unknown mile points on line strings based on the relative length of the map lines to the known mile points. The *x,y*-coordinates are ordered in the direction of increasing milepoint along a highway, by the conversion routine. In some cases, due to the random digitization, the line strings have to be reversed to achieve the directional order. Options within this function allow the user to report on map mile post linkage problems such as overlaps or gaps in the linkage.

Divided Highway Duplication

The divided highway duplication function is used to generate parallel lines for all divided highways in the state map. The state map maintained on the Intergraph system contains single lines representing a centerline map. This is a common problem in GIS systems. In the PMS, data are stored separately for each side on divided highways to allow separate performance and rehabilitation analysis. This function produces the parallel lines so that data can be attached to each side on the map. The distance between the parallel lines can be controlled by the user when setting up the map file. A larger-than-reality distance is required between the lines so that the data displayed along the lines do not overlap. At the network level, this provides sufficient accuracy.

Dynamic Segmentation

The dynamic segmentation function performs the linking of the sectional database to the PMS map display file. This is achieved through a resegmentation of the map line strings to match the PMS analysis sections based on concatenation of strings and breaking strings using interpolation. Section ID numbers are placed in the map display file to provide a relational linkage to the sectional database.

PMS Map Display Module

The PMS map display module is invoked in two locations within the system: in the database subsystem Sectional Map Display function and in the network analysis subsystem Optimization Result Map Display function. The Sectional Map Display function allows display and query of all sectional data; the Optimization Result Map Display function adds the capability to display projected work programs following an optimization run. As with the rest of the PMS, the display module was written in FoxPro using the dGE graphics library.

The system allows the selection of any county or maintenance district or the full state when starting the map display. When the map display is invoked, it displays the last view from the previous use (for the county/district/state).

The map display screen is shown in Figure 3. The main menu hierarchy for the map display module is shown in Figure 4.

The Map View menu includes functions for zooming, panning, and restoring a previous view. The Zoom In and Zoom Out functions retain the midpoint but modify the distance viewed by a factor of 2. The Zoom Locn function allows the user to draw a rectangle to define the location to zoom in to. The panning functions (Left, Right, Up, Down) pan the view with a 25 percent overlap. The Prev View function allows the user to return to the previous view; Init View returns to the initial view when the map display module was invoked; Full Map draws the full map view.

The Data menu function provides four functions for working with the PMS sectional data: Display is used to display data values along sections; the Point function is used to point and click on a section to bring up a screen of all of the data for the section; Query is used to highlight sections matching a user-defined condition; Range is used to color sections based on the ranges of data values.

The Data-Display function provides a menu of choices for data to be displayed along the sections' lines on the screen:

Hiway ID	Highway identification fields,
PQI	Pavement Quality Index (PQI) (overall performance index),
PDI/PSI	Pavement Distress Index and Present Serviceability Index,
Pave. Type	Pavement type,
Structure	Year of most recent rehabilitation and rehabilitation type,

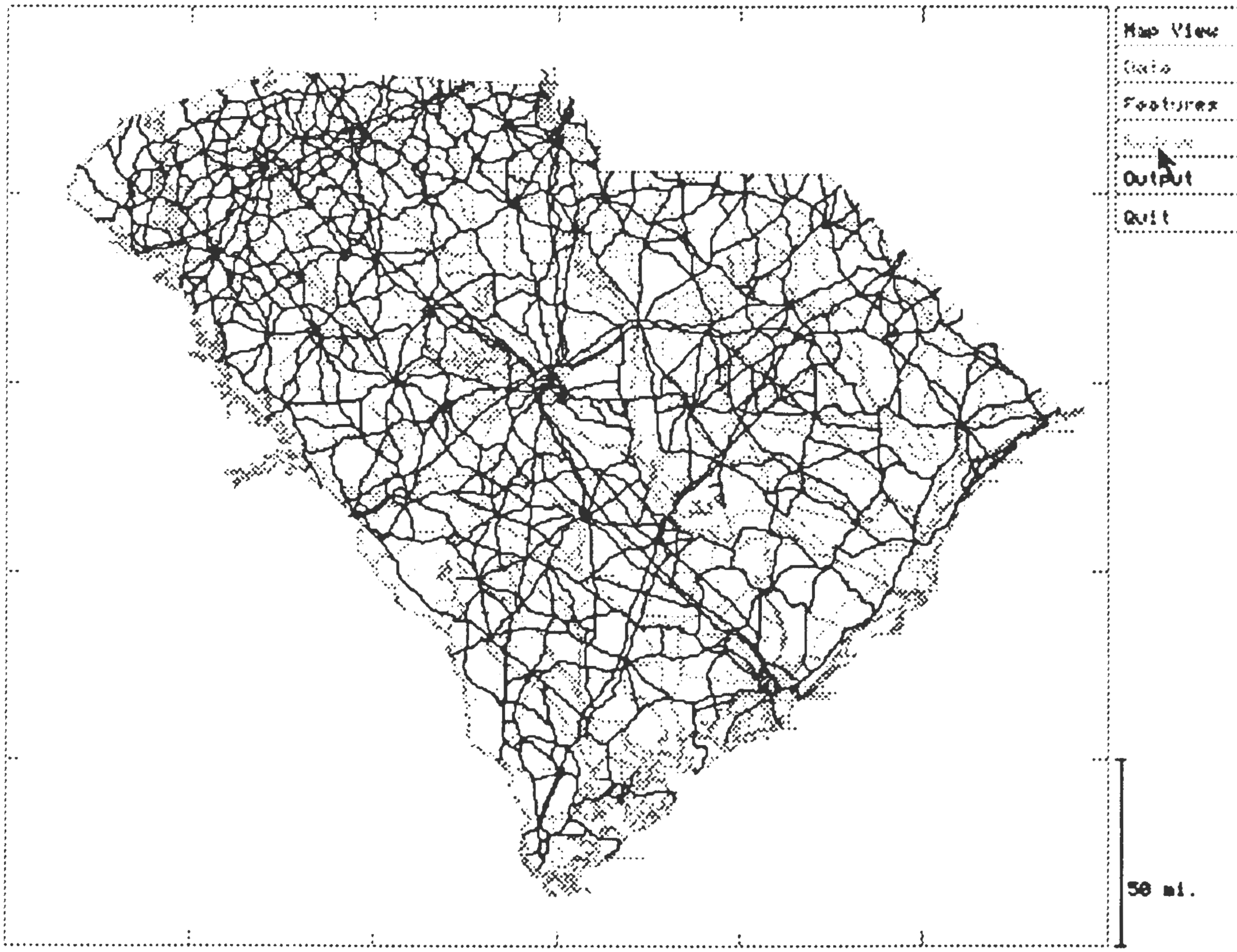

FIGURE 3 Map display screen.

AADT	Average annual daily traffic, and
Select	Provides a list of all sectional data fields for user selection of any field.

When the map display is invoked from the optimization reporting function, the projected type of rehabilitation for the selected optimization run is available on this menu. Figure 5 shows a view with PQI data displayed.

The Data-Point function allows the user to point and click on a section using the mouse. A screen of the sectional data is then displayed as shown in Figure 6. This is the same screen accessed through the nonmap database function for data browsing. Buttons on the screen allow the popup of distress and history data.

When the map display is invoked from the optimization reporting function, the sectional data screen includes the details of the projected rehabilitation for the section for the selected optimization run. A graphical screen plot showing the projected performance with and without the rehabilitation strategy is also available through this

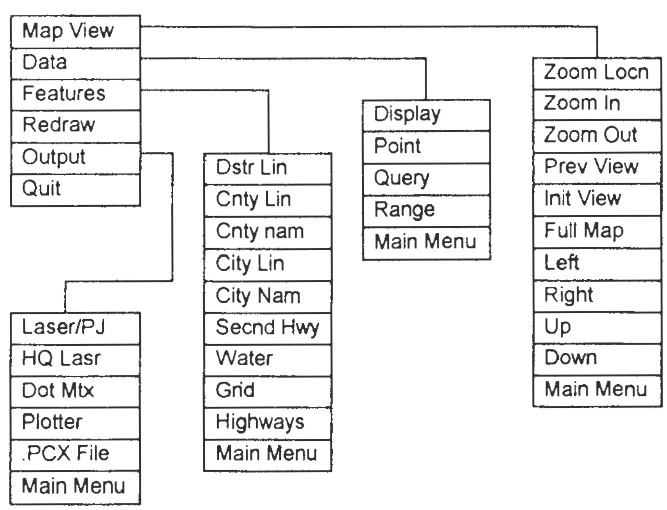

FIGURE 4 Main menu hierarchy.

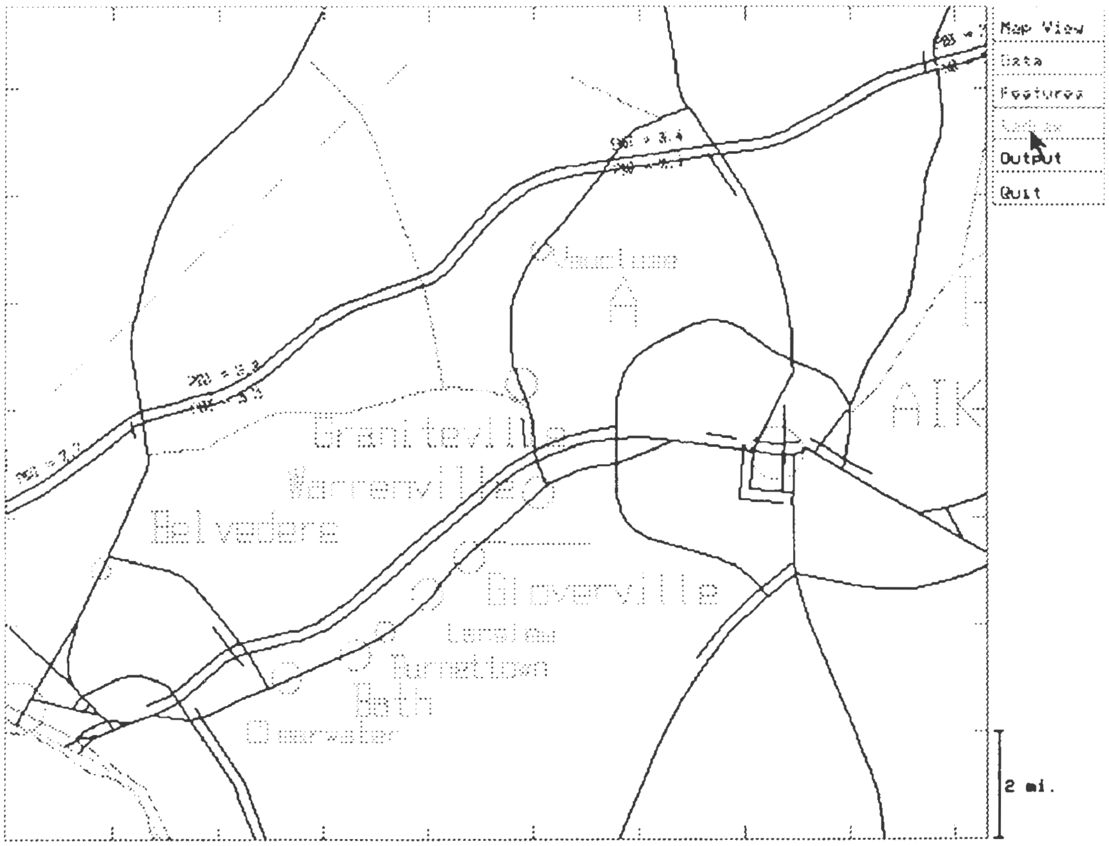

FIGURE 5 Map view showing PQI data displayed on sections.

screen. This is one of the major advantages of this approach to PMS/GIS integration—the standard PMS graphs and screen displays can be accessed through the map.

The Data-Query function allows the user to define a query based on any combination of conditions and then highlight the sections matching the query on the map display. This function uses the same flexible query builder as used throughout the PMS, allowing any combination of any of the sectional database fields.

The Data-Range function provides a menu of choices for data items to be used to color the sections based on ranges of the data:

PQI	Pavement Quality Index (overall performance index),
PDI	Pavement Distress Index,
PSI	Present Serviceability Index,
Surf Year	Year of most recent rehabilitation,
Pave. Type	Pavement type,
AADT	Average annual daily traffic,
ESALa	Annual equivalent 18-K axle loads,
SN	Structural number,
Func. Clas	Functional class, and
Def. Range	Allows the user to define a new set of ranges for the selected data item.

When the map display is invoked from the optimization reporting function, the projected year of rehabilitation for the selected optimization run is available on this menu.

The Features menu includes functions for toggling the inclusion of the various map layers, as well as for the display of grid lines. The map layers include district boundary lines, county boundary lines, county names, city boundary lines, city names, secondary highways, water (lakes and rivers, etc.), as well as primary highways.

SUMMARY

Three general approaches are available in PMS/GIS integration: total integration (where the PMS is implemented within the GIS software), PMS data export (where the PMS data are exported and then imported into the GIS), and map export (where the map is exported from the GIS and then imported into the PMS).

The total integration approach has the major disadvantage of limiting the choice of software used, since the PMS is limited by the GIS software, and often results in a less flexible system. This approach is best suited to an agency where there is a mandate for total integration or where the PMS engineer is comfortable with the limitations of the GIS software.

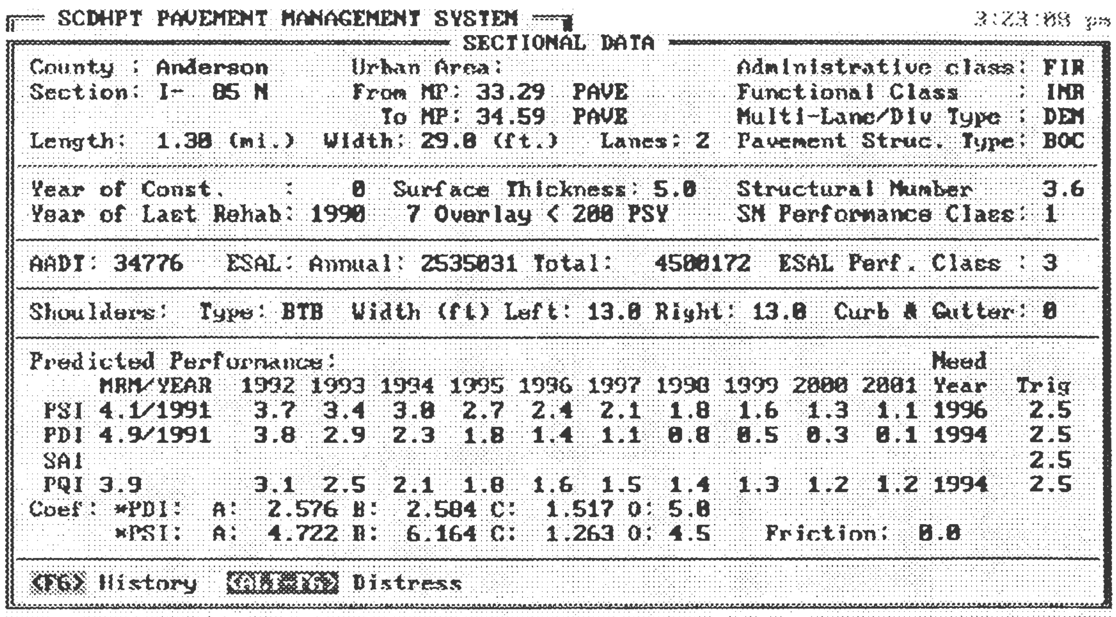

FIGURE 6 Sectional data screen.

The PMS data export and the GIS map export approaches both have the advantage that the different software can reside on different platforms allowing greater choice in the type of systems to be implemented.

The PMS data export approach has the major disadvantage of requiring the user to use to separate systems—creating data on the PMS, but then having to perform data transfer to the GIS each time the PMS data are modified to do graphical querying.

The map export approach has the advantage of being easiest to operate for the PMS engineer, allows greatest flexibility in software choices, and generally has fewer disadvantages.

The map export approach was selected in South Carolina for the implementation of the PMS and integration with the ongoing GIS implementation project. This allowed the development of a full-featured PMS on a PC workstation, incorporating map display capabilities, with the transfer of the highway map to occur on an annual basis to provide map updates.

A map import module was included in the PMS to convert the GIS (Intergraph/Informix) map into a FoxPro database. The conversion includes duplication of lines for representation of divided highways, as well as dynamic segmentation of the map lines to match the PMS analysis sections.

The PMS map display module provides an easy to use graphical display and querying tool for the PMS engineer. This module allows control of the features to be displayed, flexible map view manipulation, point-and-click selection of highway sections for full data display, display of data items along highways, coloring highway sections to match queries, and coloring highway sections by ranges of values for data items.

BETTER INFORMATION AND BETTER MONITORING PROCEDURES

Framework of Performance Indicators for Managing Road Infrastructure and Pavements

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Performance measures are the basic input to a variety of decision processes and activities in infrastructure management. These include charting progress toward achieving operational, sectoral, and policy objectives; assessing whether users are receiving services that they want at the level of quality that they are willing to pay for; and comparing competing or alternative service producers to determine the most efficient provision arrangement for infrastructure services. A framework is presented for defining consistent measures of infrastructure performance, particularly for roads and pavements. The framework identifies relevant indicators and the linkages between them. Because there are changes over time in information needs and in the types of agencies using performance indicators as well as in their relationships to one another, a framework is needed to maintain consistency in the information bases used and to update the indicators to ensure relevance. Performance is measured at five major levels: (*a*) service quality and reliability from a user's point of view; (*b*) network size and condition from a facility's point of view; (*c*) operational efficiency and productivity from a service provider's perspective; (*d*) sectoral performance measures such as investment, pricing, and provision arrangements; and (*e*) institutional performance indicators such as the effectiveness of the expenditure program, enforcement of vehicle weights and dimensions, and so forth. These are applied to the management of pavements with a listing of all the road network and user indicators but defining the measures and data quality only for the pavement component.

A number of changes in the past decade with respect to customer demand, regulation, technology, competition, and resource availability have created a focus on the performance of all infrastructure systems. Road infrastructure must increasingly be viewed in its macro context, from both an economic and an institutional perspective. Changes in ways of providing road infrastructure,—including, for example, the provision of roads and toll roads by developers—as well as a general decline in resources available for investments in road infrastructure—have made it necessary to allocate resources more efficiently across competing alternatives. Such efficiency can be achieved only if the nature of performance information used for determining the allocation strategies is consistent across the competing alternatives, which requires aggregating data from different sources and various spatial and time phases. These requirements present a need and an opportunity to reconsider the definition of performance and to develop a framework that allows integrated consideration of functional, environmental, technical, financial, and institutional issues.

Performance Measures: Objectives, Users, and Uses

Performance measures serve the following objectives:

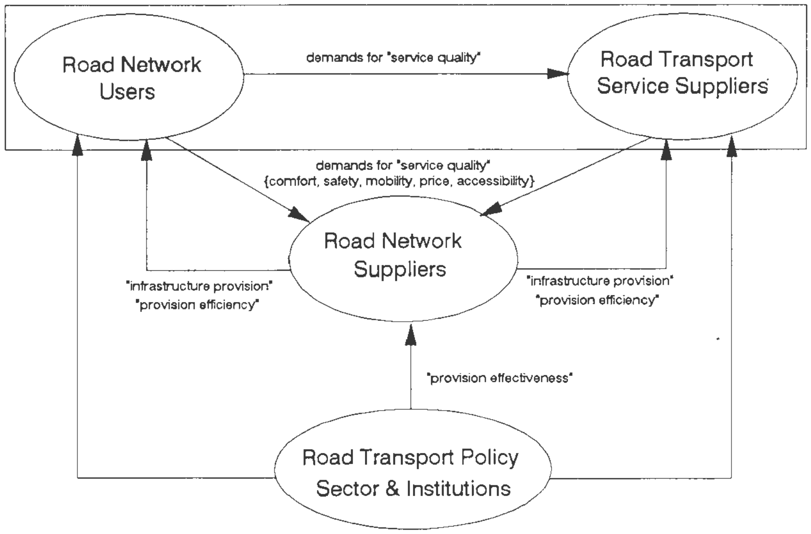

FIGURE 1 Users of road sector performance indicators.

- As a management decision-making tool they provide inputs for managerial decisions that address issues such as investment levels, maintenance expenditures, and frequencies and for day-to-day operating decisions on matters such as traffic management (*1,2*).
- As a diagnostic tool they provide an early warning system that can identify critical locations for investment and allow actions to prevent undesirable outcomes, such as accelerated deterioration of pavements (*3*).
- As a tracking and monitoring tool they help assess the adequacy of government and managerial policies by providing measures of effectiveness and mechanisms for charting the success of predefined policy objectives (*4*).
- As a signaling system they provide information to users (e.g., communities monitoring the effectiveness of municipal roads and streets) from the suppliers of infrastructure services, and they also provide information to suppliers (e.g., about safety targets at intersections) from policy makers in order to guide action toward desired outcomes (*5*).
- As a resource allocation tool they support the efficient distribution and control of public resources by quantifying relative efficiency of investments across competing alternatives [see, for example, work by Dole and Barnhart (*6*), who use performance data as an input to resource allocation ratios across states and local governments].
- As information systems they track construction costs and other data of relevance for constructing and managing infrastructure (*7,8*).

Which particular performance indicators are of interest depends very strongly on the view of the party involved in the uses of the indicators. These parties include road users, transportation service suppliers, road network suppliers, and regulating agencies, as shown in Figure 1. For example,

- Private users of road networks, such as passenger cars and pedestrians, demand a high quality of services from road transportation service suppliers (trucking and bus transportation agencies) as well as comfort, safety, mobility, affordability, accessibility, and a good driving environment.
- Commercial road transportation service suppliers are concerned with the service qualities of the road network and the impacts of policy decisions on transportation operations.
- Road network providers (owners and investors), roadway service suppliers (managers and operators), and producers of materials and services used in the supply of roads are concerned with efficiency, productivity, and effectiveness in satisfying user demands.
- Road transportation policy institutions (including regulators and enforcers) are concerned with the efficiency of investment allocation to various road agencies, with pricing and cost recovery for road-related use (e.g., fuel prices, tolls) and with compliance with road laws and regulations (e.g., safety and vehicle weights and dimensions).

Current practice in assembling performance information has several limitations. First, the data are collected by a variety of agencies, with or without formal performance-monitoring frameworks and systems, and they are collected for a variety of purposes. Second, the performance data collected often differ in nature. For example, there might be differences in (*a*) the type of data collected; (*b*) the level of detail, precision, and reliability with which they are collected; (*c*) the frequency in space and time at which they are collected, processed, and published; and (*d*) the frequency with which the various data items are updated as well as the currency of existing data types. Third, the consistency in performance data collection is variable across time, and hence the relationships between different forms of data collected across agencies are not easily established. Because of these factors, existing performance data do not lend themselves to easy aggregation. Furthermore, with increasing focus on performance, the various uses and users of performance information increasingly need to be integrated, which means that a common and consistent framework for defining, collecting, and aggregating performance information is needed.

Framework of Performance Measures

The appropriate identification of performance indicators is crucial to allow proper management and monitoring of a network of infrastructure and the flow of services generated by such a network. The set of indicators selected should measure the following:

- Whether operational, sectoral, and policy objectives are being met;
- Whether user demands are being met and to what degree the users of the provided services are satisfied;
- Whether the service providers are performing as efficiently as expected; and
- Whether the actions desired by policy makers (e.g., regulators) are being carried out and whether policy makers' actions are creating bottlenecks for service producers.

A subset of indicators that captured multiple effects and covered more than one of these four dimensions would be ideal. To satisfy these needs, performance can be viewed from five perspectives, namely, infrastructure provision, service quality, provision efficiency, provision effectiveness in sectoral aspects, and provision effectiveness in institutional aspects.

The perspective of infrastructure provision, in the case of roads, includes indicators relating to the characteristics of the road system and network such as the size, value, and distribution of the network; it also represents the performance of the facility in meeting demand for availability and access to road transportation users. The perspective is that of government and the owners of the facility considering the size, value, utilization, and appropriateness of the road stock.

The service quality indicators reflect the user's perspective, which can be measured in two ways. The first of these is in terms of the end product to the user—for example, whether the user actually receives the services desired and whether there has been an alteration, cessation, or total loss of service. This category of indicator relates more to expected than to actual quality of service. The second way of measuring service quality relates to how the services have been delivered—for example, the integrity of suppliers with respect to tolling, charging users, handling user queries, and responding to reports of incidents (e.g., accidents and slipperiness) and requests for service improvements, as measured by time required or promptness of response. This category of indicator relates more to realized than to expected quality of service.

The indicators of provision efficiency measure characteristics of the infrastructure providers and the level and efficiency of supply. Generic indicators include measures of productivity and efficiency, quantity of works delivered, and resources required per unit of output (such as employment and expenditures).

Provision effectiveness is measured in terms of achievement with respect to a goal or policy objective. At the sectoral level, effectiveness concerns measures of the overall adequacy of infrastructure provision and quality from economic, social, technical, and environmental perspectives. At the institutional level, relevant issues include the effectiveness of long-term supply strategies (maintenance backlog), the economic returns of investments in infrastructure, the ability to recover costs, and the functioning of the regulatory and enforcement bodies.

Application to Management of Road Systems and Pavements

In this section, the framework is defined for the management of road systems and in particular for road pavements. By simple extension it could also be applied to other infrastructure pavements such as airfields and industrial pavements.

The performance indicators are identified in Tables 1 through 5, one for each performance perspective, by aspect, level of detail, and unit of measurement. Under aspects, related indicators are grouped together. For example, in the case of infrastructure provision, the aspects relate to road system size, asset value of the road system, users of the system, demographic and macroeconomic environment, availability of the road system to users, and utilization of the road system.

The indicators are organized around two levels of detail. The first is general, providing the macrolevel indicators that would be used in public statistics. These indicators are readily understandable without a specialist's knowledge, but each has an objective definition and is derived from a reproducible base. The indicators provide sufficient information to chart progress toward the various performance objectives and to generate the type of information necessary for performing cross-national, cross-state, or cross-interest-group comparative studies.

The second level of detail in the tables is more comprehensive, providing the objective, detailed information on which the first level is based. Generally, this level comprises the data that would actually be measured or retrieved from a data base, and it includes the subdivision of the indicator data into smaller subunits likely to be relevant to particular applications or user groups.

The tables also present the preferred units of measurement for each of the indicators, as well as the method of reporting and aggregating the data collected. In some cases concurrence is yet to be reached on the standardization of units. In these cases the units shown are the authors' recommendations, based on their experience in international-sector studies and cross-national evaluations. In the performance perspective tables that follow, the aspects presented are somewhat selective for reasons of space; they are not exhaustive.

Infrastructure Provision

The indicators for the provision of road infrastructure characterize the size and value of the asset, the user environment, and the connection between these. They are used in tracking the amount of the largely public asset, the size of demand, and the adequacy of the road system for the demand environment. In Table 1 these uses are met by identifying the indicators within the following six aspects.

Network Size

The network size must be defined in terms of the primary elements of the publicly used road network. Road length is the total length that can be traveled by users; it is frequently subdivided at the secondary level by administrative, functional, technical, and subsectoral categories. Road space, defined here in terms of lane kilometers, is a measure of the space available for occupancy by vehicles and of the expansion of the network. The lane-kilometer unit defines space in a more meaningful way than would a unit of pure area (say, square meters); it directly translates into average number of lanes (for any road group) when compared with road length; and it is a more effective base for estimating maintenance costs than is simple road length.

Road structures should be grouped and measured in number at the primary level, that is, bridges and tunnels, and distinguished by type and class at a secondary level measured in both total length and number. Road-ferry and missing or unclassified links should be grouped as extramodal links. Road reserve area, in area units such as hectares, is a measure of land ownership and utilization.

Asset Value

The value of infrastructure assets (roads, bridges, tunnels, and road furniture) is an important measure of the capital invested and at risk in a road system; it generally constitutes from 2 to 17 percent of gross national product (GNP). It is best quantified in terms of current replacement value, which is the cost of reinstating existing structures to the as-new condition of existing standards.

Road Users

The user population is characterized by the indicators vehicle fleet and motorization. Detailed fleet data (second level) would include the composition in various categories. The present vehicle classifications extant in many countries need to be rationalized or summarized in the light of policy needs and new traffic-sensing technology. The level of motorization is one of the important indicators of the potential for growth in vehicle ownership and hence traffic growth; it can be sensitive to vehicle pricing policies.

Demography and Macroeconomy

The demographic and macroeconomic environment is an important determinant of demand and utilization of capacity, sustainability and revenue generation, and the costs of provision. The primary indicators are total population, country area, urbanization, and GNP.

Availability

The availability of the road network for consumers is typified by the network density (in kilometers per 100 square kilometers) and road-space availability per capita. The availability for producers and the economic sustainability of the network are characterized by road space per unit GNP, termed road-space sustainability.

Utilization

Utilization reflects the realized demand from users, which is sensitive to service quality, economic factors, and regulatory policies. It is a strong determinant of total energy consumption and total vehicle emissions. The prevalent indicator is vehicle travel, colloquially known as VKT (vehicle kilometers traveled per year), or VMT (vehicle miles traveled). Secondary indicators are transportation-oriented aspects such as heavy vehicle travel, passenger travel, and freight travel, which are useful adjuncts distinguishing the main user types for policy purposes. The traffic volume level on the network is the mean traffic volume, calculated from the vehicle travel divided by the road length.

Service Quality

The quality of service sought by users consciously or subconsciously relates to perceptions of (*a*) quality of the surface and functionality of the facility, (*b*) safety risk, (*c*) ease of using the facility in terms of the quality of mobility and the risks of delay and access denial, (*d*) costs of usage and particularly the avoidable vehicle operating

TABLE 1 Indicators of Infrastructure Provision

ASPECT	INDICATOR	UNITS[1]	NOTES & SOME SECOND-LEVEL INDICATORS
NETWORK SIZE	Road Length	km	Lengths: by road class, jurisdiction, function, technology, (surface type), subsector (interurban, urban, rural)
	Road Space	lane-km	Total and by road category (access-controlled, primary, secondary, tertiary)
	Bridges and Tunnels	m number	Bridge and tunnel categories.
	Extra-modal Links	m number	Road-ferry and Road-rail links, etc.
	Road reserve area	ha	
ASSET VALUE	Replacement value	$M	Current replacement value by component (roads, structures, furniture, facilities, land area)
USERS	Vehicle fleet size	Mveh.	Vehicle fleet, i) by category, heavy, light; ii) class: articulated trucks, trucks, buses, lights, cars, other motorized.
	Motorization	veh/1000 inhab.	Licensed drivers (licensees per 1000 inha.)
DEMOGRAPHY & MACROECONOMY	Total population	inhabitants	
	Area of country	km^2	II: Climate range, topography, etc.
	Urbanization	%	
	Gross National Product	I$M	
AVAILABILITY	Network density	$km/100km^2$	
	Road-space availability	lane-km/M inhab	
	Road-space sustainability	lane-km/$M(GDP)	
UTILIZATION	Vehicle travel	G.veh-km/yr	Vehicle Travel by road class and vehicle class.
	Traffic density	veh/lane-day	
	Passenger travel	psg-km/yr	
	Freight travel	tonne-km/yr	

Note:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

costs, and (*e*) judgments by users and nonusers on the usage environment of air quality and noise. The indicators proposed for these various aspects are defined in Table 2 and discussed in the following.

Road Surface

The primary performance characteristics demanded of the pavement surface by road users are riding quality, tracking quality (that the surface be free from bias by ruts, grooves, uneven crossfall, or excessive crossfall), friction quality (having sufficient skid resistance, dependent on demand, and minimal potential for hydroplaning), minimal spray and splash, and acceptably low surface noise levels.

It is proposed that all the service quality characteristics demanded of the road surface be summarized in just two new indicators, one representing all aspects of ride and tracking (because these all relate to profile and demand for 100 percent of travel time) and one representing all aspects relating to the safety supplied by the road surface (which is in varying demand, depending on location and time). The indicator dimension should be the incidence of adequate, tolerable, and inadequate levels of service, and the relevant weighting is by vehicle travel, because that is the appropriate dimension of exposure and demand.

The ride and tracking quality would combine measures of longitudinal unevenness, transverse unevenness, and interior noise ratings. Preferably the indicator should be defined as a quantitative function of objective measures, for example, roughness/unevenness [using the international roughness index (IRI) in meters per kilometer], rut depth mean divided by rut depth standard deviation, macrotexture and megatexture depths, and normalized with respect to the nominal traffic speed or the standard for the given road class. Some effort is required to formulate and gain consensus on this indicator.

The Surface Safety Adequacy would combine a measure of the skid resistance and hydroplaning potential relative to demand. A good model for this is the British two-level classification of adequate or investigatory friction determined from sideways force coefficient (SFC) values relative to standard values for 13 categories of road site (*9*). Similar demand levels could be set using other measures, such as skid number, or the new international friction index expected to emerge from the recent international experiment (*10*). A similar approach to classifying hydroplaning potential would involve the parameters of

TABLE 2 Indicators of Service Quality for Roads and Pavements

ASPECT	INDICATOR	UNITS[1, 2]	NOTES & SOME SECOND-LEVEL INDICATORS[3]
ROAD SURFACE	Ride and Tracking Quality Surface Safety Adequacy	Incidence (% VKT) [A/T/I] Incidence (% VKT) [A/T/I]	Surface profile measures = {IRI, RDM/RDS, TX2, Vnom} Skid resistance relative to demand, hydro-planing potential
ROAD CORRIDOR	Geometric Standard Driver Guidance Collision Mitigation	Incidence (% km) [A/T/I] Incidence (% VKT) [A/T/I] Incidence (% VKT) [A/T/I]	{Curvature, Gradient, Width, Shoulders, Sight Distance} Road markings, signage, message Barriers, obstacles, distractions
USER SAFETY RISK	Fatality risk exposure Injury risk exposure Accident risk exposure	fatalities/100k. veh-km injuries/100k. veh-km accidents/100k. veh-km	
MOBILITY QUALITY	Total Vehicle Delay Incidence of Congested Flow Average travel speed	veh-hrs incidence (% VKT) [A/T/I] km/h	{Nominal speed, Avg. travel speed, VKT} Ranges of V/C, incidence adjusted for time and length by VKT. Average speeds by road class, adjusted by VKT.
ACCESSIBILITY QUALITY	Link closure incidence	No. link-days	Number of days a link is impassable (washout, flooding, blockage, etc.) annually summed overall links.
ROAD USER COST	Average VOC/veh-km Avoidable VOC	I$/veh-km I$/veh-km	 [Program Total VOC - Optimal Program Total VOC]/Total VKT
ENVIRONMENT	Emissions incidence Noise incidence	% km [A/T/U] % km [A/T/U]	Time subject to elevated levels, location of areas Time subject to elevated levels, location of areas

Notes:
1. Code for compliance categories: A = Adequate; T = Tolerable; I = Inadequate.
2. Units: I$ = Reference Currency (US$, ECU, etc) indexed to normative year's value. $ = Reference currency in nominal (current) value.
3. VKT = veh.km/yr travelled; RDM = rut depth mean, RDS = rut depth standard deviation; TX2 = macrotexture TMS depth, mean; Vnom = nominal (design or posted) speed; V/C = volume-capacity ratio; VOC = vehicle operating costs; [] = expression; {} = function.

macrotexture, permeability, crossfall, road width, superelevation transition, and gradient, or simply a median value of surface water-film thickness.

User Safety Risk

The user safety aspect of performance is the extant levels of bodily risk to which the user is exposed through use of the road facilities; this involves many more factors than the surface characteristics. The appropriate indicator is the extant risk relative to the level of exposure, namely the fatality, injury, and accident risk exposures, determined from the annual rates relative to vehicle travel, that is, per 100 000 VKT.

Mobility Quality

Mobility needs are experienced through the amount of delay in travel times, the uniformity and level of traffic flow, and the overall travel time required to make a trip. Indicators of the quality of service are difficult to measure and rare in practice but sorely needed. Those suggested include total vehicle delays, in vehicle hours; delay risk, defined by the spatial incidence of encountering acceptable, tolerable, or inadequate traffic flow; and average travel speed, most usefully separated into interurban travel speed and urban travel speed.

Accessibility Quality

The quality of the access to road space is dependent on how often the road space is not available because of impassability, closure, blockage (by debris or snow), washout, flooding, and so forth. The duration of impassability is, in turn, an indication of the responsiveness of the maintenance agency. Since closure affects the utility of the entire link, the indicator is the link-closure incidence, in units of link days closed per year.

Road User Cost

The costs of vehicle operation (VOC) in the system are an indication of how well the benefits of the road expenditures are transferred to the user. The key element relevant to service quality is the level of avoidable user costs, which is the difference between the extant costs and optimal user costs. The most appropriate measure is relative, such as percentage of the optimal cost, which avoids currency units. Ideally the base optimal VOC should be the unconstrained optimum, because both underspending and budgetary constraints are restrictions on the service quality delivered to users. The extant VOC is the total VOC calculated for the network under current conditions at the beginning of the program year. The base total optimal VOC is that calculated for the theoretically optimal program of works and expenditures, without budgetary constraint. Calculation of the optimal VOCs must rely on the use of a life-cycle simulation analysis [such as HDM-III (*10*) or a similar model].

Provision Efficiency

The efficiency indicators address the productivity and efficiency of the agency providing the inputs into the road system. The productivity is the measure of the resource throughput (quantity of works, amount of expenditures, number of staff, equipment, etc.) during the defined period. The efficiency is the measure of how much resource was required to produce a unit of output.

Table 3 presents certain aspects and indicators of provision efficiency. The aspects relevant to pavement management include expenditure productivity, output productivity (works, operations, etc.), output efficiency (output per unit of resource, such as expenditure or employee), and provision mode (use of public and private providers). Omitted here for brevity's sake, for example, is a description of the service providers (financiers, constructors, owners, managers and operators, manufacturers) and their respective modes of provision (private contract, own account, etc.).

Expenditure Productivity

Statistics of expenditures are commonly used, fulfilling a general auditing type of function. For primary performance indicators, the expenditures should be aggregated and summarized in ways that relate to the major purposes of funding. The four categories recommended as suitable for universal use, which avoid the diverse uses of financial terms such as capital, investment, and recurrent, or work categories such as construction and maintenance, are the following:

- Adjustment expenditures: expenditures for all works of extension (new construction, new roads and structures, etc.), betterment (upgrading of surface or functional standard, realignment, minor widening), and expansion (additional lanes, highways, etc.) to the road networks, inclusive of pro rata administrative costs when these works are executed by public agency staff (i.e., realistic overhead costs).
- Preservation expenditures: expenditures for all other works on the existing system (pavement, structures, furniture) such as rehabilitation, resurfacing, restoration, routine maintenance, emergency maintenance, and so forth, inclusive of pro rata administrative costs when these works are executed by public agency staff (i.e., realistic overhead costs).
- Operations expenditures: expenditures for all traffic management (traffic control, control equipment, staffing), safety management (enforcement of safety measures, vehicle weights and dimensions, incident response, etc.).
- Administrative expenditures: expenditures on policy development, regulation, the preparation of expenditure plans and work programs, supervision of contracts and agencies, monitoring of road system conditions.

Output Productivity

The indicators for output productivity are the quantities of service provided during the period. For works, the as-

TABLE 3 Indicators of Provision Efficiency for Roads and Pavements

ASPECTS	INDICATORS	UNITS[1]	NOTES & SOME SECOND-LEVEL INDICATORS
EXPENDITURE PRODUCTIVITY	Total Expenditures	I$	Civil works expenditures, total and allocation by works category.
	Adjustment Expenditures	I$	All extension, betterment and expansion works expenditures
	Preservation Expenditures	I$	All other works expenditures on the road system
	Operations Expenditures	I$	Traffic and safety management expenditures
	Administration Expenditures	I$	Preparation and supervision of policies, plans, programs, etc.
OUTPUT PRODUCTIVITY	Adjustment Works	lane-km	
	Preservation Works	lane-km	
	Operations Works	veh-km	
OUTPUT EFFICIENCY	Average Preservation Cost	I$/lane-km	(Civil works expenditures/VKT: Total, and by works category.
	Average Operations Cost	I$/veh-km	Operations includes traffic management, enforcement, emergency support, etc.
	Expenditure-staff ratio	I$/employee	Total expenditures/total agency staff.
	Employment-Output Ratio	p-yrs/veh-km	Total agency staff/Annual Vehicle Travel
PROVISION MODE	Private Supply Participation	%	Contract expenditures/Total expenditures.
	Contract: Force Account Expenditure ratio	%	Contract expenditures/Agency force account expenditures.

Note:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

pects are similar to those for expenditures, that is, adjustment works measured in road space (lane kilometers), with subsets of space added, upgraded, or bettered; preservation works measured in road space when presented in aggregate or in subsets of road space for pavement rehabilitation and resurfacing, number of structures for structures works, and road length for routine maintenance. Fairly typically, agencies would report the subsets within each aspect since the distinctions are of interest, but those should be considered as second-level indicators.

For operations, the relevant indicators would be vehicle travel, number of incidents, and so on. For administration, the indicators would comprise, for example, number of projects, road space monitored, and so forth.

Output Efficiency

The output efficiency indicators provide summary measures of the unit costs of delivering the output services. The average preservation cost, in expenditures per unit of length, and average operations cost, in expenditures per unit of vehicle travel (vehicle kilometers per year), will indicate over time how well the agency is managing to contain or reduce costs of preserving and operating the existing road system. The adjustment works cost is the expenditure per unit of road space provided, that is, constant currency per lane kilometer.

Useful indicators for human resources are the expenditure-staff ratio, indicating the total expenditures disbursed per staff employed, and employment-output ratio, being the total person years involved per unit of output (for an aggregate indicator the unit of output should be vehicle travel, but in subsets the unit of output should be road space for works and vehicle travel for operations). As the institutional efficiency rises and as more services are supplied under contract, this indicator should decrease significantly.

Provision Mode

The extent to which the private sector is involved in the supply of services is indicated by the private supply participation, being the proportion of expenditures implemented through the private sector. The contract volume, measured in terms of funds and number, is a second-level indicators.

Sectoral Effectiveness

The sectoral effectiveness perspective of provision concerns how closely the condition and operation of the road facilities match the optimal state. These are the technical and functional qualities as evidenced by the physical condition of the facilities and the quality of service provided to road users. The primary aspects of relevance to pavement and road management are presented in Table 4.

Roadway Function

Roadway function assesses the provision, in technical dimensions, of those components that affect service quality to the user. Being viewed from the sectoral rather than the service perspective, the indicators measure the spatial incidence of adequate standards achieved by the provider or providers.

TABLE 4 Indicators of Sectoral Effectiveness

ASPECTS	INDICATORS	UNITS[1, 2]	NOTES & SECOND-LEVEL INDICATORS
ROADWAY FUNCTION	Evenness Adequacy	% lane-km [A/T/I]	{Roughness incidence (km x IRI-level)}
	Friction Adequacy	% lane-km [A/IV]	Incidence of skid resistance not at investigatory level.
	Blackspot Incidence	No./1000 km	
	Traffic Flow Adequacy	% lane-km [A/T/I]	Thresholds of average travel speed or volume/capacity ratio.
	Environmental Adequacy	% km [A/T/I]	Thresholds of adequate noise, vibration and exhaust emissions.
PRESERVATION EFFECTIVENESS	Pavement Condition	% lane-km [G/F/P]	{Roughness (IRI), Residual Capacity, Surface Distress (SDI)}
	Sideworks Condition	% units [G/F/P]	Sidework components (sidedrains, signs, barriers, culverts, etc.)
	Structures Condition	% units [G/F/P]	{Bridge, tunnel condition scores: incidence by structure class}
ROAD SAFETY	Total fatalities	persons	
	Total injuries	persons	
	Total cost of accidents	I$M	
	Number of accidents	Number	

Notes:
1. Code for compliance categories: A = Adequate; T = Tolerable; I = Inadequate; G = Good; F = Fair; P = Poor; FD = Functionally Deficient; IV = Investigatory.
2. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.

Ride quality concerns can be assessed from evenness adequacy, which is the incidence of road space where road roughness is better than the adequate and tolerable thresholds defined from an economic optimization analysis. This yields thresholds that become progressively tighter as traffic volumes and speeds reach higher levels. The roughness and thresholds are best defined in terms of a standard unit such as the IRI.

Safety concerns can be assessed from friction adequacy, which is the incidence of adequate road surface friction where the friction available has not dropped to investigatory levels (*9*). The blackspot incidence, in number of blackspots per 1000 km of road length, is another indicator that is useful when blackspot is defined.

The provision of capacity and management of congestion is assessible by traffic flow adequacy, which reflects the spatial incidence of adequate capacity and road geometry. To cover this range, the most objective measure of adequate flow is one such as this: "The average travel speed exceeds 0.8 of the general posted speed for at least 90 percent of the time." Finally, environmental adequacy would indicate the road length over which noise, load vibration, and exhaust emissions met applicable standards.

Preservation Effectiveness

The aspect preservation effectiveness assesses the adequacy of response to preserving the condition and integrity of the infrastructure asset. Here, the indicators measure those factors affecting the physical condition rather than function of the facility. These would include indicators for each of the major components of a road facility, such as pavement condition, sideworks condition, and structures condition. Condition is represented by a composite indicator, normalized by thresholds depending on the technology, environment, and use. Incidence would be expressed in terms of road space for pavements, road length for sideworks, and length for structures.

Pavement condition has three elements that would be distinguished at a secondary level. There are: (*a*) pavement residual capacity, a structural measure of the remaining life of the pavement in terms of structural capacity for the traffic load being carried; (*b*) roughness (or unevenness), the surface profile element measured in IRI units; and (*c*) pavement distress index, the surface integrity element, which could be an index such as the pavement condition index (PCI) (e.g., ASTM D5340-93), or preferably another distress index that distinguishes between maintenance inputs and pavement distress. The combination of these into a single indicator, condition, can be done using one of a number of existing indexs and defined values of good, fair, poor, and bad.

Sideworks condition measures the defects in the sideworks components (comprising surface drains, culverts, verge, signs, barriers, etc.). An effectiveness indicator for sideworks could be based, for example, on the quantitative ratings given in an Organization for Economic Cooperation and Development manual (*11*).

Road Safety

The road safety aspect assesses impacts on life and property through the indicators of total fatalities, injuries, accident costs, and number of accidents.

Institutional Effectiveness

The performance of the institution on behalf of the public and road users can be defined by its effectiveness in identifying the necessary programs and budgets needed to optimize the total costs of the road system and to meet institutional goals. Recommended indicators are shown in Table 5. The resource lag and the economic return are two aspects of the most relevance to pavement management. They measure the effectiveness of long-term infrastructure supply strategies. Cost recovery covers the ability to recover costs in terms of revenue-to-expenditure ratios, expenditure-to-investment ratios, and maintenance–to–capital expenditure ratios. Regulatory goals cover the effectiveness of regulations and enforcement, such as the incidence and level of overloading, and road safety targets. More aspects could be added—for example, investments in research and training and choice of appropriate technology.

Resource Lag

The backlog comprises the works that could not be included or accomplished in the previous year's authorized program of works but that had been identified as economically feasible for some time up to that year in the long-run (e.g., 5-year) optimal program. Because the program is often being adjusted if it is a "rolling program," the most practical definition of backlog is "the sum of works were economically feasible in the previous year but were not included or achieved under the authorized program." The indicators represent this in physical terms of lane kilometers (usually for each main budget category of works) and as a percentage of the current budget. Shortfall is the amount of additional funding that would have been needed in the current year in order to accomplish all the works in the backlog.

Economic Return

Economic return is a measure of the economic return on the investment of funds in the road system, limited in this paper to meaning expenditures on the road pavements. To determine economic indicators, the program analysis in

TABLE 5 Indicators of Institutional Provision Effectiveness

ASPECTS	INDICATORS	UNITS[1]	NOTES & SECOND-LEVEL INDICATORS[2]
RESOURCE LAG	Backlog Value Backlog Road-space Annual shortfall	% (budget) lane-km % (budget)	Backlog ($) by budget works category Backlog (lane-km) by budget works category
ECONOMIC RETURN FOR PAVEMENTS	Program Benefit: Cost ratio Average NPV/km Rate of return Network Depreciation	fraction $/km % %	Yearly total program net benefit (NPV)/Program total expenditure (may be limited to civil works) Yearly total program NPV/Network length. Summary statistics of project EIRRs (Minimum, Median). Depreciated value/Replacement value of network
USER SAVINGS	Net Usage Savings	$/veh-km	[(Base total VOC -Program total VOC)/Total VKT]
COST RECOVERY	Revenues Revenue/Expenditure ratio Revenue/Maint. Expenditure	I$M % % (Maint.Exp)	Revenue breakdown (fuel tax, user charges, appropriation)
SAFETY GOALS	Fatalities reduction Injuries reduction Accident cost reduction	% % %	By composition (type of accident, impacted parties, etc)
RESEARCH & TRAINING	Expenditures	%	Research and training funds/total road expenditure (%)
TECHNOLOGY CHOICE	Employment generation	Total Workforce (public and private)	

Notes:
1. Units: I$ = Reference Currency (US$, ECU, etc.) indexed to normative year's value. $ = Reference currency in nominal (current) value.
2. NPV = Net Present Value (economic); EIRR = economic internal rate of return.

the management system must generate cost time-streams of total road costs comprising road works expenditures, road user costs (VOCs and accident costs), and other costs and benefits, all expressed as economic costs, that is, net of taxes and subsidies. The indicators are based on project-level statistics for (*a*) the net present value (NPV) of the project relative to the base case (usually "do minimum" maintenance strategy), computed at the appropriate discount rate (opportunity cost of capital), and (*b*) the economic internal rate of return (EIRR).

The works program benefit, which is the aggregate economic benefit of all projects on the network, is compared with the works expenditures in the program benefit–cost ratio, and the average NPV per kilometer. The recommended indicator for the rate of return for a program is to cite the minimum and median project EIRR values, because the EIRR is not strictly additive across projects. Finally, an indicator that proves highly valuable when justifying road user charges is the net usage savings derived from the program—this is the works program benefit divided by total vehicle travel. Normalizing the net usage savings as a percentage of total VOCs may be found more appropriate than a currency value.

Producing Pavement-Related Information

The data required for generating the performance indicators discussed here need to be included under the regular monitoring procedures used for the planning and management of road expenditures, for reasons of efficiency and to avoid duplication and discrepancies. Thus, it is important to identify the necessary and sufficient data for calculating the performance indicators and to develop guidance on the amount of detail and accuracy required and the norms to be followed in the calculation.

For the information specifically relating to road pavements, traffic, and their impact on users, most of the indicators are likely to be developed by aggregation from data collected on a link- or section-specific basis, which would be maintained in the data base of a road or pavement management system, if these exist. Such data vary considerably in amount of detail, depending on the system and on the originally intended usage. A classification of the level of detail, based on the number of attributes used to describe a particular item of information, has been defined first by Paterson and Scullion (*12*) and is being developed further.

The options for determination of the performance indicators, therefore, fall in three categories: namely, detailed data collection and aggregation, sampling and projection, and the processing of bulk or aggregate statistics. The relative use of these methods varies with circumstances, but the trend is toward greater use of detailed collection and aggregation as information technology has improved the ease of collection, storage, and processing of data.

Conclusions and Future Work

The framework presented here for defining performance indicators for the road sector was developed in the broader context of the modern trend to monitor performance and increase the accountability of those who provide services and are responsible for public expenditures. In the specific context of the task of managing pavements, the framework is particularly apposite. The indicators identified here are of relevance and interest to the various transport groups involved, namely, private and commercial road users, policy makers and regulators, and the many groups of providers (including highway agencies for planning, programming, budgeting, and implementation services; consulting service agencies for design, supervision, and so forth; suppliers of goods and materials; and funding or financing agencies).

The paper has identified a number of specific performance indicators to satisfy these goals and defined these sufficiently to indicate the information that is needed. However, it has stopped short of defining all of these quantitatively and unambiguously, partly because this work is still in progress but also because of the need for consultation in the sector to reach consensus. In some cases the measures currently available from pavement management systems are adequate or can be made so with little recomputation. In several instances, though, the paper indicates a need to rethink and redefine some old parameters in a more relevant way.

Particular efforts are in progress to define the indicators of service quality and provision effectiveness, because the physical measures now becoming available from modern road and traffic monitoring technology make the performance indicator goals more capable of being realized. Several national, international, and standards agencies are active in these aspects. One objective is to define an improved set of statistics on the highway sector to be used worldwide in the reporting and analysis of highway and infrastructure data.

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Performance Indicators in Product-Based Management in Finnish National Road Administration

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The Finnish National Road Administration (FinnRA) is the national highway authority of Finland. The organization of FinnRA is divided into nine independent road districts and a small central administration. FinnRA has undergone several organizational reforms in recent years. For better management of the road system, FinnRA was required to change its organization from a management-by-objectives system to an internal business enterprise and its management style into product-based management. The system was tested with two districts in 1993; the whole administration will use product-based management in 1994. There are three kinds of roadkeeping objectives in Finland: effects on society, economical objectives, and additional objectives. Objectives for the effects on society are set by the Ministry of Transportation and then transferred into maintenance and rehabilitation quality standards for each product in the performance contracts made between the central administration and the districts. The performance of paved roads is the main roadkeeping priority in Finland. The quality standards of pavement performance are defined using four main condition variables: rut depth, roughness, surface defects, and bearing capacity. Surface condition variables are measured every year at main roads; the standard measurement cycle is 3 years. Bearing capacity is measured every 3 or 5 years. Best practices in road management can be based only on good data and analytical procedures. All levels of an road administration share needs in developing road improvement programs and evaluating their impacts.

The Finnish National Road Administration (FinnRA) is the national highway authority of Finland, responsible for the country's 76 000 km of public roads. The organization of FinnRA (see Figure 1) is divided into nine independent road districts, which carry out the everyday road maintenance and rehabilitation actions, and a small central administration for funding and policy direction and for technical support with the help of separate service units.

FinnRA has undergone a number of organizational reforms in recent years as well as the development of management by objectives (MBO) into the product-based management.

Figure 2 shows that a road agency's work encompasses the management, planning, and execution involved in the development, rehabilitation, and routine maintenance of the road system.

This three-part division corresponds to the policy and budget-making practices of most public infrastructure agencies and to the time horizon of decisions: development for the long range, rehabilitation for the intermediate range, and routine maintenance for the short range.

There are at least two administrative decision-making levels in each highway program area: network and project levels. The former, often exercised by the central management in the administration or the ministry, deals with policy making. The latter, normally performed by the district offices charged with executing the policies, deals with planning and design. The programming level lies between

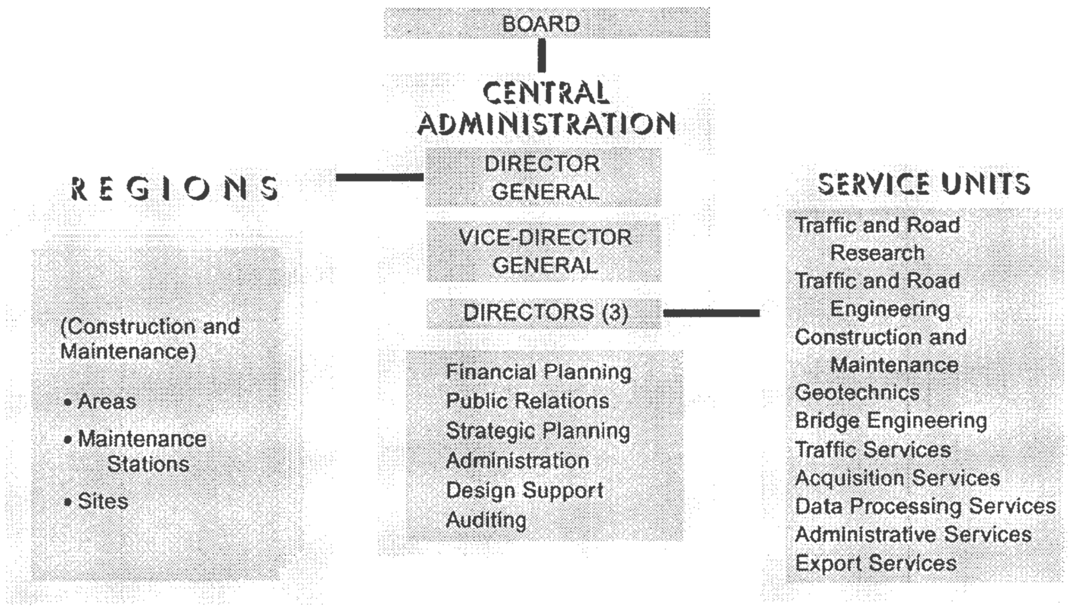

FIGURE 1 FinnRA organization.

the network and project levels. Its function is to program the actions over years to implement the policies set at the network level: the multiyear road program.

The current organizational structure of FinnRA can be called a fractal organization, because each lower level is a replica of the higher level. This organizational structure does not mean that everything is delegated. Terms such as general purpose and comprehensive responsibility apply to management of activities that are performed at a given level (e.g., programming and executing road condition surveys, rehabilitation or maintenance of roads at the regional level, etc.). Centralization, decentralization, and delegation depend to a large extent on technology, especially information technology. Organization structure should not get in the way of employing information technology efficiently.

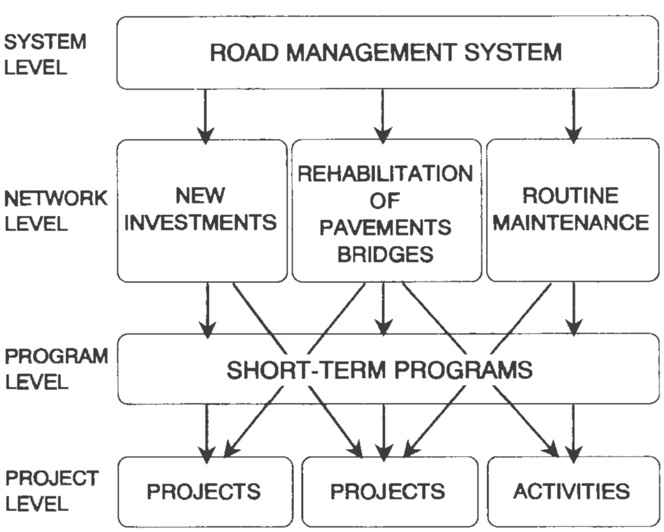

FIGURE 2 Decision-making levels.

The three decision-making levels described earlier enable the simplification of the complex decision-making problem and permit the development of models that serve the decision makers and encourage the types of decisions made at each level.

The best practices in road management can be based only on good data and good analytical procedures. All levels of a road administration share needs in developing road improvement programs and evaluating their impacts. For better and higher management of the road system and better service for the "road clients," FinnRA was required to change its organization into a so-called internal business enterprise and its management style into product-based management. The system was tested with two districts in 1993, and the whole administration will be managed by product-based management in 1994—which is, however, still a test year.

Product-Based Management

The new organizational structure, and the aim of better efficiency and more savings in road keeping by better service for the customer, has driven FinnRA to change its management into product-based performance contract negotiations. These negotiations take place between the central administration and road districts in coordination with the overall MBO approach between the Ministry of Transport (MOT) and FinnRA.

The system is shown in Figure 3, and it is more thoroughly discussed in two FinnRA reports (*1*). The government (i.e., MOT) sets FinnRA the targets for economic objectives (return of investment, productivity, etc.) as well as for level of service (traffic safety, environment, pavement performance, etc.). The objectives include long-term goals and strategies as well as the first-year budgets. This has been done by normal MBO procedure, with yearly negotiations between FinnRA and MOT, since 1988. Objectives set by MOT for 1994 are given in Table 1.

The procedure continues up to the performance contract negotiations between the central administration and the districts. The emphasis on the district's long-term road maintenance strategy will increase in the near future. It should be consistent with the administration's long-term strategy set by MOT within the overall road maintenance objectives pertaining to the whole country. The key elements in the maintenance strategy should be the effects on society, product demand and supply in the region, service to the clients, and the profitability of the organization.

There are three kinds of objective: effects on society, economic goals, and additional objectives.

Objectives for the effects on society are set by the MOT and then transferred into maintenance and rehabilitation quality standards for each product in the performance contracts made between the central administration and the districts. The geographical and circumstantial differences among the districts are considered in the contract when the standards of quality are set up.

TABLE 1 FinnRA Objectives, 1994

Result Area/ Objective	Weight (%)	Total Weight (%)
Road and traffic conditions		45
Traffic safety	15	
Winter maintenance	10	
Pavement condition	20	
Environmental impacts		5
Environment	5	
Productivity and profitability		50
Productivity	25	
Overhead costs	15	
ROI	10	
Total		100

The economic objectives are set by each district and are adjusted to the national objectives set by MOT. These objectives are transferred into normal income statements and balance sheets for each district and should be consistent with the performance contracts.

Additional objectives include such items as development of management and personnel.

The procedure follows a formal timetable and documentation. For instance, in 1993 the bidding documents were sent to the districts in May and their bids came into the central administration in October. After careful analysis and difference adjustments among the districts, the final negotiations took place in November.

The intercourse between the central administration and the service units as well as between the districts and the service units is also done on a contractual basis.

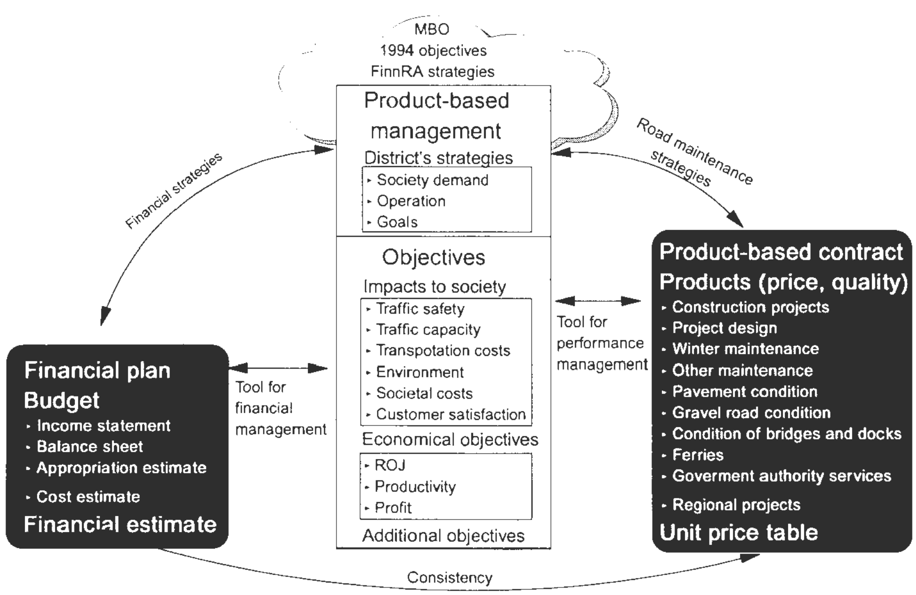

FIGURE 3 Product-based management concept.

Performance Indicators

The performance of paved roads is one of the main priorities in Finland. The description of pavement performance is made using four main condition variables:

1. Rut depth,
2. Roughness,
3. Surface defects, and
4. Bearing capacity.

Each of these variables can be measured and defined in different ways. Ruts, roughness, and defects are used in the definition of road surface condition, and bearing capacity determines the structural condition of the road.

Selection of Performance Indicators

According to Haas (2) the main performance indicators at network-level management are the following ("H" signifies "high," and "L" signifies "low"):

Indicator	*Importance*
Roughness	H
Surface distress	H
Surface friction	H
Deflection	L

Table 2 shows the performance indicators used in Finland and how they influence both road users and road maintainers.

As one can see, these two indicator sets differ from each other in one respect: the Finnish set does not include surface friction but has rut depth as one indicator. This selection is due to the use of studded tires, which cause about 75 percent of the rut problem in Finland but, at the same time take care of most eventual skid resistance problems. The indicator set used in Finland was tested by factorial analysis in 1989 (*4*), and the results suggested a similar choice.

TABLE 2 Condition State Indicators and Their Influence on Road Users and Road Agencies (*3*)

Indicator	User	Agency
Rut depth	Traffic safety Riding comfort User costs	Water layer Winter maintenance problems
Roughness	Riding comfort User costs	Dynamic loads
Surface defects	Riding comfort Bad impression	Water leakage Reduced bearing capacity
Bearing capacity	No straightforward influence	Higher deterioration rate

Definition and Measurements of Performance Indicators

Rut Depth

Ruts are measured by a special road surface monitoring (RSM) vehicle, designed by the Technical Research Center of Finland. The measurements are done at the normal traffic flow speed (40 to 80 km/hr) using 15 ultrasonic sensors each with a separate beam attached to the front of the RSM car (Figure 4). The transverse road profile is measured at 2-m intervals, and the average values (in millimeters) of maximum rut depths at each point are calculated for 100-m sections, which are stored into the data base.

Roughness

Road roughness is measured by the same vehicle as rut depth (Figure 4). One laser sensor is attached at the front of the right front wheel to measure the distance between the car and the pavement surface. In addition, an accelerometer measures vertical acceleration. The data are recorded every 4 cm; these data are used to calculate the international roughness index (IRI), in millimeters per meter, for each 100-m section.

Surface Defects

Visual road surface defects are recorded from a van that is driven at walking speed (3 to 4 km/hr). The measurements are executed at the beginning of the thaw period, which takes place in spring (April or May).

Defects are recorded on special paper or via a digital board. The following six main types of defects are recorded and summed in a defect index, using the weight factors. The measurement section is 100 m, and the defect index is standardized to a road of a width of 7 m.

Crack Type	*Unit*	*Weight*
Alligator cracking	m^2	1.0
Longitudinal cracking	m	0.5
Transverse cracking	#	0.1
Joint cracking	m	0.1
Potholes	m^2	1.0
Patching	m^2	1.0

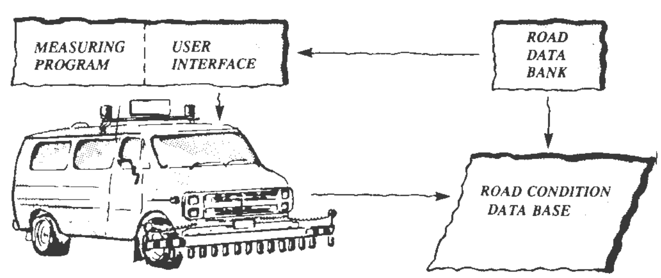

FIGURE 4 RSM vehicle.

Bearing Capacity

Road bearing capacity is measured with a falling weight deflectometer (FWD). Ten measurements are made for each road section (average length of 5 km), and the values of the defection curve are stored in the road data bank. The main indicators currently used are the average spring bearing capacity, KEVKANT, which is calculated from the maximum deflections (converted to MN/m^2), and the bearing capacity ratio, which is the ratio between KEVKANT and the target bearing capacity, which is a function of design standards and cumulative axle loads.

Equipment and Measurement Cycle

FinnRA has five RSM cars and 12 FWDs. Each road district has established several groups for yearly defect inventories. This capacity enables the following measurement cycles to be followed:

Measurement	*Cycle*
Ruts	Main roads at least every year, minor roads every second year
Roughness	Every second year
Defects	Every third year
Bearing capacity	Every fourth year

Road condition information is stored in the road condition data bank KURRE in the road districts. Copies of these regional data bases are transferred to the central administration to ensure data consistency.

If a road section is not measured during the analysis year or the data are totally missing, the previous measurement data are updated to the current year using performance prediction models (*5*).

Classification of Road Condition

FinnRA has determined a set of overall threshold values that are used in all road-keeping activities. These average values were defined during special research projects (*6,7*) and are presented in Table 3.

In the performance contracts for 1994, the threshold values and limits are somewhat different (Table 4).

TABLE 3 Threshold Values for Road Condition Variables (*3*)

	Roughness (mm/m)	Rut Depth (mm)	Defects (m^2)	Bearing Capacity Ratio (%)
Excellent	≤1.3	≤5		
Good	1.4–2.6	≤18	06–20	≥70
Fair	2.7–4.1	19–24	21–40	<70
Poor	4.2–5.5	25–80	41–80	
Bad	≥5.6	≥81		

TABLE 4 Condition Standards for 1994

	Traffic(ADT)		
	>1500	350–1500	<350
Rut depth (mm)	20	—	—
Roughness (IRI)			
Average	1.8	2.5	3.1
Maximum	2.7	4.2	5.6
Defects (sum)			
Average	7	30	45
Maximum	20	60	120
Allowed below standard (%)	16	18	16

Management Systems

The pavement management system (PMS) used in Finland is shown in Figure 5. The PMS uses two main data banks, the road data bank (RDB) and KURRE. The decision-support tools used are the Highway Investment Programming System (HIPS), which is a network-level PMS used in the central administration, and PMS91, which is a project-level PMS used by paving engineers in road districts. The contents, purpose, and technical data of these systems are presented in Table 5.

Case Example

The following example shows the performance contracting procedure in the case of rehabilitation and maintenance of paved roads in one road district. The example is divided into three steps: definition of product, bid, and evaluation of bid.

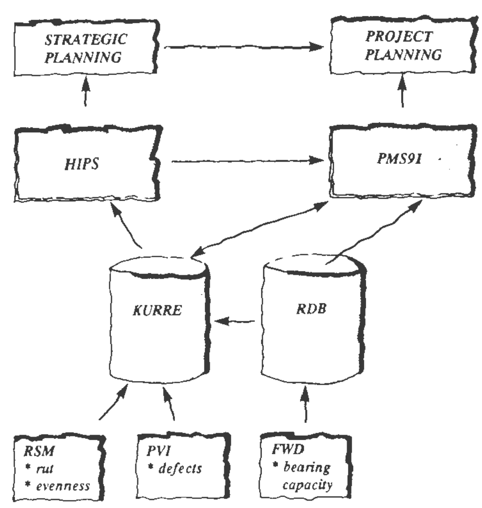

FIGURE 5 Pavement management system.

TABLE 5 Systems and Their Details (*3*)

RDB	KURRE	HIPS	PMS91
• road address reference system • basic data of roads and traffic • the data is given in codes	• detailed condition data: history, present, future	• prediction models • actions and effects • user and agency costs	• prediction models • decision rules • actions and effects
Administration • research • statistics **District** • input data for PMS91 and other planning systems • statistics	**Administration** • research • input data for HIPS • statistics: present and predicted condition state distribution • annual objective setting **District** • input data for PMS91 • statistics • data for planning reconstruction	**Administration** • strategic planning and goal setting • cost-effective maintenance policy **District** • input data for PMS91	**District** • recommendations for individual roads • programming of repaving • effect analysis
• CODASYL-database • in use since 1970's	• ORACLE-relational database • in use since 1991	• programming language C • in use since 1989	• PARADOX-relational database • programming language C • in use since 1987

Definition of Product

The product was defined by the central administration, consistent with the objectives set by MOT and was sent to the districts in May 1993.

1. Product: performance and condition of paved roads.
2. Definition: averages and distributions of condition indicators.
3. Contents: maintenance and rehabilitation actions used in fulfilling the quality objectives set below.
4. Objectives: the objectives are defined separately for three classes of average daily traffic (ADT). The main objectives are to keep the current condition distribution at the national level and to reduce differences among road districts. The threshold values and allowed exceptions are as follows:
   –Rutting: for the ADT class of more than 1,500 vehicles per day (vpd), no ruts exceeding 20 mm are allowed.
   –Roughness: for ADT classes of more than 1,500, 350 to 1,500, and fewer than 350 vpd, the IRI class limits are 2.7, 4.2, and 5.6, respectively.
   –Defects: for ADT classes of more than 1,500, 350 to 1,500, and fewer than 350 vpd, the class limits for the defect index are 20, 60, and 120, respectively.
   –Deviations: for ADT classes of more than 1,500, 350 to 1,500, and fewer than 350 vpd, 16, 18, and 16 percent roads exceeding the roughness or defect threshold values are allowed.
5. Contents of bid: the following information is to be presented:
   –Maintenance and rehabilitation, in kilometers and Finnish marks (FIM) per kilometer, and
   –Reconstruction, in (kilometers, FIM/kilometer, and payment schedule). Prices should include all costs (work, material, and overhead).
6. Quality control: RSM and defect inventories are used. Minimum measurement cycle is 3 years. Missing or old data are updated with PMS prediction models.
7. Depreciations: a proposal for depreciations is to be included.

Bid

The contents of a bid are made by the districts. This bid example was sent to the central administration in October 1993.

The following bid example is from the Häme district ($1.00 U.S. = 6 FIM).

1. Product: performance and condition of paved roads.

2. Contents: maintenance, rehabilitation, and reconstruction of paved roads.

3. Objectives: the condition of paved roads is kept at the current level. For each ADT class, an agreed-upon amount of roads is allowed to not meet the standards. Maintenance and rehabilitation actions are designed with the PMS91 system. The threshold values defined in the product card are used.

Traffic (ADT)	*Below Standard (%)*	*Requirement (%)*
>6000	2.8	16
1,500–6,000	13.0	16
350–1,500	11.3	18
<350	11.4	16
Total	10.8	

For roads with ADT of more than 1,500 vpd, no ruts exceeding 20 mm are allowed;

4. Costs: prices include work, material, and overhead as shown below:

Traffic (vpd)	*FIM/km*	*Total*
>6,000	36,200	22.0
1,500–6,000	26,600	37.2
350–1,500	24,000	39.7
<350	17,100	15.5
Total	25,000	114.4

5. Quality control: RSM and defect inventories are used. Measurement cycle is from 1 to 3 years. Missing or old data are updated with PMS prediction models.

6. Depreciations: if more than 10.8 percent of roads are below standard, a deduction of price of 0.5 percent/1 percent is proposed.

Evaluation of Bid

The central administration evaluates all bids. The following information is used in the comparison and evaluation of all bids:

- HIPS,
- Simulation of different strategies,
- Statistics from KURRE, and
- Current and predicted condition information.

If the results of HIPS, KURRE, and other analyses differ from the bids, extra negotiations and tuning are needed. The final contract with the Häme district was signed in November 1993.

Conclusions

Basically, traditional MBO would be enough, but product-based management yields these further advantages:

- The use of better information and procedures improves the management and service for road clients and for the society as a whole.
- Better preparedness for business-oriented management results in more effectiveness and cost-effective road keeping.
- Productivity and motivation of personnel increase.
- The return on investment for state property is higher.
- By acting similarly to private companies, districts gain internal competition among themselves, which is followed by the optimal unit price for different products, productivity and quality programs, personnel cost savings, new operating freedom in financial and personnel management, all of which increase the productivity of work and of capital utilization and the cut in overhead costs.
- Creation of better links between operations and customer/traffic and service are created, and the organization and resources are adapted to service demand.
- Personnel are encouraged to better performance by reform of employment and contract and bargaining systems; job assignment and placement and voluntary mobility, a more flexible pay system; improved focusing on the demands of the job, personal performance, and results achieved.

In developing the necessary management systems, setting up the objective measuring procedures, and evaluating the data definitions and needs for all levels of administration, better information systems, more advanced use of annual statistics on the key indicators, and better knowledge of the impacts on the society are required.

Several problems remain:

- Differing views on the necessary key indicators for products, especially at the different decision-making levels, and on network and project levels;
- More accurate data needs for "optimal" pricing of products;
- Definition of revenues in the internal state business enterprise approach; and
- Interrelations between the societal impact objectives and the quality standard of the equivalent products.

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Condition, Safety, and Asset Value Monitoring in Hungary

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In Hungary the adequacy and asset value of the road network have been evaluated periodically since 1979. This assessment, covering pavements, drainage, alignment, capacity and cross section, junctions, bridges, and culverts and lighting, was based on annual surveys of the road network and a series of standards established for the various road classes. The data collected were used to produce a number of performance indicators of the condition and performance of the network overall as well as their trends from year to year. The indicators, converted into scores, were used to determine the level of funding required for capital and maintenance works. In particular, the loss of asset value, expressed as the ratio of the net value (depreciated value of deteriorated pavement or structure) to the gross value (current replacement value of the roadway and foundation), was used to justify the amount of funds for road works to be made available. Since 1990 continuous automated survey methods have been used and pavement management has been progressively implemented. The time series of accident data, which have already been collected in Hungary for several decades, are also used for several management goals.

Hungary is a central European country 93 000 km^2 in area; it has 10.7 million inhabitants. There are 30 000 km of national highways and 76 000 km of local highways, and the total length of agricultural and forestry private roads exceeds 53 000 km. Ninety-three percent of national highways are paved. In density, Hungary is about the middle-ranking country in Europe with its 321 km of national highway per 1000 km^2. There are plans to triple the present 315-km total length of motorway network, using concession financing, in the next 6 years.

The optimal allocation of highway funds—which since 1990 have come from a special highway fund and are far below the country's realistic needs—has constituted one of the most important tasks of the Hungarian highway administration. That is why monitoring of the condition, safety and asset value, and safety of the highway system was initiated some decades ago. The data series obtained and the pavement management systems (PMSs) can be used by the highway operators, and indirectly by the road users, in regard to various areas of information.

Main Features of Monitoring System

To facilitate decisions on road management, the Hungarian Ministry of Transport initiated the monitoring of the main technical and economic highway indicators on a periodic basis. These performance indicators are condition, traffic, accidents, and asset value data.

Condition Data

In the late 1970s, it was decided in Hungary to create gradually a PMS. In 1979 the first sufficiency survey of the entire national highway network, 30 000 km in total length, was performed. (The sufficiency of a section of highway is given by the comparison of the present feature value of a road section with a series of standards. Thus, it is a time-dependent ratio.) The survey covered—besides the investigation of alignment, capacity, cross section, junction, bridge and culvert, and lighting data—the following pavement condition information types:

- Pavement bearing capacity,
- Unevenness (roughness),
- Pavement surface quality,
- Rut depth, and
- Drainage condition.

The pavement bearing capacity was measured using Benkelman beams or the Lacroix deflectograph. The sufficiency can be determined by the comparison of the measured and the permissible deflection values (Table 1). Recently a Swedish dynamic falling weight deflectometer (FWD) was applied. The bearing capacity of the total network has been measured every 5 or 6 years.

The longitudinal unevenness (roughness) of the asphalt concrete pavement sections (nearly half of the whole network) was characterized using bump integrators (BIs) until 1991. Because of insufficient survey equipment and the risk of damage to equipment on rough roads, the other half of the network, mostly asphalt macadam pavement, was classified on the mostly asphalt macadam pavement sections using a three-score subjective ranking system. Measurements were taken using vans traveling through each section. Since 1991 the roughness has been measured by the Swedish Laser-RST (L-RST). (Scores are calculated according to Table 2.) The survey frequency for the BI and subjective method was 5 years on average. The international roughness index (IRI) values supplied by RST, which have a fairly good correlation with BI values, are given every 3 years.

Following a common international practice, the pavement surface quality is classified using a five-grade score

TABLE 1 Rating of Pavement Bearing Capacity

$\frac{S_{meas}}{S_{perm}}$ x 100 (%)	Score	Rating
above 105	1	good
86-105	2	satisfactory
71-85	3	tolerable
56-70	4	at the end of design life
below 56	5	over design life

TABLE 2 Roughness Scores as Function of IRI and Road Type

Score	IRI (m/km) on motorways	on first class main roads	on secondary roads
1 (good)	-1,20	-1,50	-2,80
2 (satisfactory)	1,21-1,50	1,51-2,20	2,81-4,10
3 (tolerable)	1,51-1,81	2,21-2,80	4,11-5,20
4 (unsatisfactory)	1,81-2,20	2,81-4,10	5,21-6,30
5 (poor)	2,21-	4,11-	6,31-

based on a visual assessment of the site condition. The objectivity of this evaluation is increased by special condition rating guides that contain higher requirements for main roads and asphalt concrete roads (Table 3). Recently pavement defect recognition has been enhanced by the use of a special board apparatus with a keyboard and site identification facility, and evaluation of the data has been aided by the software employed. The pavement surface condition is evaluated by the same operator in each county once a year.

Rut depth measurements covering the entire highway network have been performed only since 1991, when the RST apparatus started to evaluate this condition parameter as one of its yearly measuring functions on the 10 000- to 12 000-km length of the network. This is equivalent to a 3-year measuring frequency.

The drainage system is evaluated on the basis of the common conditions of the shoulders and surface ditches by a three-grade visual ranking. It is carried out once a year by the help of a condition evaluation guide (Table 4).

TABLE 3 Pavement Surface Quality Scores on Various Road and Pavement Types

Main roads, asphalt concrete pavement	Score	Secondary roads, asphalt macadam pavements
Homogeneous surface of good riding quality	1	Homogeneous, dense surface
Some ravelling, finely repaired pot-holes, filled cracks	2	Max 5 % cracked, fatted or patched surface
Max 5 % cracked, fatted, patched or deformed surface	3	6-20 % cracked, fatted, patched or rutted surface
6-20 % cracked, patched or deformed surface with max 20 mm rut depth	4	21-50 % cracked, patched, fatted or deformed surface with max 20 mm rut depth, some pot-holes
More than 20 % cracked, patched or deformed surface, several pot-holes, ruts with more than 20 mm depth	5	More than the half of the surface is failed, condition hinders the continuous traffic flow

TABLE 4 Drainage Condition Evaluation Guide

Score	Characteristics of the drainage system
1	Suitable drainage (adequate gully-holes, shoulder slope, ditches)
2	Hampered drainage (drain or gutter sludge, plash) on pavement or shoulder, ditches sludged to a certain extent)
3	No drainage (blocked gutters,shoulder retaining water on pavement, large plash, washaways on pavement and shoulder, ditches filled with sludge, water standing in them)

Since 1990 continuous automated survey methods (L-RST) have been used in Hungary, and several measures were taken to ensure the equivalence of the measurements made before and after 1990 (*1*). The Institute for Transport Sciences (KTI) organized a comparative test on eight sections in which the RST and the following measuring devices were run simultaneously: BI, Sideways-Force Coefficient Routine Investigation Machine (SCRIM), Hungarian Deformmeter (electromechanical towed rut depth measuring apparatus), and Hungarian Roadmaster. The main results of the correlation test were as follows:

- A good correlation ($r = .896$) was obtained between the IRI of RST (meters per kilometer) and BI value (centimeters per kilometer):

$$RST_I = 0.393 + 0.0146\ BUMP_{BI};$$

- The function between the fine-texture parameter of RST and the SFC of SCRIM had only a fair correlation ($r = .509$):

$$RST_f = 0.0526 + 2.52.10 - 3SFC;$$

- An acceptable correlation factor ($r = .799$) could be found only on relatively even main roads between the rut depth values of RST and Deformmeter:

$$RD_{RST} = -0.194 + 1.18RD_{Def}$$

- Practically no correlation ($r = .340$) could be found between the numbers of wide cracks registered by RST and Roadmaster.

These results were used in the decisions about the possibility of continuing the data time series after 1990.

Traffic Information

Regular traffic censuses have been carried out on the Hungarian national highways for several decades. The frequency of representative traffic counts was usually 5 years, although the last one was 3 years. The traffic census is performed at 4,000 counting stations on the network for a relatively short period. To monitor the traffic features a systematic census is done on 400 cross sections. One hundred continuous stations serve in determining the traffic time-dependent regularities. Most traffic counts are done using an automatic vehicle counting device; only a small proportion are performed manually.

Accident Information

Data on highway accidents involving personal injuries are gathered by the police in Hungary. The statewide summary of these data is performed in the Central Bureau of Statistics. All important information about accidents, including their possible causes, is standardized. This kind of registration has made it possible to carry out several special evaluations and processings. Since 1992 the Central Road Data Bank has received the highway accident data from the Central Bureau of Statistics to store the condition, traffic, and safety data of roads and bridges together.

Economic Data

Until 1992 highway maintenance, operation, and construction data were collected only in an aggregated form. Since then the various maintenance technique types and costs have been stored and identified using the highway reference system of the Central Road Data Bank (to be explained later).

The regular determination of gross and net values of the total national highway system can be considered a more important task, since the net/gross value ratio can present very informatively, in a simple percentage form, the degree of the physical deterioration of the total highway network. After the first sufficiency survey, it became possible to monitor the actual deterioration level of roads objectively, in numerical form.

Using the actual road registration data, the gross value is calculated as replacement value, as if the road were reproduced today with original features. The calculation is performed separately for the road subgrade, the pavement structure, traffic engineering and drainage facilities, and bridges.

When the net value of pavement structure is calculated, amortization-type percentages are used for the consideration of bearing capacity, pavement surface quality, and roughness scores (Table 5) (*2*).

Data Storage and Road Data Bank

Technical data on roads have been stored since the early 1970s in a central main computer. Central data registra-

TABLE 5 Remainder Value Multipliers Used for Calculating Net Value of Pavement Structure

Score	1	2	3	4	5
Bearing capacity	1,0000	0,9503	0,8265	0,6200	0,3310
Pavement surface condition	1,00	0,96	0,92	0,86	0,80
Drainage condition	1,00	0,90	0,70	-	-
Amortization-type ("moral") deterioration	1,00	0,90	0,80	0,60	0,50

tion including condition data became decentralized to the regional highway directorates in 1989. This decentralized data base is stored on personal computers. The registration managing program was developed further in 1993.

The present data registration system has two levels: local and central. It is an important principle that all data enter the system on the local level. On the central level, the entire detailed data base is stored. The developmental speciality of the data bank is that, besides the storing of all data in the main system together with the reference, condition, traffic, and safety data, other data are stored in special subsystems. If common data are stored in the main system and subsystems, they first enter the subsystem. The common local reference system allows the transfer of data from the subsystem to the main system. The main system and subsystems are presented in Figure 1.

As a road reference system, the traditional highway number + kilometrage (chainage) system was used before the present computerized system. The link node system was introduced along with the decentralized computer registration system. However, this system has not become popular, although it is much more reliable, especially for automated measurements. That is why both reference systems are used simultaneously, with automatic conversion.

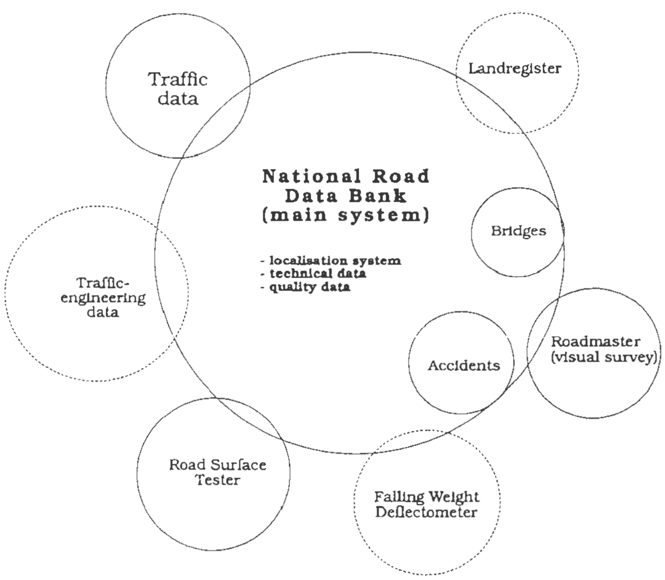

FIGURE 1 Connection of main and subsystems of National Road Data Bank.

DATA UTILIZATION

Using the data is the final goal of data collection and storage. The connections between these activities, with their main application areas, are shown in Figure 2. Subsequently the most important utilization areas—statistics and pavement management—will be shown here.

Statistical Use

As mentioned, the visual pavement surface condition evaluation initiated in 1979 is performed once a year as a part of the sufficiency survey. In the initial years this condition rating was carried out in autumn, when the condition of the pavement is relatively good. From 1984 on, however, it has been performed during spring or at the end of the winter when the pavement condition is usually unfavorable. In 1991 a data collecting device promoting objectivity and a uniform data processing software were introduced. The pavement condition quality shows a continuously deteriorating trend (Figure 3), indicating an increasing backlog of maintenance.

Pavement bearing capacity has been classified by continuous measurements during longer, 5-year periods. A kind of quality polarization can be observed: the bearing capacities of asphalt main roads and heavily trafficked secondary roads are relatively good, whereas the bearing capacity of macadam surface pavements of secondary roads is poor (Figure 4). The deterioration of unevenness (roughness) is only virtual partly because lightly trafficked secondary roads were classified visually in earlier surveys. Since 1991 classification has been done using a measuring apparatus. This reflects, however, realistic considerations as well as the actual deterioration of secondary roads (Figure 5).

The calculation of the net/gross highway value ratio uses the condition scores mentioned. It has been done using practically the same calculation technique since 1981. Unfortunately, a continuous worsening in condition has been demonstrated by the time series (Figure 6).

The traffic volume of roads grew continuously from the 1960s until just recently. The most recent years show a decrease in traffic volume, primarily as a consequence of industrial structural change and growing fuel prices (Figure 7). The number of highway accidents is high in comparison with the level of motor vehicle use in Hungary. The number of fatal accidents, especially, is extremely high (Figure 8).

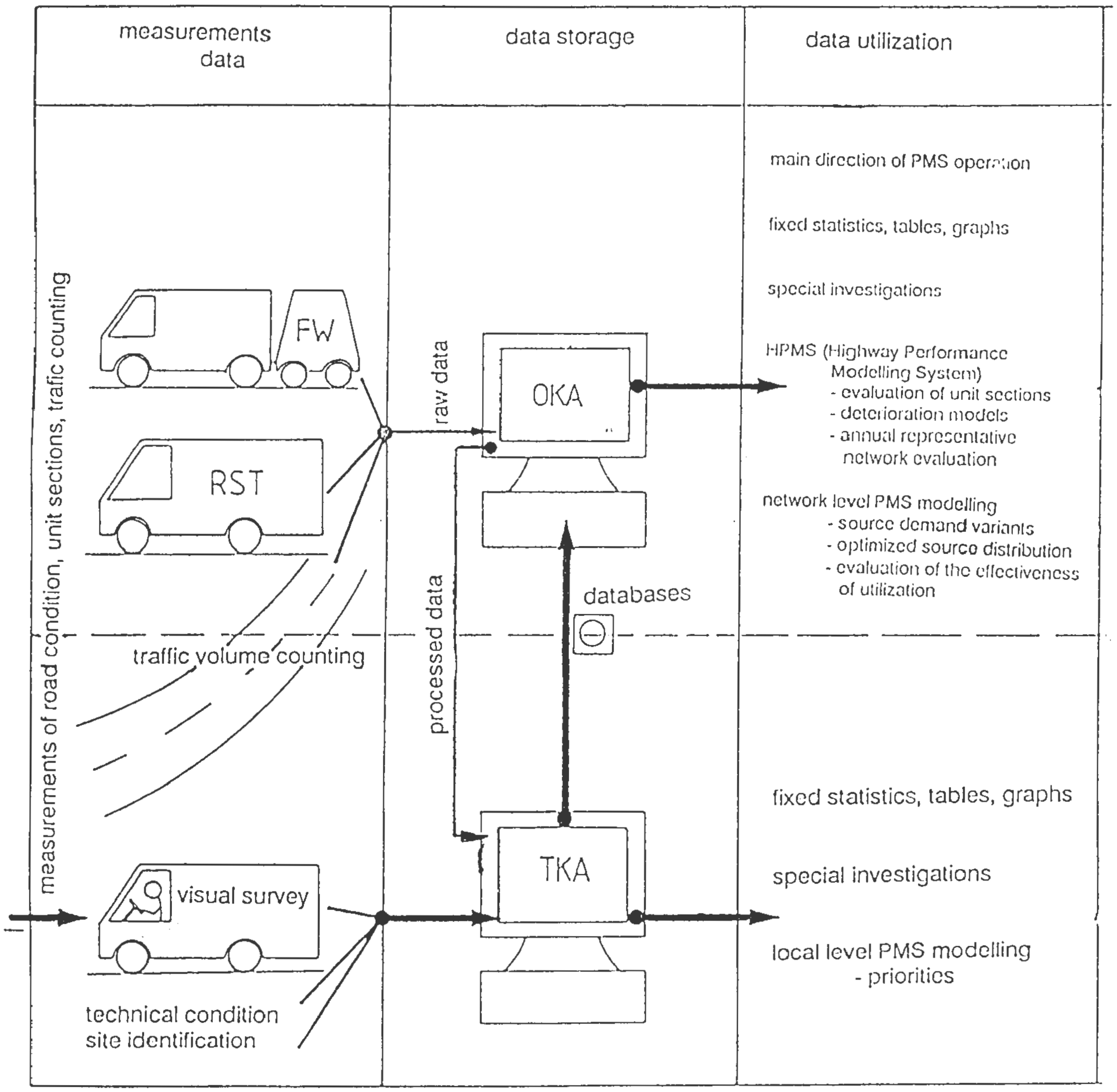

FIGURE 2 Scheme of activities in Road Data Bank system.

Road Management Use

The results of the sufficiency survey and the regular traffic census supply the important inputs of the first Hungarian network-level PMS (*3*). The main variable of the Markov transition probability matrices of the system is the integrated condition parameter coming from the combination of pavement bearing capacity, roughness, and surface quality notes. Traffic information is used in the selection of the appropriate Markov matrix. The unit costs of various intervention types are determined using the coordinated country-wide cost data collection recently begun. Even the elements of Markov matrices (probabilities of the transition from a condition variant to another one) were calculated using the road condition data stored in the data bank (*4*).

Some years ago a simplified project-level PMS (OPMS) was developed in Hungary that can rank the candidate projects from an engineering point of view. The system uses as inputs the condition data of sufficiency surveys and traffic information.

The actual values and the time series of the gross/net values of road networks can be utilized—among others—for comparing the financial means used in the counties for highway purposes, taking into consideration their actual needs.

The accident data time series can be used in the identification of accident "black spots" that can be investigated if there is a possibility of improving the situation by road maintenance, rehabilitation, or reconstruction. The procedures developed for the efficiency calculation of various highway maintenance and rehabilitation techniques also use information on road condition, traffic, and safety.

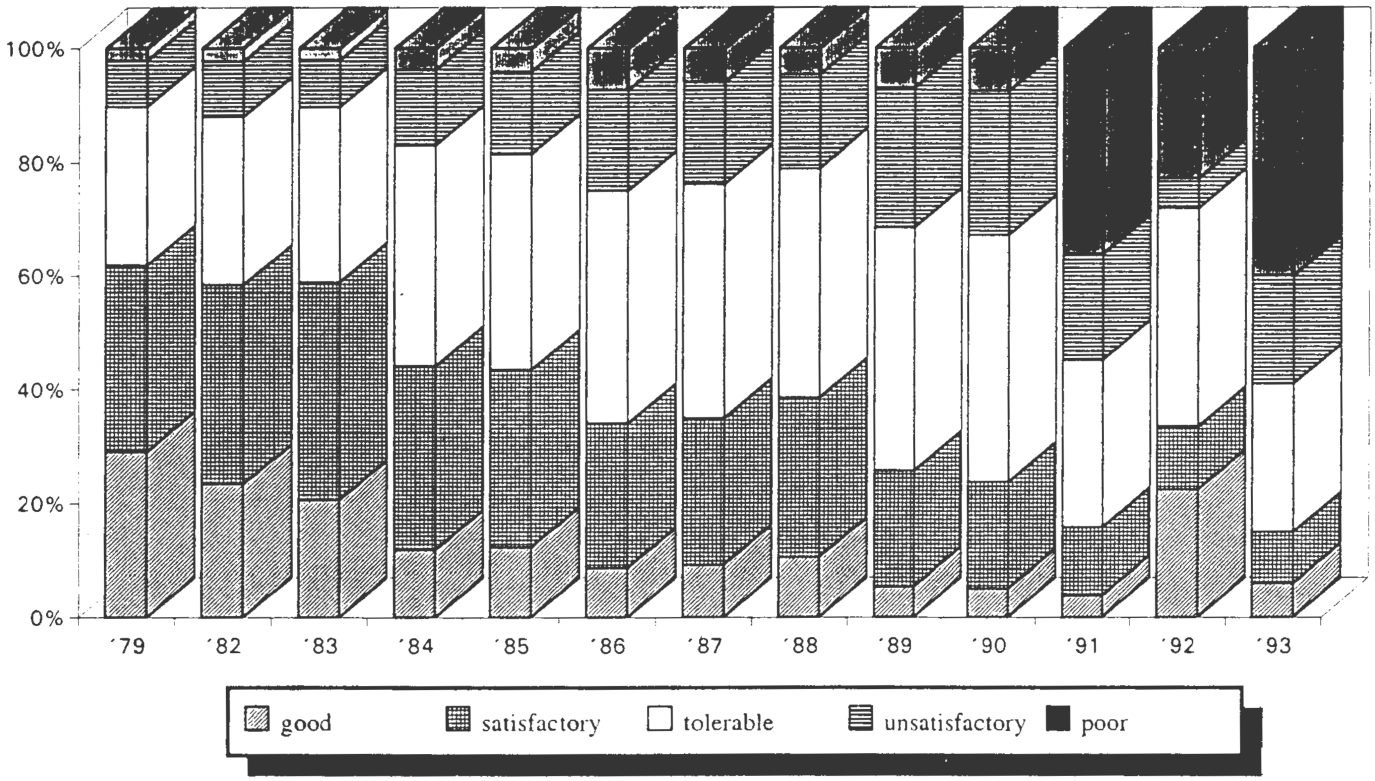

FIGURE 3 Surface condition categories, 1979–1993.

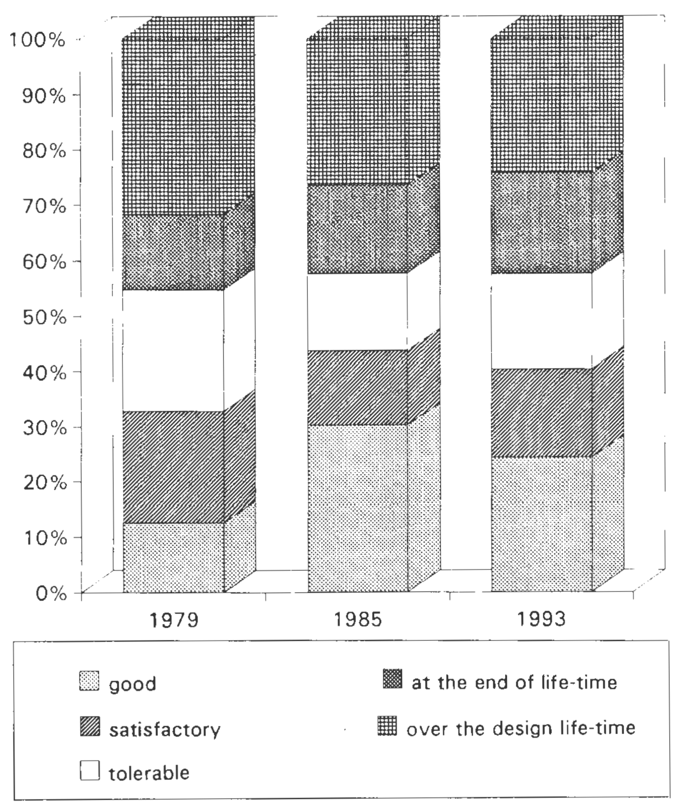

FIGURE 4 Bearing capacity categories, 1979–1993.

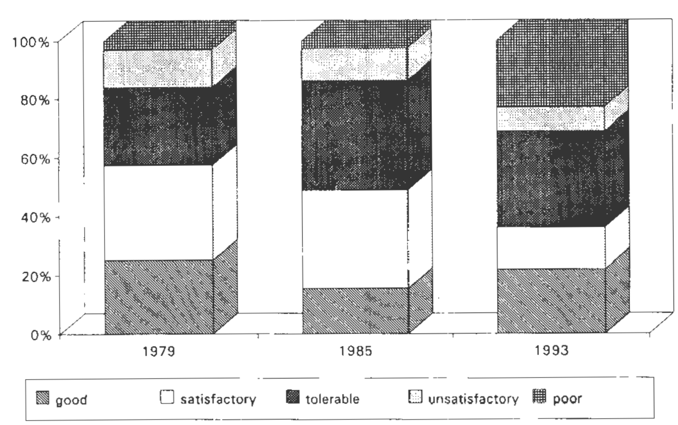

FIGURE 5 Roughness categories, 1979–1993.

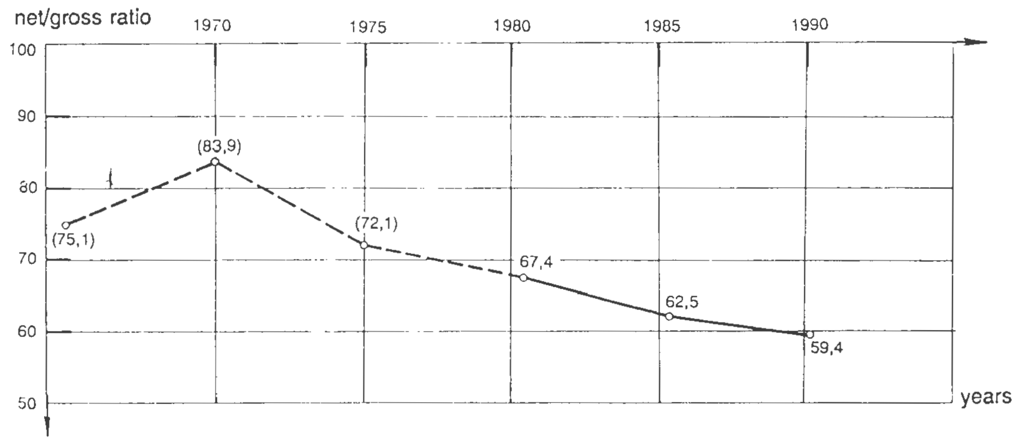

FIGURE 6 Changing of net/gross value ratio of network, 1970–1990.

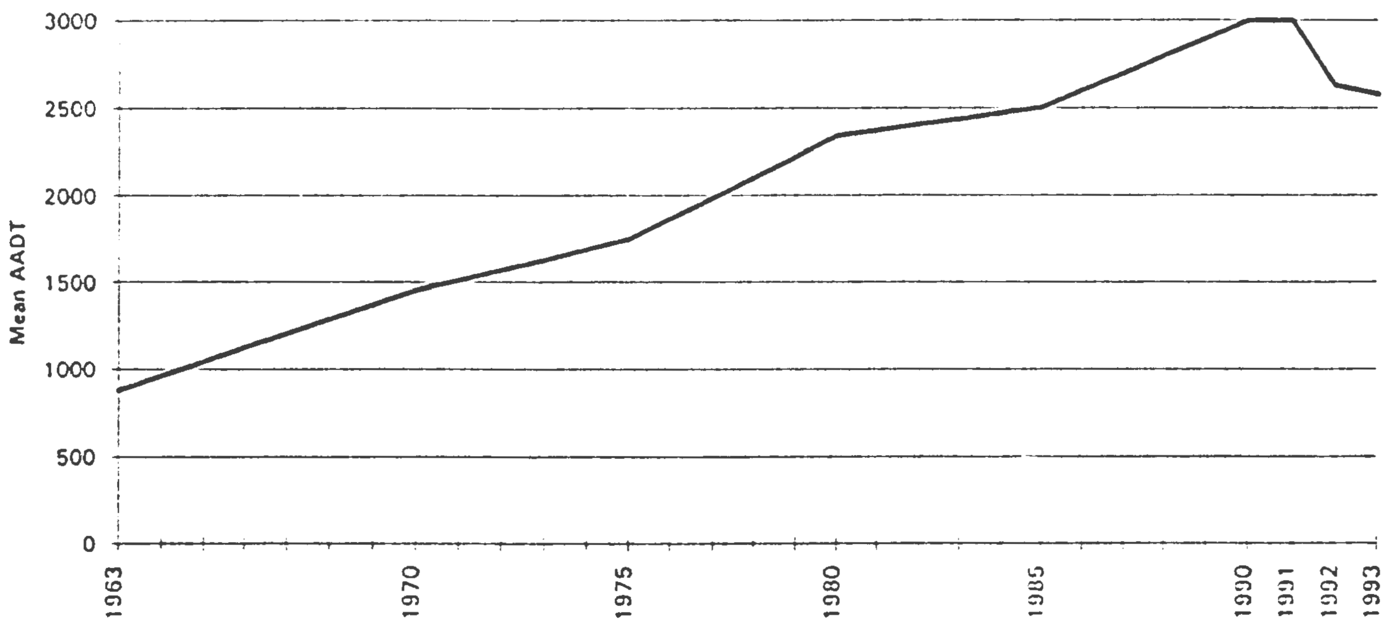

FIGURE 7 Traffic growth on national roads, 1983–1990.

Future Plans

Several directions for the development of Hungarian pavement management rely on the condition and economic data time series of the highway network.

In 1991, 54 unit sections, each 2 km long, were selected that have been measured once a year using Swedish RST (IRI and rut depth), Hungarian Roadmaster (pavement surface quality), and Swedish FWD (pavement bearing capacity). The data measured here are used in the application of a highway performance modeling system in 19 road types, as a function of pavement structure types, traffic volumes, and subgrade California bearing ratio values. These models are updated each year.

In 1993 the establishment of the so-called Time Series Subsystem connected with the Central Road Data Bank was initiated. Its main goals are as follows: (*a*) creation of the data series of various deterioration functions on 500-m-long sections of the highway network, (*b*) the subsequent developing of regression performance models of various pavement structure types, and (*c*) the yearly presentation of previously measured condition data using the performance models of the same road section type.

As part of the activities aimed toward the adaptation of the World Bank's HDM-III model for Hungarian conditions, the Hungarian condition data series are to be used in the determination of the actual value of model coefficients suitable for the local conditions.

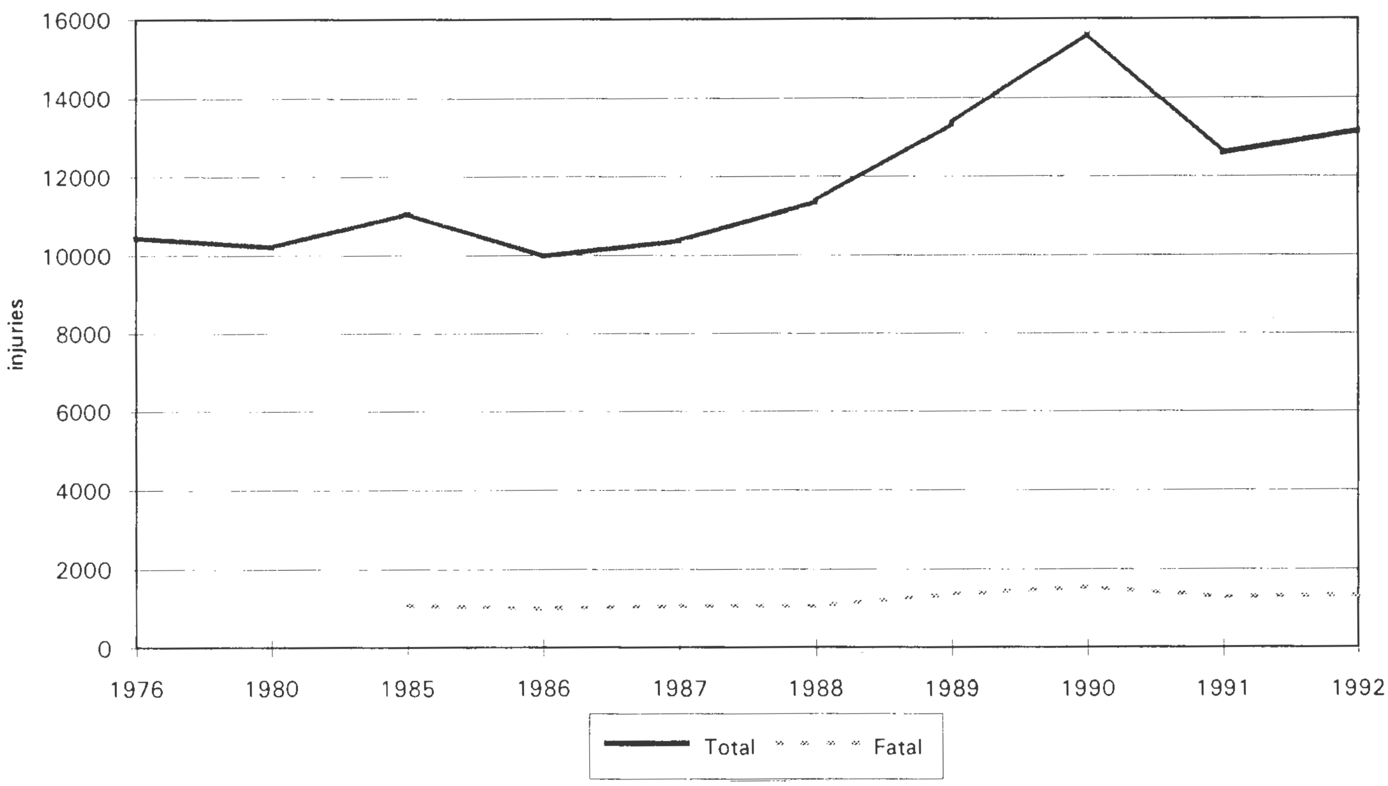

FIGURE 8 Accidents involving personal injuries on national roads, 1976–1992.

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Toward a New Pavement Management System in Germany: Organization, Data Collection, Experiences, and Innovations

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In the Federal Republic of Germany the design of a new, complete pavement management system (PMS) is under way. Major components are already operational. Meanwhile, data on road conditions have been collected with high-speed monitoring systems for approximately 20 000 km of German autobahn lanes. The data were assembled according to evenness, skid resistance, and surface damage and subsequently classified via a special grading system. By applying special algorithms, a service value, a structural value, and an overall condition value were developed. The results of the survey can be presented in lists, route section graphs, and network graphs with different colors indicating where specific target, warning, and threshold values are exceeded. By means of continuous feedback, the information collected is used to improve and adjust the system's components and the plausibility of the output. There is agreement that for an effective PMS application, repeated automated network monitoring is necessary. To minimize necessary monitoring and evaluation efforts, the use of multifunctional automated monitoring systems is envisaged, which will collect all necessary data during a single pass. Fully automated operation with direct computerized evaluation is necessary here. The structure of the overall PMS and its major components is outlined.

Until the beginning of the early 1980s, road construction and network expansion to meet rapidly increasing motorization were the main fields of highway engineering in Germany. Meanwhile, maintenance and rehabilitation of existing roads became more and more important. [In 1990, the gross fixed assets were about DM 700 billion (*1*).] This is especially true for the five new federal states, where there is a considerable backlog in pavement rehabilitation. In this context, road service in its original, wider sense describes a road's ability to ensure safe and comfortable driving conditions and withstand the stress and strain caused by traffic, climate, and weather. At the same time the highest possible degree of environmental compatibility must be guaranteed. Thus, maintenance of this road service means consideration of the overall economic aspects. Financial means can only be assigned effectively to road maintenance if the pavement condition is evaluated on the basis of standard rules and objective criteria.

Definition of Data Needs

Pavement conditions and their changes are described by means of condition characteristics and associated indicators. A distinction is drawn here between

- Primary characteristics that are design and construction factors—grade, curves, roadway geometry, evenness, texture and brightness, and
- Secondary characteristics that describe effects resulting from the vehicle-roadway interaction—driving dy-

namics, surface drainage, skid resistance, splash and spray, reflection, tire noise, and rolling resistance.

These groups of characteristics allow one to judge objectives such as traffic safety; driving comfort; environmental compatibility; energy savings; prevention of damage to roadway, vehicle, and vehicle load; and maintenance of the road substance.

In addition, the structural pavement condition can be described by characteristics such as bearing capacity, overall drainage, and surface damage. In 1990, the Federal Republic of Germany started surveying and assessing the federal highway and autobahn network pavement condition (*2*).

Problem-Solving Capacity of Data

To rationalize data identification and data collection for these purposes, the process was governed by the need to ensure the problem-solving capacity (PSC) of every collected parameter either singly or in combination with others. PSC is the power—generally of a set of data—to contribute to the solution of a given problem (*3*).

In the case in question, the expected usefulness of the data collected for and within a pavement management system (PMS) was of paramount importance. But PSC is only guaranteed if the algorithms for the subsequent processing of the data collected exist a priori, although adaptions and alterations of such algorithms, of course, are still possible. Furthermore, the availability of the necessary technology for the collection of the data and the costs involved versus the putative benefits of the entire operation have to be assessed. Last but not least, a high quality of data and reliability has to be ensured. Thus, the existence of adequate plausibility check systems is a prerequisite as well.

Within the frame set by these boundaries, data identification turned out to be an extremely complex process: One had to part with philosophies and desires of road maintenance engineers associated with PMS of the past and their tendencies to collect a large set of data merely assumed to be useful later. This was ultimately overcome via the assessment of the PSC of each individual parameter for pavement management purposes as well as the anticipation of the usefulness of each parameter in combination with one or all the others. The parameter "skid resistance," for example, has a PSC of its own, because a value below a set level leads to immediate maintenance measures. On the other hand, "skid resistance" when above the "warning level" is entered into combined PMS values to indicate an overall condition of a section of road.

Types of Data Collected

Germany's federal highway and autobahn network includes about 11 000 km of autobahns and 45 000 km of federal highways. The autobahn pavement condition surveys were only possible by monitoring with high-speed survey systems and automated registration (at a survey speed >60 km/hr). Visual inspection would have placed crews and road users at risk and led to traffic congestion. Moreover, survey data density and data precision are considerable advantages of automated monitoring. Furthermore, surveys can be objectively and easily repeated. The survey results at network level allow one to establish a condition rating and to identify sections needing maintenance. With these goals it was possible to define the problem-solving capacity of a limited but sufficient amount of data.

A certain type of pavement data, for instance, tire noise, is of little importance for the mentioned target values, its influence having already been taken into account in the design and construction specifications. Therefore, such characteristics do not need to be considered in a periodically conducted survey at the network level.

Other indicators of secondary characteristics can be extracted from evenness and texture profiles and do not need to be measured directly. Unfortunately, it is not yet possible to register the microtexture elements, and it is still necessary to measure skid resistance as an important performance parameter describing vehicle-roadway interaction (*4*).

Environmental preservation and energy economy are normally taken into account by the design standards.

Ultimately the decision was taken to collect the following four main data groups:

- Longitudinal evenness with respect to unevenness profiles,
- Transverse unevenness profiles,
- Skid resistance, and
- Surface damage.

On the basis of characteristics, the pavement condition can be described sufficiently and evaluated with respect to the objectives. In many cases, maintenance measures can be derived directly from the network pavement condition data. Thus, rehabilitation of a section showing only poor skid resistance may simply be milling or thin coating. Deficiencies in longitudinal evenness, rutting, and surface damage, however, require more thorough rehabilitation measures. In cases of doubt not clearly pointing at one or the other maintenance measure, a second and more detailed survey is necessary, including the evaluation of bearing capacity and core lifting.

From a Pilot Survey to a Complete Data Collection Program

Survey and Assessment Concepts

The relevant characteristics and indicators of the road surface, surveyed either by visual inspection or by automated monitoring according to the directives set up in the Federal Republic of Germany (5,6), are shown in Figure 1. The corresponding condition data have different dimensions (millimeters, percentage, etc.). For the subsequent processing of these data for a particular road section (100 m), they are transformed (with the help of standardization functions) into dimensionless and comparable condition values, ranging from 1 to 5 (very good to very poor). These values subsequently are weighted and linked by particular algorithms resulting in two values, namely, a service value and a structural value. The poorer of these two is selected as the relevant overall value of a section.

The standardization procedure is outlined using the example of rut depth (Fig. 2). Target values, alert values, and threshold values have been defined for each condition indicator, partly on the basis of technical requirements and partly on frequency distributions computed from representative road section collectives. Normally, the target value is set at the value required in acceptance specifications for new or renovated roads; according to the German evenness requirements, this is 4 mm for rut depth. The alert value describes the situation in which maintenance planning is due. It has been set at 10-mm rut depth. The threshold value characterizes a situation in which maintenance measures or traffic restrictions are to be initiated. It has been set at 20-mm rut depth.

The condition data plotted on the abscissa are translated via the standardization function into the condition value grades plotted on the ordinate. Grade 1.5 is assigned to the target value, grade 3.5 to the alert value, and grade 4.5 to the threshold value.

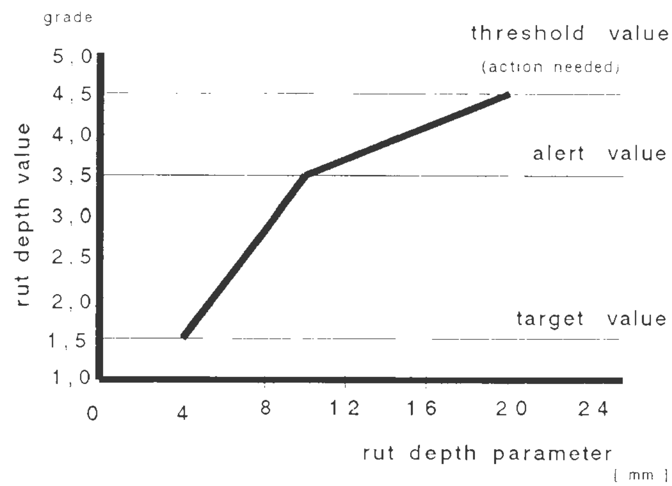

FIGURE 2 Example of standardization from condition parameter to condition value: rut depth.

	BITUMINOUS CONCRETE		CEMENT CONCRETE	
GROUP OF CHARACTERISTICS	CONDITION CHARACTERISTICS	CONDITION PARAMETERS	CONDITION CHARACTERISTICS	CONDITION PARAMETERS
EVENNESS	LONGITUDINAL UNEVENNESS	meas. $\Phi_h(\Omega_0)$ [cm^3]	LONGITUDINAL UNEVENNESS	meas. $\Phi_h(\Omega_0)$ [cm^3]
	TRANSVERSE UNEVENNESS	rut depth [mm] water depth [mm]	TRANSVERSE UNEVENNESS	rut depth [mm] water depth [mm]
SKID RESISTANCE	SKID RESISTANCE	coeff. SFC [-]	SKID RESISTANCE	coeff. SFC [-]
SURFACE DAMAGES	NET CRACKING	part of surface [%]	LONGITUDINAL/TRANSVERSE CRACKS	[m] number of slabs [%]
	RAVELLING	part of surface [%]	CORNER DEMOLITION	[m^2] number of slabs [%]
	PATCHES	part of surface [%]	EDGE DAMAGES	[m] number of slabs [%]

FIGURE 1 Condition characteristics and parameters for bituminous concrete and cement concrete.

The linkage of the condition values to the service value is shown in Figure 3. The following percentages of the values are taken into account:

- Maximum of unevenness value or rut depth at 25 percent,
- Theoretical water depth at 25 percent, and
- Skid resistance at 50 percent.

The service value is obtained by linking the weighted values on the basis of a combination law and a logarithmic function.

The structural value is obtained in a similar manner, but different weightings for asphalt and concrete are used, as follows:

- Bituminous Concrete
  - –Structural Value
    - —Patches, 10 percent
    - —Ravelling, 20 percent
    - —Net cracking, 50 percent
    - —Maximum longitudinal-transverse unevenness, 20 percent
  - –Service Value
    - —Maximum longitudinal-transverse unevenness, 25 percent
    - —Water depth, 25 percent
    - —Skid resistance, 50 percent
- Cement concrete
  - –Structural value
    - —Longitudinal-transverse cracks, 30 percent
    - —Corner demolition, 20 percent
    - —Edge damage, 15 percent
    - —Maximum longitudinal-transverse unevenness, 35 percent
  - –Service value
    - —Maximum longitudinal-transverse unevenness, 25 percent

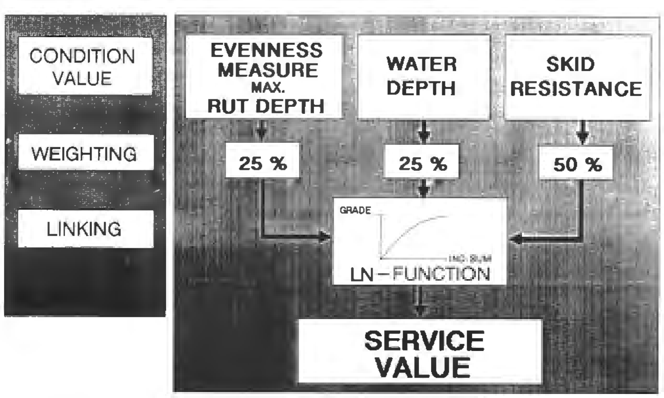

FIGURE 3 Formation of service value.

    - —Water depth, 25 percent
    - —Skid resistance, 50 percent

The service value implies traffic safety and driving comfort and is oriented toward the road user. The structural value, on the other hand, is intended as an orientation for the needs of the financing authorities.

First Survey of Autobahns

Surveys and the assessment of the pavement condition of the federal highways and autobahns in Germany are the responsibility of the federal states. However, as part of the establishment of a new road information system, the Federal Ministry of Transport (BMV) financed the first survey on these roads. The Bundesanstalt für Strassenwesen (Federal Highway Research Institute) (BASt) advises and assists the authorities. It was decided in 1989 to start with the survey of autobahns, because they are of paramount importance for road transport in Germany (7). Before the unification of Germany, without the new states, this meant surveying about 40 000 km of roads. At that time, neither the monitoring techniques nor the assessment concepts had been thoroughly tested. The survey was conducted in two steps: The first step consisted of a 3000-km roadway pilot survey in the states of Bavaria, Hesse, Lower Saxony, and North Rhine–Westphalia. Two-, three-, and four-lane unidirectional roadways, asphalt and concrete pavements, and sections with and without emergency shoulders were monitored. The monitoring and organizational results were used as the basis for

- Launching a first survey bid for all autobahns,
- Drawing up instructions for survey preparation and execution,
- Developing the basis data for 16 states,
- Limiting the survey to the necessary extent, and
- Adapting the existing concepts to the particular conditions of automated monitoring.

After the pilot survey it was possible to start the second step of the first survey at the network level in all 16 states (8,9).

Although it had been possible to cut the price per survey kilometer from approximately DM 400 to DM 270, it was believed that further reduction of the monitoring expenses was necessary and possible. The original concept envisaged monitoring of about 56 000 km in total. This was reduced to 22 000 km by deciding to survey all traffic lanes in the new states and only the right-hand lanes in the old states.

The survey was begun in April 1992 and completed in September of that year.

Measuring Systems—Needs and Possibilities

The following measuring systems were used to register pavement condition in the pilot survey:

- Longitudinal evenness: High-Speed Road Monitor (HRM),
- Transverse evenness: Automatic Road Analyzer (ARAN),
- Skid resistance: Sideway-Force Coefficient Routine Investigation Machine (SCRIM), and
- Surface damage: Groupe d'Examen Routier par Photographie (GERPHO).

All measuring devices performed satisfactorily during the pilot survey.

It soon became obvious that simultaneous monitoring of longitudinal and transverse evenness was necessary to reduce costs. In the subsequent survey of the autobahn network, the Swedish system Laser Road Surface Tester (LRST) was used for this purpose. The remaining characteristics were registered again using SCRIM and GERPHO.

Random checks of the measuring systems, the registration process, and the evaluation of the data were made during the entire operation. Longitudinal and transverse evenness were checked with the newly developed German Automatic Road Condition Graduating Unit System (ARGUS), and skid resistance with SCRIM.

The British HRM registers the longitudinal evenness values using laser probes attached to an inflexible beam (*10*). In Germany, this system is the calibrational standard for longitudinal evenness monitoring. The measuring interval for the unevenness peaks is 100 mm in the direction of driving. Transverse evenness profiles cannot be monitored with the HRM.

The Canadian ARAN calculates the longitudinal profile by means of a vibration replace system including the measurement of vertical acceleration. Transverse profiles are surveyed by means of a front beam (width up to 3.60 m) equipped with ultrasonic detectors placed at 100-mm intervals (*11*).

The Swedish LRST device registers the longitudinal evenness by using a laser probe in combination with a vertical acceleration meter (*12*). The transverse profiles are measured by means of a 2.50-m front beam fitted with 20 laser probes. They are placed in an angular position permitting a total registration width of 4.0 m.

The German ARGUS measures the longitudinal profile on a laser basis using the HRM principle (*13*). Transverse profiles are also measured using laser detectors that are mounted on the front beam at 100-mm intervals. For longitudinal evenness, it is now accepted that a measuring system must collect profile data approximating the real longitudinal profile that enable the calculation of the parameters relevant for the condition rating.

The profiles resulting from surveys carried out with HRM, LRST, ARGUS, and ARAN were compared and proved to be quite consistent, in particular where isolated irregularities and longer unevenness waves are concerned (Fig. 4). In Germany the unevenness value ϕ_b (Ω_0) is used as relevant indicator in the condition rating process. The differences of the mean uneveness values are in the tolerance range of $0.6 \cdot 10^3$ mm^3. The value ϕ_b (Ω_0) is derived from the unevenness spectral density and represents the height in the balanced spectrum near 6-m wavelength. However, investigations are currently being made as to

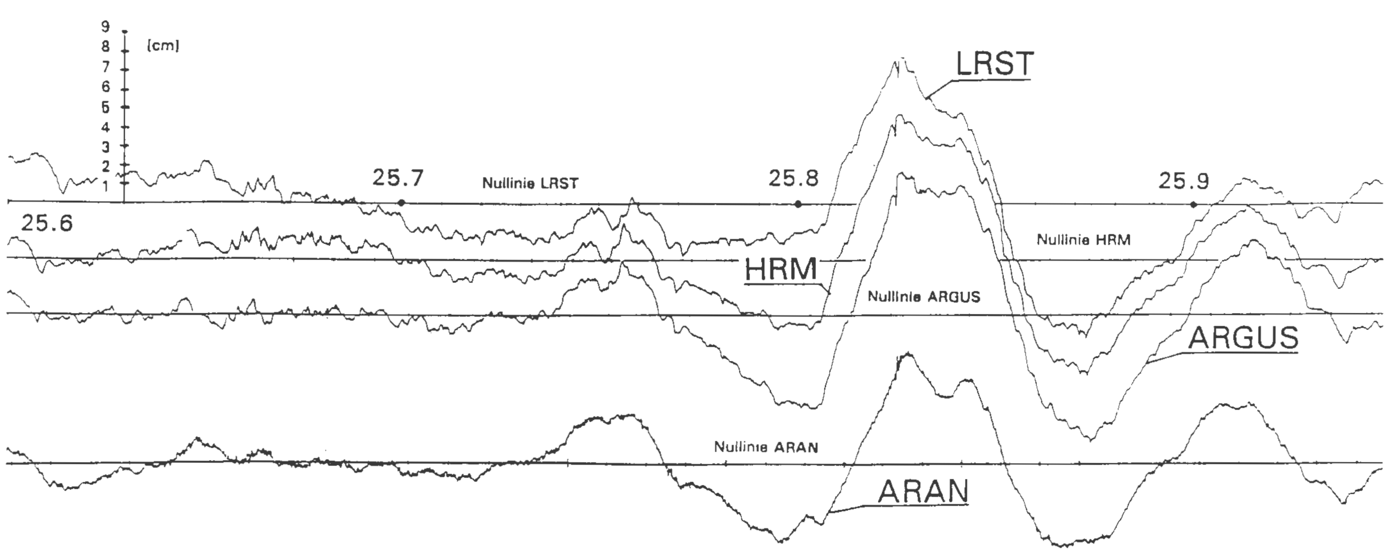

FIGURE 4 Comparison of longitudinal profiles taken by ARAN, ARGUS, HRM, and LRST: A4 from Km 25.6 to 26.0.

how far single irregularities and periodically occuring irregularities have to be taken into account.

Transverse evenness studies revealed that the rut depth can vary considerably within just 1 m and does not remain steady over the distance of longer sections. This has to be considered when one is comparing measuring systems calculating the rut depth at different intervals in the driving direction. It was observed that the results of ARAN, LRST, and ARGUS calculations of the average right-hand lane rut depths are quite consistent. The differences of the mean rut depths are smaller than the standard tolerance of 1 mm. Apart from the rut depth, the theoretical water depth is also relevant for the condition rating. This value is calculated using the transverse profile in connection with the transverse grade.

Six SCRIM are currently used in Germany for routine skid resistance measurement (*14,15*). The pavement wetting devices have been significantly improved. Measuring results of the systems have been compared and proved to match (Fig. 5). The differences of the mean SCRIM values are below the tolerance value of 0.018.

With the French system GERPHO, the pavement surface is filmed continuously at a driving speed of 70 km/hr (*16*). Cracks of 0.7-mm width can still be registered. Surveys are only carried out at night to guarantee the same exposure to light.

The developed films are assessed according to the procedures of visual inspection. The condition parameters for asphalt pavements are expressed as a percentage of the damaged areas. In the case of concrete roads, two condition parameters exist for each type of surface damage. One describes the average development of damage, the other the number of the slabs affected.

Data Processing, Evaluation, and Presentation

In order to allow an accurate and correct allocation of the condition data, a network system that is independent of possible changes in length or road classification in the road network is needed. In Germany, this is realized by means of the so-called network nodes coding system serving as a basis for the road data information system. Roads are subdivided into several network sections, each one defined by two network nodes. Signs in the form of triangular boxes (Fig. 6) are set up in situ.

For each monitored 100-m section, condition data, condition values, service values, and structural values, as well as overall values, are established from the raw data using the mentioned concepts. Most of the programs were developed during the pilot survey. The results were compiled in dBase data files. Results can be presented in the

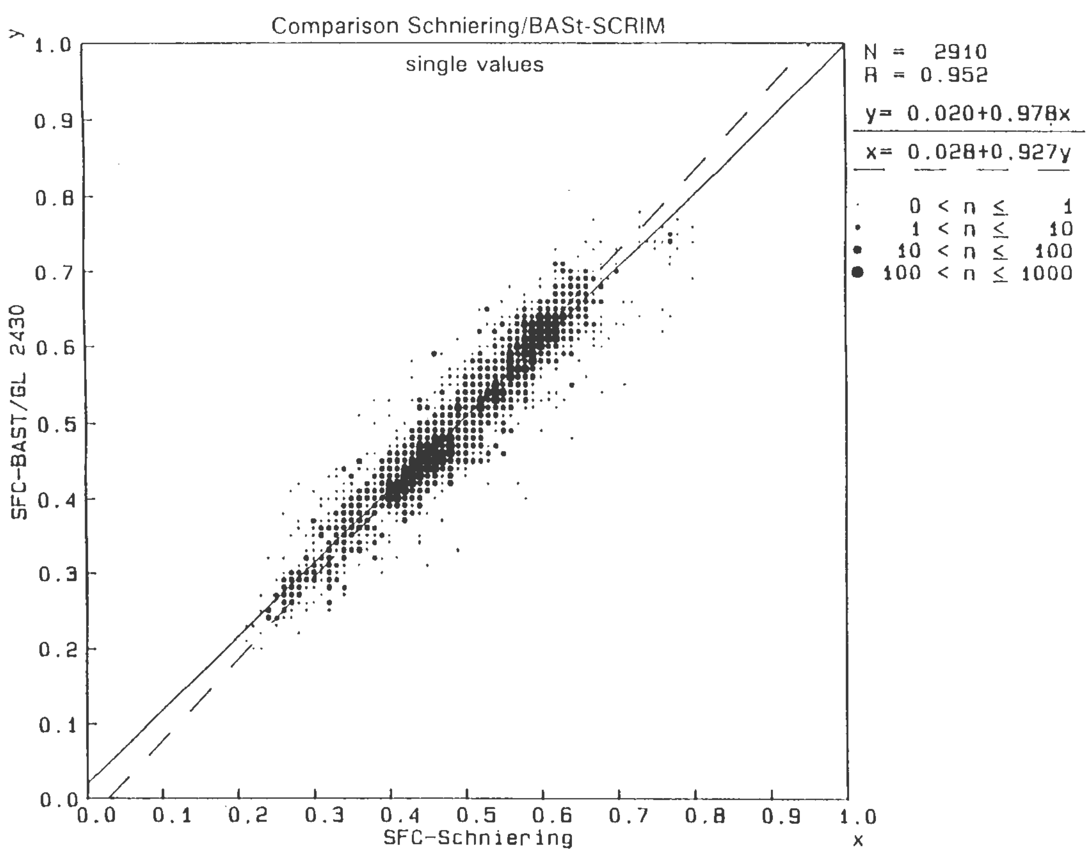

FIGURE 5 Correlation between two German SCRIM.

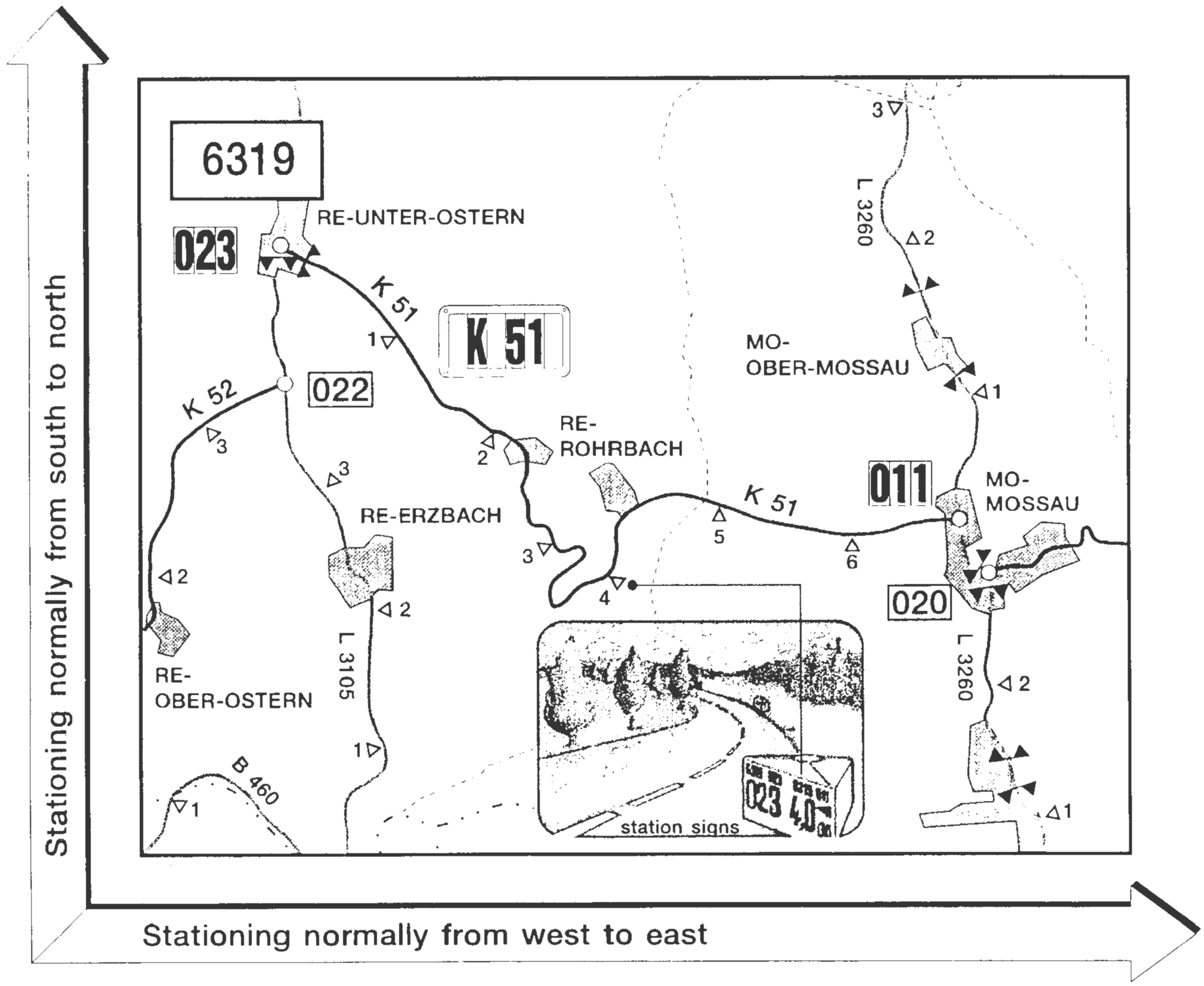

FIGURE 6 Network node system.

form of lists, section profiles, frequency distributions, and network graphs (Figs. 7–11).

In order to present a condition rating "at a glance" in a map, four color classes were assigned to the respective grades. These color ranges are divided by the target values, the alert values, and the threshold values. The colors used and their meanings are the following:

- Blue, condition of a new road;
- Green, no measures necessary;
- Yellow, attention: reasons for deficiencies should be analyzed and maintenance measures planned; and
- Red, very poor condition: maintenance measures should be carried out and traffic restrictions introduced.

With these colors used the network deficiencies are made visible "at a glance." Subsequently it is easy to look at a particular poor section and start a detailed, object-oriented study of the corresponding raw data material. It is also possible to choose other forms of assessment, incorporating, for instance, other information drawn from the basic data (e.g., the type of pavement) or from the section characteristics (Fig. 10).

In order to judge the condition rating for federal states, autobahns, traffic lanes, and construction types, frequency distributions were plotted in eight condition categories with half-grade steps (Fig. 11). Graphic illustrations linking frequency items with the service value and the structural value by means of a matrix are especially appropriate for further analysis and decisions concerning measures to be taken.

OUTLOOK

Feedback into the Evaluation System

The survey and the condition rating of the German autobahn network have been an important step toward a complete PMS (*17,18*). For the first time, a condition rating at

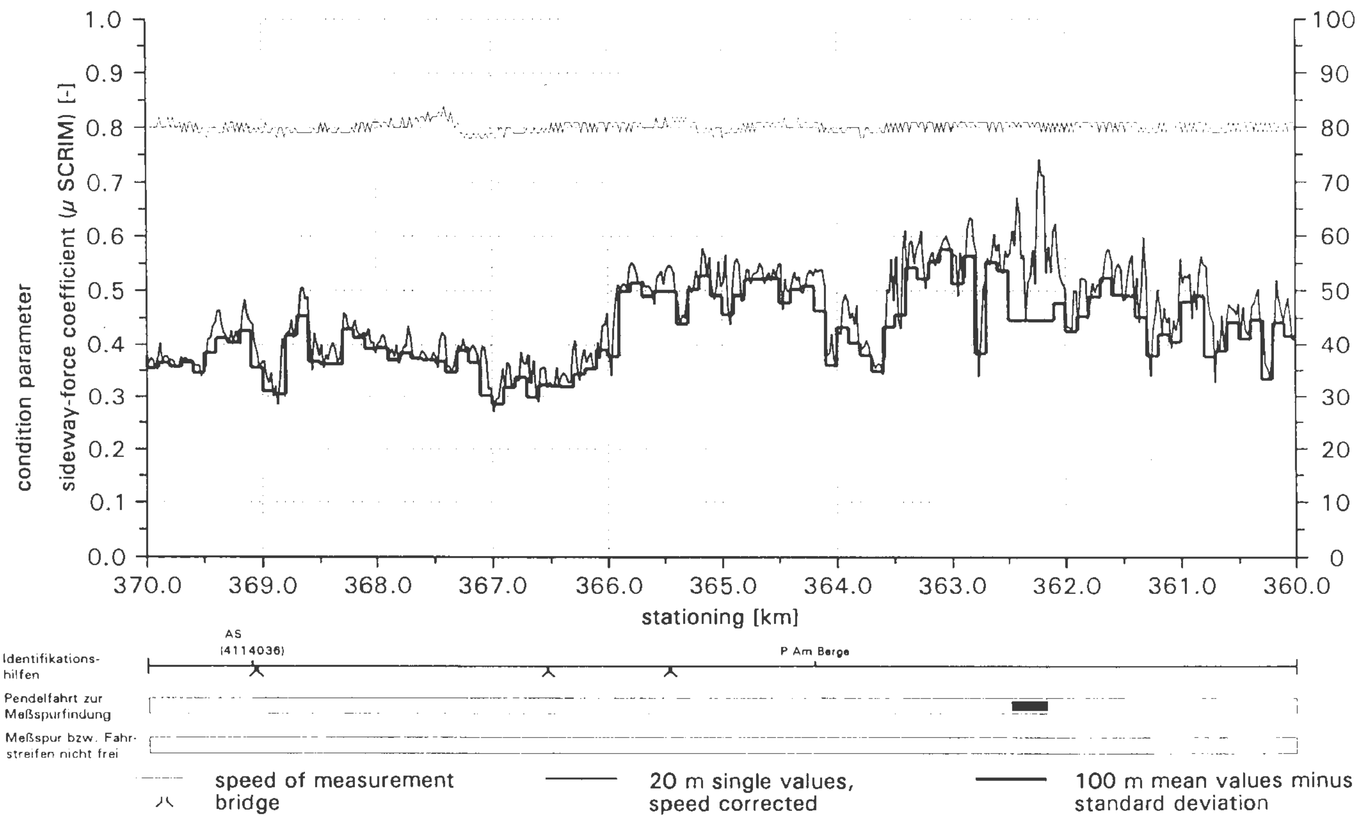

FIGURE 7 **Profile of condition data skid resistance (source: Auswertungen Schniering/IFTA).**

network level is possible. The modification of the survey methods and assessment system, started right after the pilot survey, will be continued taking into account all future findings. The assessment rules are presently checked with respect to their plausibility in sensitivity analyses. For this purpose, frequency distributions for condition parameters, condition values, and partial and overall values have to be established in order to gradually improve the algorithms in a quasi-iterative process.

The relevance of single-condition indicators must be checked with respect to the objectives, in particular to the user aspects, environmental compatibility, and the appropriateness of maintenance measures. For instance, the validity of the unevenness value $\phi_n(\Omega_0)$ is being studied more in detail. The limits defined in 1985 will be verified in vehicle simulators. When one is defining rut description indicators, it will be considered whether parameters other than rut depth and water depth are to be taken into account to allow a better choice of maintenance measures. In Germany, rutting appears as

- Deformation in the upper asphalt layers, showing lateral uplifting with heavy flank inclinations, and
- Insufficient bearing capacity leading to flatter ruts without uplifting.

These influences can also overlap. Therefore, surface damage detection must be as accurate as possible. Where damage is identified, the entire graphic documentation has to be consulted for further object-oriented maintenance planning. This is also the case if the automatic evaluation has already taken place simultaneously with the survey, and image storing was not intended originally.

Moreover, efforts will be made to reduce the amount of data by means of correlations and linkages of different condition indicators. In this context, also, aspects currently discussed within the framework of the European standards harmonization have to be taken into consideration.

Refinement and Integration of Additional Information

The results of the survey allow a rating of the road sections with respect to their condition. Weak points can be identified, and it is possible to reduce risks caused by safety-relevant deficiencies, for example, by limiting traffic speed. Pavement management requires the linking of damage reasons to condition characteristics—one by one or in combination. Characteristics such as age, traffic load, construction data, construction material parameters, and maintenance history have to be taken into account as well. Subsequently there is a need to typify deficiencies so that appropriate maintenance measures can be recommended.

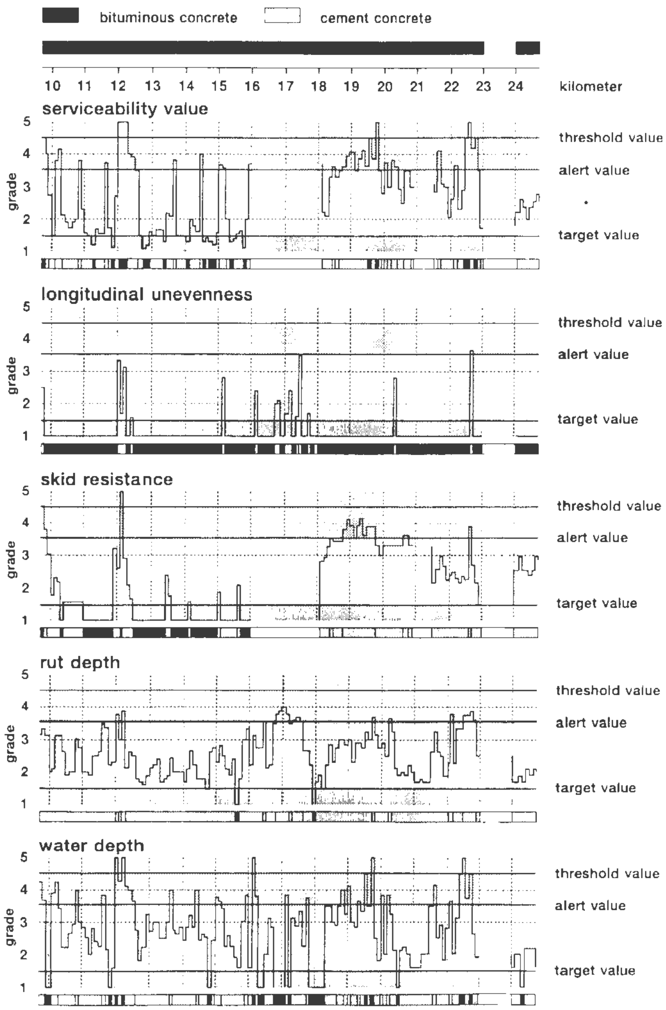

FIGURE 8 Profiles of service value and the associated condition values (source: Auswertungen ASTRA).

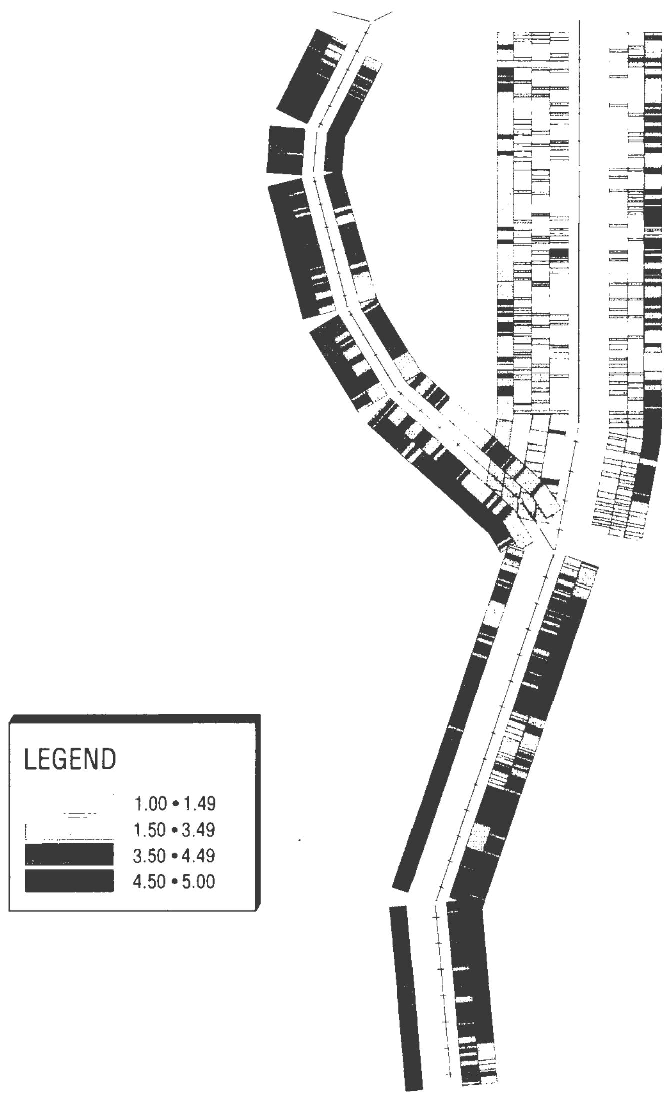

FIGURE 9 Network representation of the overall value (source: Auswertungen DASTRA).

In addition, attempts to typify statistically the behavior of different pavements are made by means of classification. There is an indication that strengths and weaknesses of various pavements and appropriate maintenance strategies can be identified in this way. Findings here can be used to improve concepts for forecasting models and the especially important modalities for repeated monitoring.

For the survey of pavement changes, the following procedures need to be fixed in the future:

- Target values as acceptance values in construction contracts leading to the examination of the construction performance based on the rules of condition rating—the so-called initial test—at the time of the acceptance of a contract, and
- Repeated monitoring in fixed time intervals.

A network- or section-based strategy and requirement planning can be developed based on the actual changes. In certain cases more detailed investigation may be necessary, requiring additional data, such as bearing capacity, construction material type, or layer thickness, which must be integrated into the PMS data pool. The same goes for the results of in situ condition monitoring carried out continuously by the autobahn operation centers.

Repeated monitoring requires that measuring and evaluation costs be kept as low as possible. For this purpose pilot versions of multifunctional monitoring systems are already in operation in Germany and elsewhere. These systems are capable of surveying nearly all relevant condition characteristics using light-optical reading of the road surface geometry and eventually also registering deflections during a single pass. Subsequent data processing is computer-aided without manual intervention. For an overall PMS, apart from the network node system, information

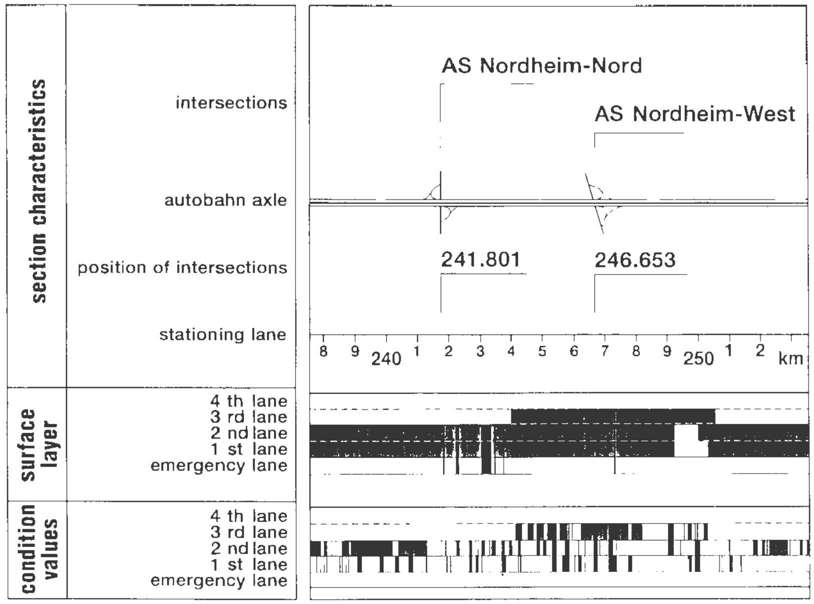

FIGURE 10 Condition values, section characteristics and type of pavement (source: Auswertungen Technische Überwachung Hessen).

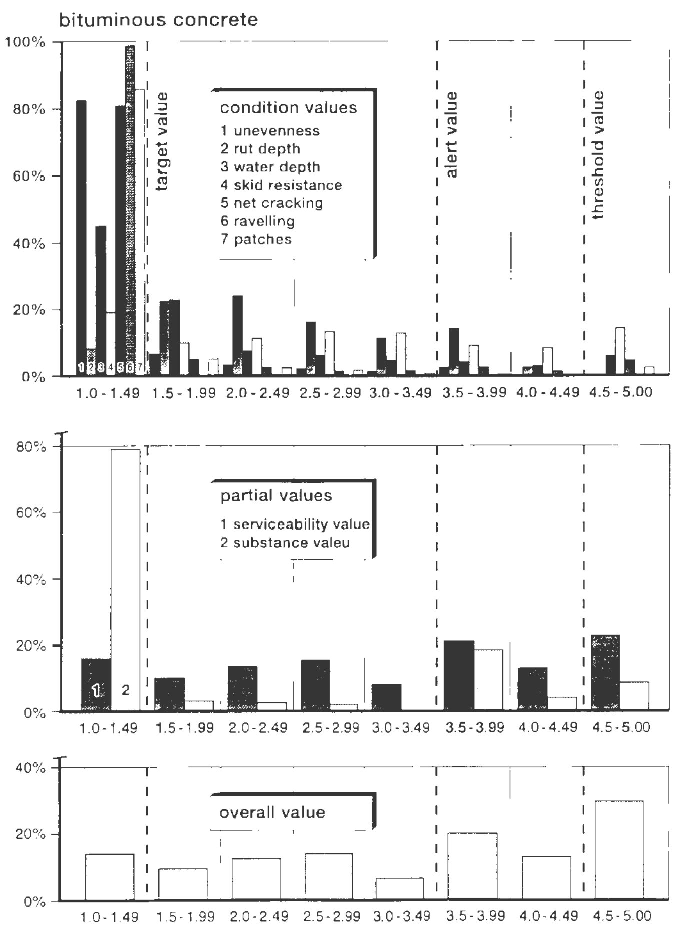

FIGURE 11 Frequency of condition, service, structural, and overall values (source: Auswertungen ASTRA).

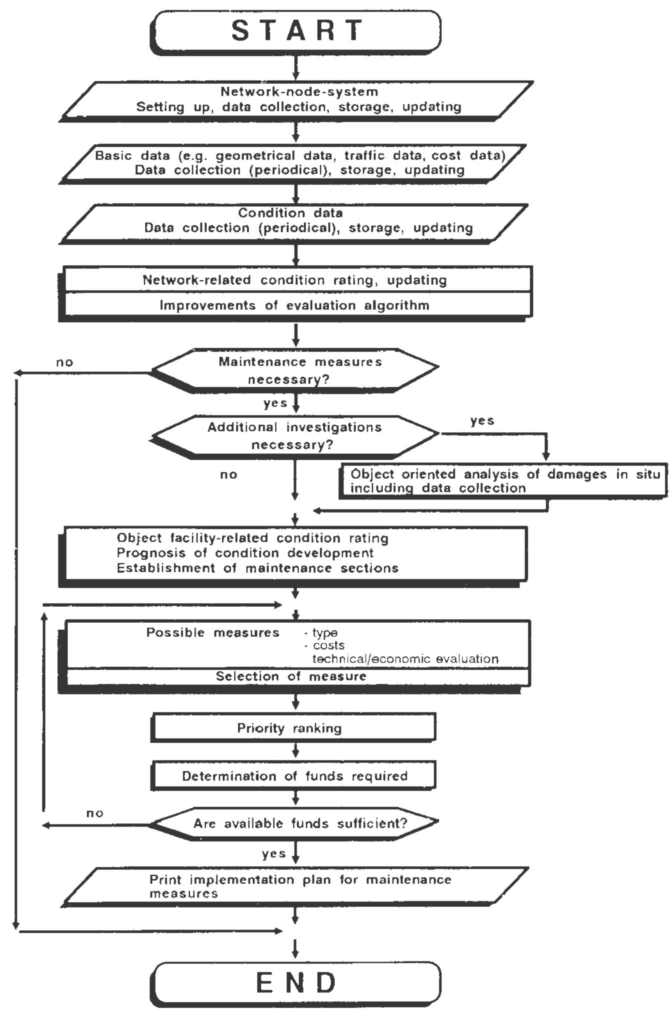

FIGURE 12 Flowchart for object-oriented PMS.

about the design, construction, traffic, and costs as well as environmental aspects has to be accessible in a special data base. Only when these requirements are fulfilled is a priority rating of different maintenance alternatives possible with respect to available financial means, political priorities, and economic aspects.

In the present stage a stepwise approach is used to arrive ultimately at an overall PMS. Provision is made to guarantee the independent use of the various components of the system.

Figure 12 shows the flowchart of the system to plan highway maintenance measures and allocate available funds. The system is based on the basic data of the road network and the evaluated monitoring data. Object-oriented surveys are optional. The various components of the system are presently introduced in simple forms. With later data and based on the experience gathered, they can be replaced by more sophisticated algorithms.

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Evaluation of French National Highway Network Based on Surface Damage Surveys

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In 1992 the managing authority of the French National Roads Network decided to modernize the means of evaluating the condition of its roads. The tool set up to do this is based primarily on a systematic survey of pavement surface damage, completed by skidding resistance measurements. Sixteen Regional Public Works Laboratories were assigned to gather road information. For the evaluation tool to have the expected qualities, there has been a special effort to make the damage survey a means of investigation as reliable as a measurement. The laboratories use a highly formalized method that precisely fixes the conditions in which the survey must be performed, the type of information to be recorded, and its codification. Training incorporating an introduction to the method, practical work on sections of road, and days spent coordinating the terms complete the arrangements made to ensure the reliability of the survey. The information gathered on the road network is then realigned on the official distance markings of the road network and accepted in 200-m lengths before being transferred to a data base. There it is processed to provide a series of ratings qualifying the condition of the pavement structures and the safety that the pavement offers the user.

The definition and application of a maintenance policy on a large road network assumes that the owner has a suitable tool for periodic evaluation of the condition of its roads. In 1992, the Roads Managing Authority of the French Ministry of Infrastructure, owner of the National Roads Network (NRN), decided to modernize its evaluation tool. This decision reflected a twofold concern: on the one hand, to better evaluate the maintenance needs of the NRN to specify and justify the costs necessary for this maintenance, and on the other to better manage the use of these costs in partnership with local project supervisors.

The attention of the Roads Managing Authority was directed first to the preservation of the enormous asset constituted by 34 000 km of roads and motorways, most of which must carry high levels of traffic and therefore consist of wide pavements, treated with hydraulic or bituminous binders, in large thicknesses. But the road user's safety has not escaped attention—quite the contrary. Thus, the evaluation tool takes into account these two aims of maintenance. There are two specialized ratings, one reflecting structural condition and the other, surface condition. From these ratings are derived a global quality rating, which gives an overall picture of the condition of the road, and a users' rating, which reflects how the road is perceived by those who travel on it.

General Considerations Relating to Information Gathering

Choice of Indicators

The evaluation tool is based primarily on a survey of pavement surface damage for the whole of the road network. This survey is simple but rigorous. It covers permanent deformation of the pavement, cracking (with a distinction between shrinkage cracks and other types of cracks), wearing course damage, and repairs. Each of these categories is characterized by its extent and its severity. Cracking and deformations are essential indicators to evaluate not only the condition of a pavement at a given time, but also its likely short-term evolution. The deformations are also used, with the wearing course damage, in evaluating the level of safety provided for the user.

Measurements (sand patch texture depth, coefficient of transverse friction) complete the indicators used in the calculation of the safety ratings, because it is impossible to judge the skidding resistance of a surface from a visual impression alone.

The deflection measurement is not taken into account in the calculation of the structural ratings. This choice does not result from considerations of the pertinence of this measurement to the objectives of the evaluation tool. Practically, it turned out to be impossible to make this measurement on 34 000 km of roads within the cost and time limits fixed by the managing authority in 1992. However, it is not impossible that this indicator will be reinstated in the evaluation tool in the future. More important, it is still considered in the downstream stages of the sequence of maintenance studies: scheduling of work, especially diagnosis of structural problems.

Conditions of Gathering of Indicators

For the evaluation tool to meet the expectations of the owner, it is first necessary that the data collection methods should be reliable (i.e. repeatable, reproducible, and as accurate as possible). These conditions do not pose too many difficulties for skidding resistance measurements. On the other hand, the difficulties inherent in the damage survey are well known: subjectivity of the information entered, influence of many external parameters such as lighting, dampness of the road, and so forth. To overcome these difficulties, the survey procedure selected for the evaluation tool is defined carefully and precisely. It is based on a detailed and rigorous survey method that the Public Works Laboratories have developed, and more particularly on one of its procedures, M3, specially conceived for the rapid evaluation of a road network. A computer-assisted recording system, named DESY, which is totally coherent with the survey method, guides the operator in the application of this procedure and makes his or her work much easier. All teams performing this survey undergo a certification procedure that includes training in the use of the DESY system and in the application of the M3 procedure, and regular cross tests. The arrangements so instituted (method + apparatus + training + cross tests) ensure the quality of the survey.

LPC Surface Damage Survey Method

General Principles of Method

For several years, the French Public Works Laboratories have become increasingly aware that to make the surface damage survey a reliable and precise tool, it is necessary to formalize the survey method rigorously, codify the damage, configure the survey assistance apparatus, and train the teams. This growing awareness led first to the drafting of a precise and complete method (*1*) that can be adapted to all circumstances in which the damage survey can be used. For this purpose, the method includes six distinct, complementary procedures (see Table 1) in which the way that damage is recorded is carefully described. According to the objective, the type of study for which it was conceived, the procedure more or less finely differentiates the damage to be recorded. Three of these procedures are to be used in normal surveys:

- M1: detailed procedure, for diagnostic studies;
- M2: standard procedure, recommended for programming of maintenance work; and
- M3: a summary, but still rigorous, this procedure is applicable to the evaluation of networks; it may also be used (with some reservations) for the programming of maintenance work.

The three other procedures are devoted to special surveys:

- M4: special procedure for Gerpho surveys, recommended for evaluating and programming maintenance work on motorways;
- M5: special procedure, extremely precise with graphical report of degradations, for monitoring of test sections; and
- M6: special procedure for evaluating and programming maintenance work (with some reservation) on urban networks.

In the procedures, the damage is classified into different main headings according to type, and for each head-

TABLE 1 Circumstances of Maintenance Studies and Corresponding Operating Procedures in Damage Surveys Method

<table>
<tr><th>Management conditions</th><th>"high"</th><th>"normal"</th><th>"light"</th><th>special urban</th></tr>
<tr><td>Evaluation</td><td rowspan="4">M4</td><td rowspan="3">M2</td><td rowspan="3">M3</td><td rowspan="3">M6</td></tr>
<tr><td>Programming of works</td></tr>
<tr><td>reinforcement</td></tr>
<tr><td>diagnosis</td><td>M1</td><td rowspan="2">-</td><td>M1 - M5</td></tr>
<tr><td>monitoring of test sections</td><td>M5</td><td></td><td></td></tr>
</table>

ing, into two subheadings according to severity. Tables 2 and 3 give the lists of the headings and subheadings of the M1 (detailed) and M3 (light) procedures. The comparison between the two tables illustrates one aspect of the refinement between the procedures. With respect to the previous situation in France, one of the innovations of this method is that it considers the severity as well as the extent of the damage. This parameter has been recognized as having a major role in the assessment of pavement condition.

M3 Procedure

For the evaluation of the NRN, Mode M3 was selected. Its domain of application, which is defined as "light survey applicable to the evaluation, surveillance, maintenance scheduling, and overlay studies of all types of pavements in the open country," exactly matched the objective of the tool. In this procedure, a vehicle equipped with a DESY survey system slowly travels the route to be investigated. Two operators are on board, one driving the vehicle and describing the damage seen, the other entering this information into the DESY system. The damage is classified into five main headings, and for each heading, into two subheadings (see Table 3). Each item of damage is represented by beginning and ending abscissa on the x-axis if it has some longitudinal extent (e.g., longitudinal crack, damage of surfacing, etc.) or by a single abscissa if it is localized (e.g., transverse crack).

TABLE 2 Headings and Subheadings of M2 Operating Procedure Indicating Corresponding Damage

headings (damage)	sub-headings (severity)	extent	observations
ruting	light serious	lm lm	> 15 mm > 30 mm
other deformation	light serious	lm lm	> 15 mm > 30 mm
surface defects	bleeding raveling	lm lm	damage of the wearing course
potholes		number	
transverse cracks	visible serious	number number	no spalling with spalling
longitudinal joints	visible serious	lm lm	opened with crack
longitudinal cracks	visible serious	lm lm	no spalling with spalling
other		lm	
alligator cracking	visible serious	lm lm	
square cracking		lm	
repairs	local large	lm lm	< 1/2 lane > 1/2 lane

lm : linear meters of pavement concerned with the distress

TABLE 3 Headings and Subheadings of M3 Operating Procedure Indicating Corresponding Damage

headings (damage)	sub-headings (severity)	extent	observations
deformation	light serious	lm lm	> 15 mm > 30 mm
surface defects	bleeding raveling	lm lm	damage of the wearing course
transverse cracks	visible serious	number number	no spalling with spalling
long. & alligator crackings	visible serious	lm lm	no spalling with spalling
repairs	local large	lm lm	< 1/2 lane > 1/2 lane

lm : linear meters of pavement concerned with the distress

In this procedure, the survey is done in a single pass per pavement, during which is recorded damage on the lane on which the survey vehicle is traveling and on the adjacent lane. The procedure states what to do when several items of damage are present on the pavement simultaneously: if they are of different types, they are all recorded; if they are of the same type, only the most severe is recorded. Note that, as a general rule, damage is recorded only if it is clearly identifiable (the pavement gets the benefit of the doubt).

Training of Teams and Cross Tests

All damage survey teams receive thorough training in three stages:

1. The first stage is an introduction to the method and to the use of the DESY survey apparatus, also including an exercise using slides illustrating all types of damage likely to be encountered and their different levels of severity.
2. During practical work immediately after this training, all teams, one after another, perform the damage survey on a section of road, then jointly discuss the results of these common surveys. This discussion covers, in particular, differences found between the different surveys in the type, severity, and extent of the damage records and so serves to eliminate any ambiguities that may persist after the first step.
3. After a few weeks of operational practice of the survey, harmonization surveys bring together all or some of the teams and take them again to another section of road where the foregoing exercise is repeated.

All the data collected during the third part of the training were processed. The global quality rating was calculated for each team and on each 200-m section of road. This first analysis showed that 90 percent of the ratings from different teams, on a same section, are within ±20 percent of the average value. Complete repeatability and reproducibility tests were forecast by the end of September 1993.

Computer-Assisted Recording System: DESY

The DESY system (2) has been used since 1990 by the network of Regional Public Works Laboratories for the collection, processing, and formatting of road data with a view of their introduction into data bases. The collection device itself (Figure 1) takes the form of a small rigid carrying case that is easy to carry inside any type of vehicle. It includes a personal computer (PC)-compatible microcomputer with a hard disk and a floppy disk drive, along with two special units to perform the functions specific to the system.

Two complementary keypads each having 20 keys flank the standard keyboard; each key can be dedicated to recording one of the types of road data required by the application. Figure 2 shows the configuration of the specialized function keypads used to record pavement damage according to the M3 procedure. This configuration provides one key per level of severity of each damage heading, plus one for the mandatory recording of identification points along the route. Thanks to a specific device (a sensor connected to the vehicle's gearbox), DESY knows its position along the road being surveyed in real time.

The principle of a survey using DESY is simple. After identifying the section of road concerned (geographical department, type of road and number, localization of start and end of section, direction of trip) the operator travels along the section of road. Each time he or she judges that damage belonging to one of the aforementioned headings for Method M3 has begun, the operator assesses its severity and presses the associated function key, which automatically enters the corresponding starting point.

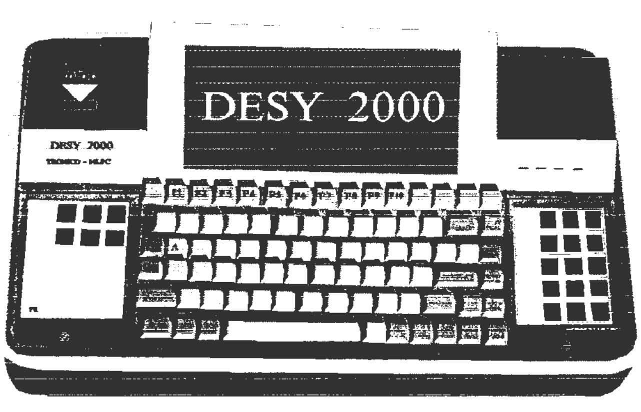

FIGURE 1 Computer-assisted recording system DESY used for damage survey (with its two specialized-function keypads).

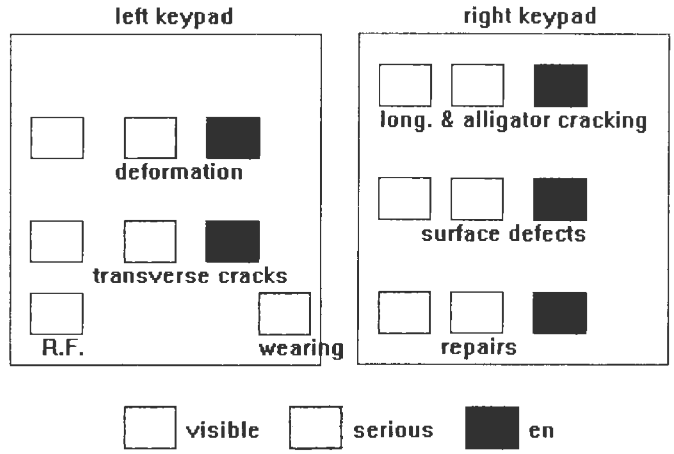

FIGURE 2 Specialized-function keypads for application of M3 operating procedure.

Preprocessing of Data and Their Introduction into VISAGE Data Base

Preprocessing of Data

It is generally not possible to transfer road data directly into a data base. The information that is fed into a road data base in effect comes from different collection devices: DESY, deflectograph, longitudinal profile analyzer, Sideways-Force Coefficient Routine Investigation Machine (SCRIM), and others. Each device uses a location reference system that is specific to the device. Within a data base, all this information must be location-referenced by the same reference system, failing which there may be rejection or (much worse) pairing of information concerning different sections of pavement in the same processing. Furthermore, it is important not to overload the data base with useless elementary data that consume space and computing time. The DESY system has, in addition to the functions described earlier, a set of software that enables it to manage and control these problems. These functionalities were widely used for the evaluation of the NRN.

To start, a special function is used to import into DESY the identification file extracted from the road data base into which the recorded information is to be transferred. Thanks to this function, all the surveys and measurements made on the NRN were harmonized and realigned with respect to the reference points. Then the raw data imported into DESY were combined in sections of constant length (200 m) and stated in terms of relative extent for each damage heading and subheading and in terms of mean values for the measurements. This was done with a view of calculating the structural condition and global quality ratings by section. This preprocessing was completed before the information was transferred to the data base.

It should be noted that at the end of the stages of preprocessing and generation of the derived headings, there was a possibility of displaying the results on linear route diagrams. The systematic plotting of route diagrams was an important step in the validation of the data collected on the NRN, before their incorporation in the data base.

Incorporation in the VISAGE Data Base

The last stage (Figure 3) entrusted to the DESY system consisted of reformatting the results to make them compatible with the VISAGE data base and to allow them to be imported into it. DESY has, for this purpose, an effective and powerful interface with the VISAGE data base.

Processing of Recordings and Measurements

Type of Ratings Calculated

The ratings produced by the evaluation tool, calculated for sections 200 m long, are intended for two distinct decision levels:

1. The structural (as opposed to surface) condition ratings inform the local project supervisor in charge of maintenance of the presence of defects in the structure to guide maintenance studies and work; they are obtained by processing the recordings and the measurements.
2. The global quality (as opposed to users') ratings inform the owner about the global condition of the asset through its maintenance needs (rather than users' perceptions of the road); they are derived from the foregoing two ratings in accordance with the diagram in Figure 3.

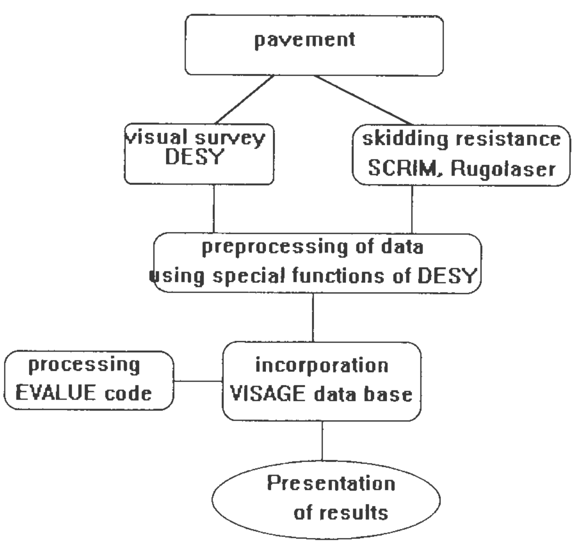

FIGURE 3 Acquisition and processing line of evaluation tool applied on French network of national roads.

Principles of Rating

The rating system was created by the Centres d'Etudes Techniques de l'Equipement (CETE), the Laboratoire Central des Ponts et Chaussées (LCPC), and the Service d'Etudes Techniques des Routes et Autoroutes (SETRA).

The structural condition rating N_s reflects the difference between the condition found by the survey and measurements of the pavement and a reference condition defined by the fact that in this condition, there exists less than r percent risk of having to maintain the structure of the pavement within 20 years; r depends on the traffic. The difference between the condition found and the reference condition is quantified as follows.

- The roads are classified by structure (untreated base, base treated with bituminous binders, base treated with hydraulic binders) and by traffic range (four ranges);
- The pavement condition of each 200-m section is determined from a combination of pertinent indicators, chosen according to the type of structure;
- A "conventional" solution of works based on bituminous techniques, as a function of the structural condition and the traffic range, is chosen to restore the pavement to the reference condition;
- The cost C of this solution is quantified then compared with the cost C_{max} of the most expensive solution, which happens to be the one for a pavement with an untreated base, carrying the highest traffic, and in the worst structural condition (i.e., 20 cm CTM + 8 cm asphalt concrete); and
- The structural condition (N_s) rating ascribed to the section is calculated by the formula

$$N_s = \text{Ent}\,[20\,(1 - C/C_{max})] \quad (1)$$

where Ent [] means "integer part of."

As an example, let us consider a flexible pavement, with medium traffic (between 100 and 600 trucks per day). Table 4 gives the conventional solution of work on this pavement, depending on the cracks and deformations. Table 5 gives the ratings derived from the preceding through Equation 1.

The surface condition rating N_r is obtained by the same approach. But the estimate of the surface condition, and the conventional work solutions necessary to restore this condition to a reference value, are independent of the type of structure and of the traffic range. The cost of these works is again compared with the maximum value C_{max} and the rating is determined by Equation 1.

TABLE 4 Conventional Solution of Maintenance Work Depending on Damage on a Flexible Pavement with Medium Traffic (Between 100 and 600 Trucks per Day)

			D	E	F	.
		extent	0 %	=< 10 %	> 10	%
				vis. & ser.	vis.	ser.
C	v	=< 10 %	-	1 AC	1 AC	MI. + 3.5 AC
R	i	10-50 %	SD	2 AC	3 AC	MI. + 4 AC
A	s	> 50 %	2 AC	3 AC	5 AC	MI. + 6 AC
C						
K	s	=< 10 %	6 AC	7 AC	8 BTM	12 AC
S	e	10-50 %	8 AC	10 AC	12 AC	10 BTM + 6 AC
	r	> 50 %	10 AC	12 AC	10 BTM + 6 AC	14 BTM + 6 AC

vis. = visible ser. = serious (see table 3) AC : asphalt concrete
BTM : bitumen treated material MI. : milling SD : surface dressing

TABLE 5 Structural Condition Ratings, depending on Damage, on a Flexible Pavement with Medium Traffic (Between 100 and 600 Trucks per Day)

			D	E	F	.
		extent	0 %	=< 10 %	> 10	%
				vis. & ser.	vis.	ser.
C	v	=< 10 %	20	19	19	16
R	i	10-50 %	19	18	18	16
A	s	> 50 %	19	18	16	14
C						
K	s	=< 10 %	16	15	14	11
S	e	10-50 %	14	13	11	9
	r	> 50 %	13	11	9	6

vis. = visible ser. = serious (see table 3)

The global quality rating N_g is obtained by taking the smaller of the two foregoing:

$$N_g = \min (N_s, N_r) \tag{2}$$

Finally, the user rating is calculated like the surface rating, but with C_{max} in Equation 1 replaced by the largest cost of surface works.

Presentation of Results

The results of this processing are presented in different forms. First, histograms are provided:

- A series of histograms of the different ratings by category of roads, for the whole national network (see example in Figure 4); and
- A series of histograms of the different ratings by category of roads for the part of this network located in each of the 95 French departments (see example in Figure 5).

The histograms of the ratings by category of roads for the whole network provide useful information for evaluation of the maintenance needs for this network, and for balancing costs among the various categories of roads. The comparison between the "departmental" histograms and the whole-network histograms provides a valuable means for balancing the sharing of the maintenance costs among the local authorities. This presentation is accompanied by a series of maps that display, department by department, the condition of the roads (see example in Figure 6), and that the local maintenance authority can use for a first identification of the sections that probably require structural maintenance work. Of course, further detailed information is necessary on these sections. (The original map in Figure 6 is in color; in the black-and-white reproduction, the green lines are thicker and the blue and black lines are the darker spots in them.)

Preparation and Execution of 1992 Evaluation of NRN

The decision to evaluate the 28 000 km of national roads was made on April 6, 1992. The operation was supervised by SETRA and LCPC.

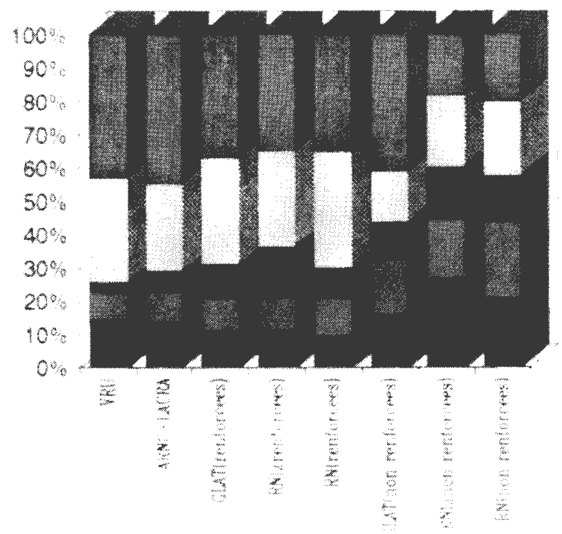

FIGURE 4 Histogram of global ratings on different categories of national roads in France (1992), example.

Visual Surveys

The visual surveys mobilized 16 Public Works Laboratories throughout the country, with each laboratory providing one or two teams. The preparation of the operation and the training of the teams took the next month. The actual survey operation was begun on May 18, 1993 and lasted 4 months. Each laboratory received a list of routes to be surveyed and a computer file containing complete position identification information on these routes. On the basis of this order, it organized the work of its team(s). Each team drove at a mean speed of 4 km/hr, on the right-hand lane of the pavement to be surveyed, recording damage as it advanced. The survey was done without interrupting traffic; the project supervisors provided protection for the teams. Adequate signaling was installed on each route during the survey and a heavy vehicle followed the survey vehicle. These arrangements allowed daily progress of approximately 30 km. As soon as a route was finished, the corresponding data were preprocessed and transferred to a regional center where they were stored in a VISAGE data base (*1*). It was in this center that the data were interpreted and the ratings calculated, section by section.

Measurements

The sand patch texture depth measurements were made using a Rugolaser system. Two systems in France are equipped to make this measurement: the SAMRA's SIRANO vehicle and the SCRIM of the Lyon Regional Laboratory. The measurements of transverse coefficient of friction were made using the SCRIM of the Lyon laboratory. In fact, a good share of the available measurements on the NRN in 1992 were produced during campaigns in previous years with these systems. In 1992 the data base was completed with 2000 km of Rugolaser measurements and 6000 km of SCRIM measurements.

Retrieval of Results

Once the surveys and measurements had been made and preprocessed by the DESY system, they were put into VISAGE data bases. In France, eight regional centers (CETE) have this data base. Each of these centers has in its data base all the information about the national roads passing through the departments for which it has administrative responsibility. The ratings were processed by these centers, which issued documents grouping the results to the project supervisors in their regions. Processing at the national level was organized concurrently to forward the results to the owner.

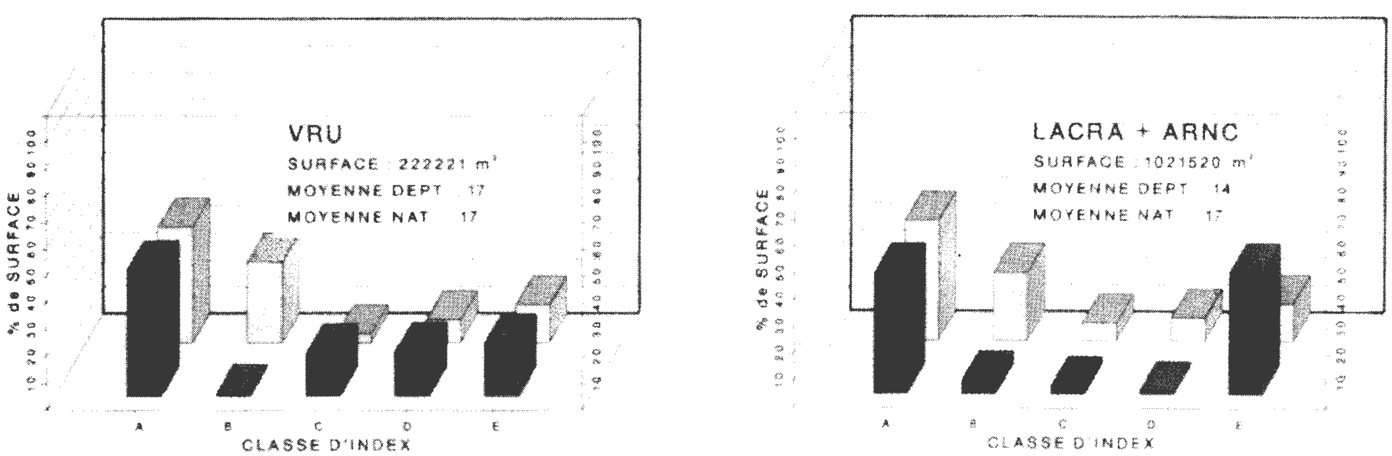

FIGURE 5 Histogram of global ratings of first-category national roads in North department (*front*) compared with national histogram on same category of roads (*rear*).

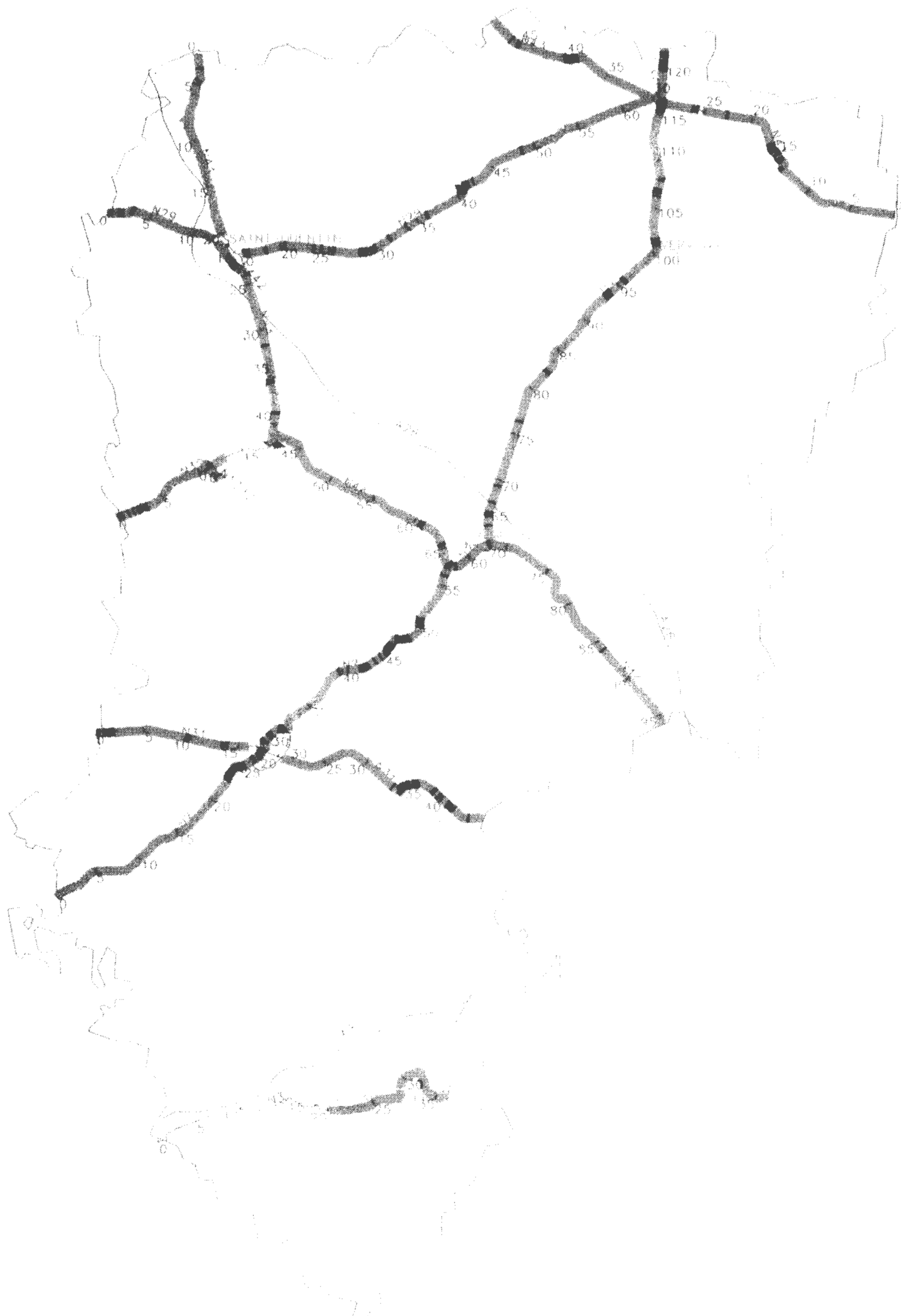

FIGURE 6 Structural rating of national roads of Aisne department; ratings less than 13 in black, ratings between 13 and 17 in blue, and ratings larger than 17 in green.

Thanks to this organization, in November 1992, 6 months after the order, all results of the evaluation of 28 000 km of national roads were submitted to the owner and to the project supervisors.

Conclusions

The Department of Roads of the French Ministry of Infrastructure decided in April 1992 to proceed with the evaluation of the condition of the 28 000 km of national roads that it owns. Six months later, it had the complete and detailed results of this operation: histograms of the ratings for the network as a whole and by department, maps of the routes showing the ratings of the sections by color codes, and so on. It was thus in a position to justify precisely the maintenance needs of this network and undertake a more rational and more rigorous maintenance policy than ever before. Such results could never have been obtained in such a short time, and with such reliability, if the Public Works Laboratories, which made the measurements, had not had a perfectly formalized method of recording surface damage and apparatus in agreement with this method. The evaluation described in this article shows that a damage survey can merit the name of "measurement," with the objectivity that that term implies, provided that it is based on arrangements associating sufficiently thorough training of the teams with this method and this apparatus.

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The Profilograph: A Technological Enhancement of BELMAN, the Danish Pavement Management System

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The integration of the profilograph into BELMAN, the pavement management system used on the Danish state road network, is investigated. In this case, the "profilograph" is a condition measurement device based on laser technology, and it must not be confused with the U.S. "profilograph." Also investigated are the establishment of suitable procedures for data handling and analysis and the performance models needed to integrate the profilograph data into the BELMAN system. Denmark began to develop a systematic approach to pavement management in the 1970s and has since developed a fully operational pavement management system that evaluates pavement management strategies for the entire Danish state road network based on performance models (i.e., the BELMAN system). The most recent enhancement to the BELMAN system is its integration with the Danish profilograph. By incorporating the exact measurements of roughness and profile data obtained through the profilograph, the BELMAN system's capabilities for planning maintenance and rehabilitation strategies have been greatly improved. The profilograph records very precise data on the geometry of the pavement surface obtained by 17 laser sensors mounted on a moveable bar, as well as gyroscopes and accelerometers. The geometrical data are processed afterward to produce longitudinal roughness (e.g., IRI), cross fall, rutting, and curvature. Integration of the profilograph's measuring system into the Danish pavement management system also involved development of suitable procedures for handling and analyzing the tremendous amount of data and information that the profilograph provides about the road network. New models for performance prediction using the profilograph data were also developed.

The Danish Road Directorate has been working on pavement management systems for the state road network since the beginning of the 1970s in order to establish a systematic approach to pavement management in Denmark. Although the present system has been in operation for 5 years, further development of the system is being carried out. One of the parameters used to evaluate the road network consists of the actual surface characteristics: longitudinal roughness, skid resistance, rutting, and others. In order to establish sufficient data for developing performance-related deterioration models for a road network, historical data from a wide variety of roads are needed.

In the late 1980s a revision of the performance model for roughness was performed based on data collected by the bump integrator over a decade on the state road network. During the same period, an attempt was made to establish a similar performance model for skid resistance measured by the Danish stradograph. Although substantial data were available, it was not possible to establish a sufficient correlation between the pavement's skid condition and age. The result of the analysis was that skid resistance was incorporated in the BELMAN system at an intervention level. The parameters that were measured randomly, for example, rutting, gave insufficient data to analyze and hence could not be incorporated into the system, although the state road network consisting of highways and motorways showed an increase in rutting due to the increase in loads.

In 1991, the Danish Road Institute, under the Road Directorate, purchased the Danish-manufactured condition measurement device, the profilograph, which is based on laser technology. At the same time, the Danish Road Institute established a joint venture with the company for further development and implementation of the equipment to perform routine measurement on the Danish state road network. The profilograph is capable of measuring surface characteristics, for example, roughness and rutting. The possibility of incorporating those surface characteristics into the Danish BELMAN system has given the system a new perspective, which will be described in this paper.

The Profilograph

The development of vehicles to measure and record surface characteristics of the pavements in a road network is changing from mechanical-based equipment to laser-based equipment. The development of this technology results in a more direct recording of the pavement surfaces, providing the same basis for determination of different characteristics, for example, roughness and rutting. Furthermore, each surface characteristic can be determined from different algorithms, depending on the desired value or unit.

The profilograph can measure the road's surface structure in the entire wave spectrum from 0.5 mm up to approximately 100 m, whereas the previously used measuring vehicles were designed to measure only a narrow wavelength range. Figure 1 shows the profilograph's measuring range compared with those of the measuring vehicles previously employed.

The profilograph measures the exact profile every 5 mm and stores the data as an average profile for every 8 cm. By use of different algorithms, it is possible to determine roughness, cross fall, rutting, and the depth of free water in the pavement ruts. Further development may lead to an expression for the road's skid resistance on the basis of the micro- and macrotexture.

In regard to operating speed, the profilograph is also very flexible, because it operates at normal traffic speed (up to 100 km/hr); therefore, it is not necessary to close intersections and disturb normal traffic.

The profilograph (see Figure 2) is equipped with the following instruments:

- Laser sensors;
- Laser box;
- Inertial navigation unit, containing gyros, accelerometers, and thermometer;
- Control desk for measuring beam;
- Distance measurer;
- Computer screen;
- Computer keyboard;
- Computer;
- Computer storage; and
- Power source.

The laser equipment, composed of the 17 lasers, is placed on the front of the car on a movable beam measuring

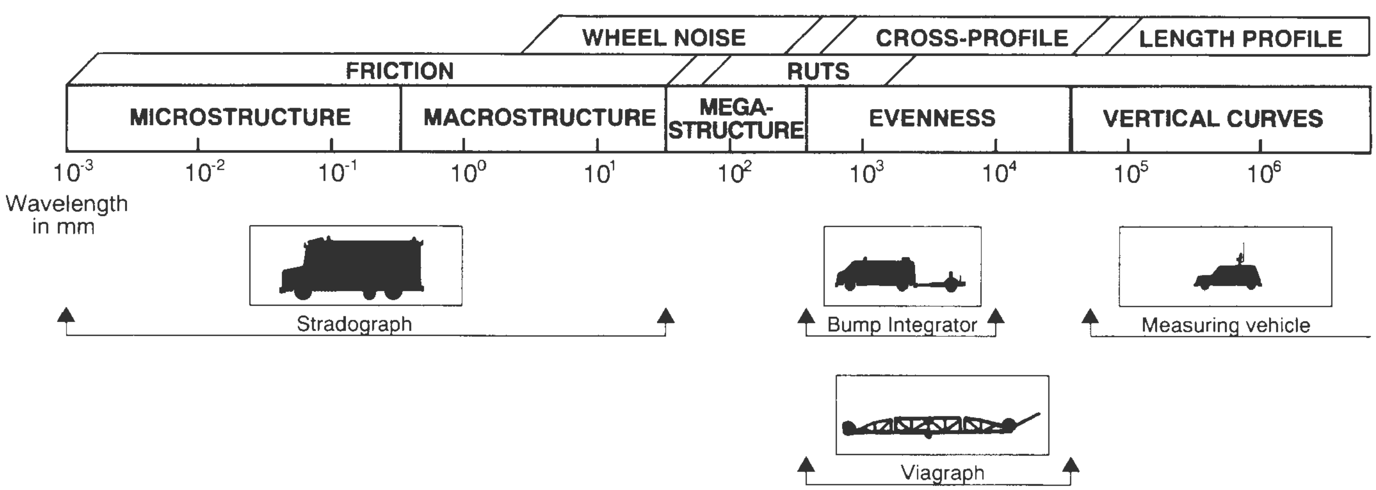

FIGURE 1 Profilograph's measuring range compared with those of the measuring vehicles previously employed by Danish Road Institute.

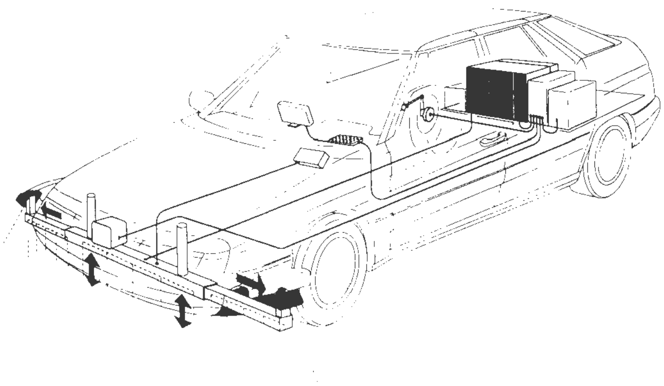

FIGURE 2 Main components in the profilograph.

2.47 m. The lasers are not placed at equal distances but are positioned most densely, where the paths of the wheels are assumed to be found. The two outermost lasers are angled, making it possible to measure a collective road width of 2.9 m.

The lasers measure the distance between the beam and the road surface by one simultaneous reading with a measuring accuracy on the lasers of 0.5 mm. The inertial unit, containing two gyros and three accelerometers, along with the car's distance measure, registers the horizontal and vertical movements. In combination, the laser recordings and the data registered by the inertial unit can provide information about cross profile, cross fall, horizontal curves, and vertical curves.

For many applications, the precise data about the geometry of the road surface need to be linked to other road parameters such as mileage posts, crossings, road signs, and changes in road conditions. The profilograph has the capability to be linked to a satellite-based global positioning system that will provide exact information on the location of the profilograph and the pavement surface it is measuring.

The profilograph's measuring quality has been tested on several occasions. In July 1992, the Strategic Highway Research Program (SHRP) in the United States performed a trial in Ames, Iowa, to compare different types of profiling equipment. Profiling equipment, including the Danish profilograph, from different countries around the world was used in this trial. The results, which were satisfying, are reported elsewhere (*1*).

In Denmark a small trial was performed on one of the state roads. In order to compare the profilograph's measurements with measurements of existing equipment, several different cross profiles were measured by the profilograph, the planum apparatus, and the profiler. The profiler is an apparatus developed at the Danish Road Institute. Basically it works the same as the planum apparatus, but instead of results being registered on wax paper, the data are stored digitally every 10 mm.

A metal wheel runs on the pavement surface; the wheel is connected to a digital transducer recording the level of the wheel relative to a reference level (the beam). The profiler is shown in Figure 3. Profiles measured by the profilograph and the profiler are shown in Figure 4; it can be seen that they are very alike.

The profiles can never be identical, because the profilograph "only" records the cross profile at 17 points, whereas the profiler measures "continuously." Also, the cross profile registered by the profilograph is an average profile of 8 cm, whereas the profiler's wheel width is only 8 mm. The profilograph will generally measure a profile that is more uneven than that measured by the planum apparatus and the profiler because the diameter of the laser beam makes it possible to record points between surface stones, whereas the wheel of the profiler only runs on the top of the stones.

Generally, the trial showed very good agreement between the profiles measured by the profilograph and the more exact measuring equipment. To illustrate the mea-

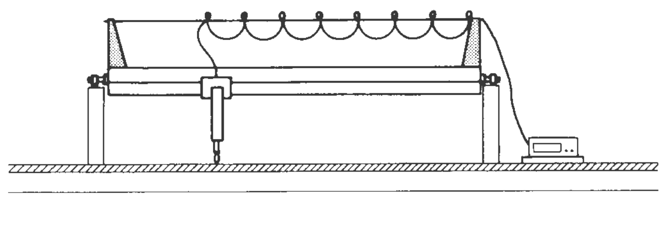

FIGURE 3 Profiler, apparatus for continuous digital measurements of profiles developed by the Danish Road Institute.

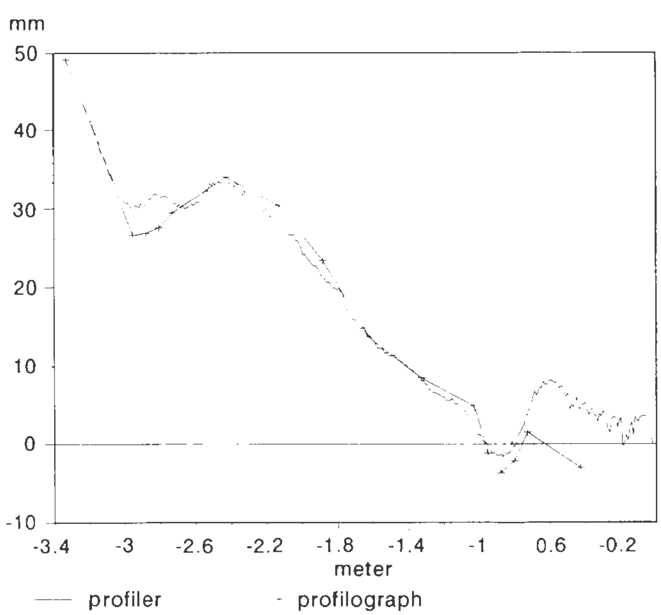

FIGURE 4 Comparison of cross profiles measured by the profilograph and the profiler.

suring accuracy of the profilograph, a statistical analysis was carried out on the profile shown in Figure 4. For this analysis, data from the profiler were used, because they are registered as digital numbers.

The mean deviation of the profiles measured by the profilograph and the profiler is calculated on the basis of values for every 10 mm of the cross profile. Values used to represent the cross profile of the profilograph at positions where no sensors are placed are linearly interpolated values.

The result of this analysis is that the profile registered by the profilograph deviates (average numerical deviation) 1.9 mm from the profile measured by the profiler, with a standard deviation of 2.9 mm. If one looks at these values, it should be kept in mind that the deviation could never be 0 mm because the profiles are not exactly the same.

The good results of these two trials has convinced the Danish Road Institute that the measured profiles from which the roughness and rut depth values are to be calculated are very reliable.

Implementation in Pavement Management System

The profilograph is the first piece of laser-based equipment in Denmark used to measure surface characteristics and hence a great deal of effort is demanded to implement it to standard practice for evaluating surface characteristics.

One of the problems of introducing new ways of measuring road characteristics is that the known and the familiar are changed to the unknown, which has to become familiar. Thus, although a new machine can be seen as an enhancement through an opportunity to get more information and often more reliable data, there is also the point that general users have to understand the numbers given by this new equipment. For road engineers in county or local government who have been used to roughness values such as those produced by the bump integrator, it is a problem to convert to other values such as international roughness index (IRI).

Another problem is to use these new measurements in a pavement management system in which existing performance models are based on the equipment used previously. It demands extensive work to redesign the existing models or to make sure that the new equipment gives results equivalent to those given by the old equipment.

One of the existing models for pavement performance in the BELMAN system is the model for roughness prediction. Roughness has routinely been measured on state roads since the beginning of the 1980s, providing good statistical data for development of a performance model, which was carried out in 1990. The implementation of a new method to measure roughness demands extensive work to correlate the existing model to the new type of measurements. Simulation of the bump integrator on actual longitudinal profiles measured by the profilograph caused some problems. Therefore, a correlation analysis—correlating roughness values on roads previously measured by the bump integrator with IRI values calculated from longitudinal profiles measured by the profilograph—was performed. Although extensive work was carried out to ensure that correct values were correlated, the correlation analysis showed no comforting relation. Therefore, it was believed that it was necessary to look into other types of algorithms.

In 1981 (2), an analysis was performed to correlate the bump integrator measurements with the slope variance used in the present serviceability index (PSI) equation developed during the AASHTO trials in the late 1950s. Ullidtz (2) shows that for the Danish state road network, the significant dominant factor in the PSI equation is the roughness, determined by the slope variance, calculated in accordance with the one determined during the AASHTO trials. This correlation was generally accepted in the Danish pavement management system to link roughness and user cost. The use of longitudinal profiles gives a more direct method to determine the slope variance, which can be used in the PSI calculation. This procedure also gives a more direct method to calculate a bump integrator value, which currently is the best understood roughness value in Denmark. How successfully this approach is working still remains to be seen as the model is incorporated into the BELMAN system, which is for research and development purposes. When the final analysis is performed for this approach and is shown to be successful, the method will be implemented in the service version of the BELMAN system.

Measurements of rutting have previously been made randomly by a straightedge, when the parameter was observed to be close to the intervention level. Within the last decade, rutting has shown an increase on the Danish state road network, caused by an increase in axle loads, tire pressure, and the use of the so-called super single tires. The increased rutting demands that routine measurements for rutting be taken into account when one is performing maintenance optimization strategies for the network. Therefore, one of the first tasks with the profilograph was to develop a method for calculation of rut depth.

The shape of a rutted cross profile depends on the mechanism causing the rutting. If the asphalt concrete layer is unstable in relation to the load from the traffic, it is often seen that the layer is pushed aside, giving the characteristic profile shown in Figure 5(a). Second, if the rutting is caused by insufficient bearing capacity in the unbound layers in the construction, it is typical that the profile has a smoother curvature, as shown in Figure 5(b).

In developing a model for calculation of rut depth, many factors have to be taken into consideration, for ex-

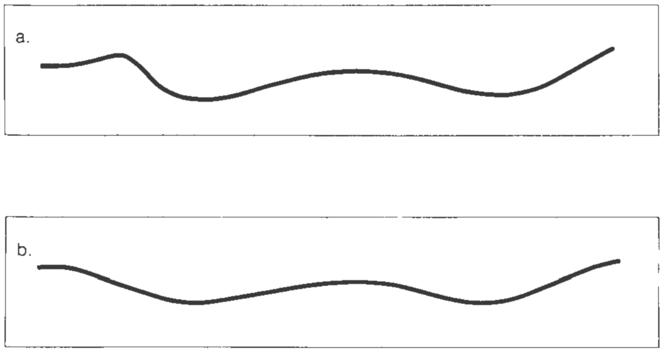

FIGURE 5 (*a*) **Characteristic road surface with instability problems in the asphalt concrete layer.** (*b*) **Characteristic road surface from a road with bearing capacity problems in the unbound layers.**

ample, to what extent the results from the algorithm have to simulate the results of the current straightedge measurement and also how to ignore different anomalies, such as curbs, longitudinal cracks, and potholes.

To find the optimum algorithm for calculation of rut depth, analysis was carried out on different models. The principles of two of the evaluated models, including their advantages and disadvantages, are described in the following paragraphs. For both models, the rut depth is defined as the largest vertical distance between the reference line and the profile. To test the models, representative profiles from two different test sections were used. A few of the profiles are shown in Figure 6, illustrating the applicability of the models.

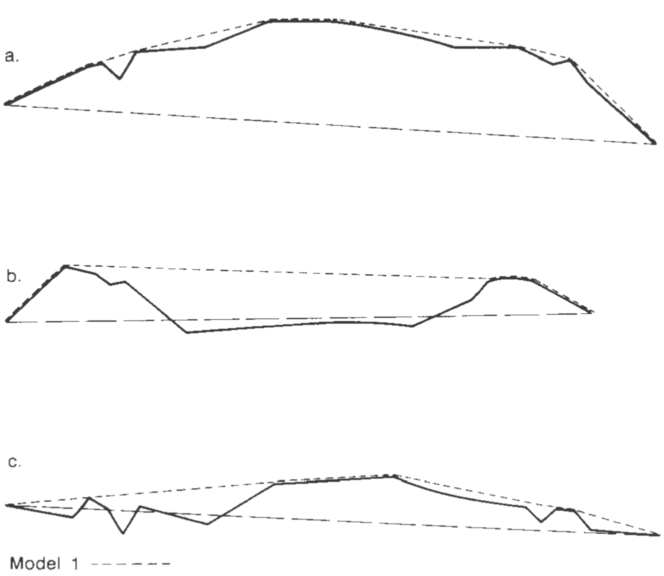

FIGURE 6 Principles of two evaluated models for calculation of rut depth employed on three different profiles measured by the profilograph (see text for description of profiles ***a–c*****).**

Model 1

The reference line simulates a stretched string attached at the two outermost laser recordings, following convex curves and overlying hollows as a straight line. An advantage is that the model is very good at convex road profiles because it follows the general shape and still takes hollows at the top into consideration (Figure 6*a*, *c*). But the model has a disadvantage that it can give very large rut depths, where the midprofile is one large basin (Figure 6*b*). Furthermore, the rut depth for concave profiles will often be calculated as only one value.

Model 2

The reference line is a straight line between the two outermost laser readings. An advantage is that in some cases for concave profiles, the two outermost laser readings give a reasonable basis for a reference line, for example, for profiles like those shown in Figure 6(*b*). But a disadvantage is that the reference line is so dependent on the outer readings that the model can give very misleading results. In Figure 6(*c*) it gives practically no rutting, where the current definition of rutting (straightedge) would give the same results as Model 1. Furthermore, the model can result in negative rut depth values when used on convex profiles (Figure 6*a*).

The algorithm, now implemented in the BELMAN system, is an improved version of Model 1. It was weighted highly that the algorithm calculates two rut depth values—one for each wheel path. Each wheel path is calculated by attaching a 2-m-long "string" to the outermost laser at that side. The rut depth is defined as the largest distance between the profile and the reference line, except for the middle three laser readings, which are not taken into account because permanent deformations in this area are not believed to relate to rutting. To avoid the use of curbs as a point from where the "string" is being stretched, the model ignores the outermost laser reading if the line between the two outer lasers (on the same side) exceeds a certain angle. Figure 7 illustrates the model used on a measured profile. This algorithm generally gives very reli-

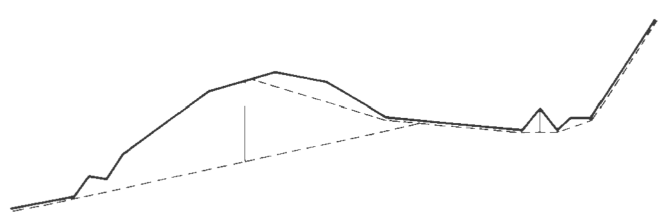

FIGURE 7 Model for calculation of rut depth implemented in BELMAN shown on a cross profile measured by the profilograph.

TABLE 1 Example of Rut Depth Information Printout from Profilograph

ID	Dist (km)	Mean-max (mm)	Rut 5 (%)	Rut 10 (%)	Rut 20 (%)	Mean-left (mm)	Mean-right (mm)
1	0,010	11,6	100	98	0	11,6	2,6
1	0,020	15,9	100	100	0	15,9	7,4
1	0,030	14,0	100	100	0	7,5	14,0
1	0,040	13,5	100	100	0	1,6	13,5
1	0,050	13,2	100	98	0	1,8	13,2
1	0,060	12,4	100	100	0	1,9	12,4
1	0,070	9,8	100	30	0	1,7	9,8
1	0,080	6,8	97	0	0	2,0	6,8

able results, which are very close to the result measured by the 2-m-long straightedge.

The rut depth used for BELMAN is a mean rut depth over a user-specified distance ranging from 1 to 100 m, given as the percentage of rutting above 5, 10, and 20 mm, as shown in Table 1. In the future, when rutting has been monitored for some years, performance models for predicting rutting and the cost of different maintenance solutions can be incorporated into the BELMAN system in order to improve the optimization procedure.

Conclusion

The introduction of the Danish profilograph has provided the possibility of greater optimization of the maintenance strategies for the Danish state road network because of the possibility of getting more reliable data on the different surface characteristics occurring on the road network. Incorporating new measures into the BELMAN system calls for some additional work in the continuous development of the system because new measures need new prediction models to be built into the system. In the future, when more historical data are made available, newly refined deterioration models can be incorporated in order to improve the planning and maintenance strategies for the Danish state road network.

When there is a possibility of obtaining more information, the question always asked is how much more is required. Currently, the second-generation profilograph has been developed. It has a slightly different laser setup (25 lasers giving a measuring width of 3.5 m) in order to give a more detailed measurement of the road surface and to be able to measure a wider track of the road. Particularly, the problem of getting sufficient information on the outer part of the cross profile is important when rutting and the possibility of hydroplaning has to be determined. It is obvious that more laser sensors mean that the acquisition system becomes more costly and that the data analysis needs more EDP time. An analysis of the cost-effectiveness for different setups is somewhat difficult to perform.

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STATE/PROVINCIAL DEVELOPMENTS AND ISSUES IN PMS IMPLEMENTATION

Special Implementation of Pavement Management for a Large Highway Network in a Developing Area of China

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Significant development of the highway network will occur in China in the next 10 years. The characteristics of the change are embodied in a relatively large investment in new construction and upgrading of the existing highway network. Consequently, it is important to manage the available funds, resources, and technology in the most efficient and cost-effective way. Although the pavement management technology was developed in North America, there is a tremendous benefit to be gained by applying it in developing countries. As a result, some developing counties have established pavement management systems (PMS) to better manage their road infrastructure assets. PMS in China have rapidly progressed from a concept to a broadly accepted practice over the past few years. A methodology is established for the implementation of a special PMS in the developing areas of China. The emphasis is on establishing road investment priorities that are adjustable and suitable to developing countries, which includes determination of the present status of the network, developing needs, and priority programs that consider the future serviceability of the network. The system was applied to an actual sample network of the Southeast Economic Developing Region of Qinghai, China, where a large amount of new construction will be undertaken while rehabilitation and maintenance of the existing pavement will carried out at the same time.

Most current pavement management systems (PMS) in developed countries have been effectively implemented after a sound network of highways has been established. This provides a good technical and economic base for decision makers in managing the existing pavements. However, it would be too late to make big changes in the pavement structures and other road infrastructure components if, after a certain number of years of implementation of the PMS, cost-effectiveness studies showed that such changes should have occurred originally.

The application of models to make investment decisions for the road sector in some developing countries has benefitted considerably over the past 10 years from the program initiated by the International Bank for Reconstruction and Development (*1,2*). However, the application of pavement management in China in recent years has posed some new and special technology challenges for the system users. Because of the recent economic reforms and high rate of development, highway transportation has been ranked as one of the four key development initiatives in China since 1985. This has been embodied in heavy investments toward the establishment of a highway network. Hence, in many areas of the country, particularly in most of the Economic Development Zone along the coastal provinces, a large number of highway construction projects, and projects to upgrade the existing highway network, are either under way or being planned. This includes new construction, rehabilitation, and maintenance of the network. Proper investment distribution among these different projects is important, and this requires the implementation of a PMS, including priority programming procedures.

Such decisions on distributing and managing the investment have significant long-term effects in costs to users of the roads and in costs to the members of general public who own the roads. If the proper sections in the road network receive funds, these long-term costs can be minimized and good value obtained.

Scope and Objectives

This paper is largely directed to describing application of a PMS specially adapted for a highway network in a developing area, Qinghai Province in China. The geographical position of the province in China is shown on the outline map in Figure 1. A large amount of new highways will be under construction in Qinghai in the next 10 to 15 years, and rehabilitation and maintenance of the existing pavement will have to be carried out at the same time. More specifically, the objectives of the paper are to

1. Identify the basic considerations, requirements, and systematic procedures for scheduling proper management activities for a highway network in a developing area, which incorporates a large-scale construction of new highways, pavement structural analysis, and performance prediction and the existing pavement rehabilitation and maintenance;
2. Briefly review recent development (modules designed for a network level) and application experience of PMS (features, limitations, etc.) in North America and elsewhere;
3. Discuss whether the commonly defined network versus project levels of pavement management are also appropriate to the situation of a provincial highway network of Qinghai, China, and what improvements have to be made;
4. Define a set of building block requirements for the provincial highway network PMS, including a staged implementation plan, components, operations, and products, which are comprehensive in scope and flexible with regard to staged implementation, including data base, needs analysis, new highway construction programming, and rehabilitation and maintenance planning and priority programming; and
5. Summarize the basic concept of managing the technical and economic efficiency of the special PMS for highway networks in developing areas for a range of implementation situations.

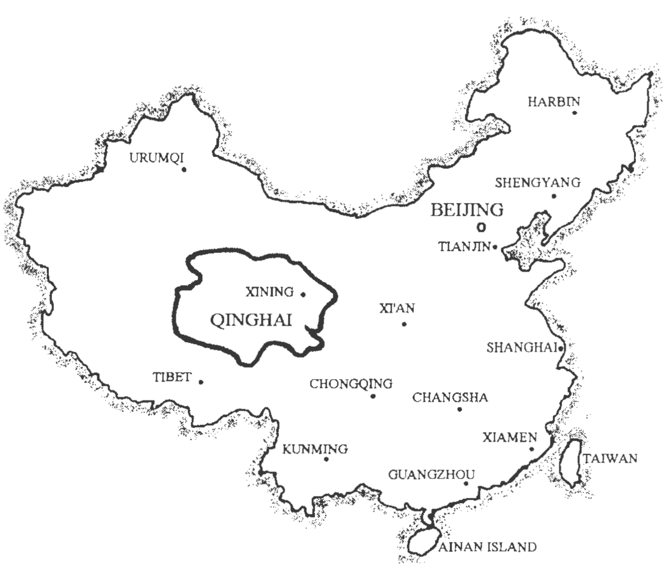


FIGURE 1 Overall outline map of Qinghai Province, China.

Basic Considerations for Scheduling Pavement Management Activities in a Developing Area

Features of Highway Network

Compared with highway networks in developed countries, some of the distinguishing features of highway networks in most developing areas of China are discussed. Unlike in developed countries, a sound network of highways and the corresponding pavement structures have not been established in China, but they are being planned, are under construction, or both. Concurrent with much new construction of highways and other infrastructure components, routine maintenance and rehabilitation of the existing pavements needs to be carried out to protect the existing investment.

Only a few high-speed freeways or special highways that serve as high-speed facilities have been built in many provinces of China. Most of this occurred in the late 1980s and early 1990s. Currently almost all of the network consists of ordinary two-lane highways, with pavements of asphalt surfacing layer or treatment or gravel surfaced. The requirements for performance functions, serviceability, and traffic volume of the highway network are not so high as those in developed countries.

Standards and specifications for pavement structural design, construction, paving materials, and maintenance are, in the situation of ordinary highways, relatively lower. Therefore, to be effective in applying a PMS in such a developing area, certain appropriate major modules suitable to this situation should be established first. These include

1. Models for combined new construction planning or scheduling and existing pavement maintenance and rehabilitation priority programming,
2. Inventory data base of the existing road network,
3. Methods and procedures for pavement evaluation and needs analysis,

4. Models for rehabilitation and maintenance priority programming, and
5. Models for scheduling the activities of maintenance, rehabilitation, and new construction, and allocating the funds available.

Structure and Functions for Qinghai PMS

The effectiveness and major functions of applying a PMS in an actual network depend not only on its structural components but also on the organization of the particular agency within which it is implemented. Because the management system and its corresponding organizational structure in China are much different from those of most other countries (each province even has its own distinctive organization), any PMS should be designed to fit a special situation or functional requirements when it is applied or developed. In the case of Qinghai, it was considered important that pavement management include the following components: the existing road network data base, present investment policies and new construction plans, pavement performance evaluation and prediction, cost-effectiveness and needs analysis, rehabilitation alternative strategy analysis, priority ranking, and maintenance program. The overall structure of the Qinghai PMS is shown in Figure 2.

The data base of the existing road network includes information on road length and surroundings (climate, topography, and subsoil conditions), road resources (geometric alignment, bridges, and other auxiliary facilities), organization (administrative district, number of staff, and length of road served), structural adequacy, roughness, distress, construction history, as well as traffic survey. A coded program in which each coding number represents a special data record was designed to facilitate the data input procedure and upgrade the data on the network periodically.

Investment policy and new construction plans vary at different periods of time. When these two major factors vary in the short term, they affect to a large extent the process of planned implementation of a PMS. For instance, if a 10-year programming period is selected, during which a scheduled rehabilitation and maintenance program has been planned under specified budget constraints based on a minimum pavement quality index (PQI) level of 4.0, when the originally designated investment amount and annual budget are raised to a higher level after 2 or 3 years' implementation, what alternative strategy should be chosen? This change in level could range from building a new highway to changing the pavement performance level from the original minimum PQI of 4.0 to a higher standard or intensifying the maintenance program.

Pavement performance evaluation subsystems are concerned with the assessment of the present service level of the network and identification of highway sections in need of rehabilitation and maintenance. The detailed

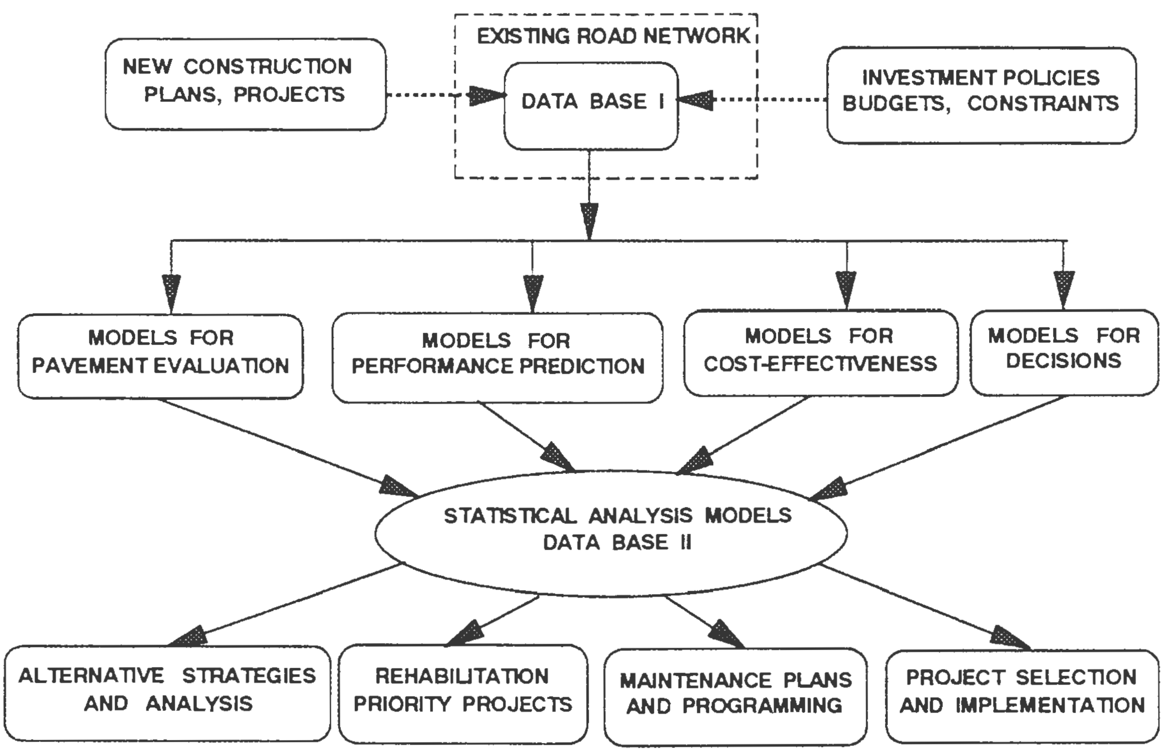


FIGURE 2 Overall structure of Qinghai PMS.

pavement evaluation procedures are subsequently described in the paper.

Cost-effectiveness and needs analysis require the use of suitable models to simulate total life-cycle performance and costs for every given action determined by rehabilitation alternatives. The rehabilitation priority projects are ranked according to the comprehensive considerations of needs and cost-effectiveness analysis. The maintenance program and project selection are finally developed with the constraints of budget or other factors.

Decision Model for Pavement Investment Planning

The basic principles for planning investments in pavements, either at the network level or at the project level, should be that the economic analysis considers all possible alternatives and detailed information for decisions. Like investments in other infrastructure components, the capital expenditure programs for highways are allocated as whole-system plans, including bridge construction, grade construction, new construction, reconstruction or rehabilitation of existing pavements, and so on. It is necessary to recognize the various existing methods that are used for preparing highway investment programs. When the total budget for highway management or construction activities in a road network level is outlined, the first stage of allocating funds is to determine the investment rate for routine maintenance, rehabilitation, and new construction. The proportion of investment among these different activities depends on the following factors: new construction plans and investment policies, performance or serviceability standard, and needs analysis of the existing road network. Figure 3 is a schematic representation of planning pavement investments.

If the purpose of investment lies in gaining as high benefits as possible, the benefits can be weighted by three criteria: preserving the existing road network, improving service level, and promoting economic development. The benefit analysis is solved by a structuring evaluation matrix, which involves a priority analysis model applied to the process of rehabilitation strategy alternatives under different conditions and provides corresponding suggestions of funds allocation (3). Figure 4 shows the structure of the analytical hierarchy model. It should be mentioned that at the top of the hierarchy are three levels that make decisions and policies for allocating annual budgets in pavement improvement: administrative juris-

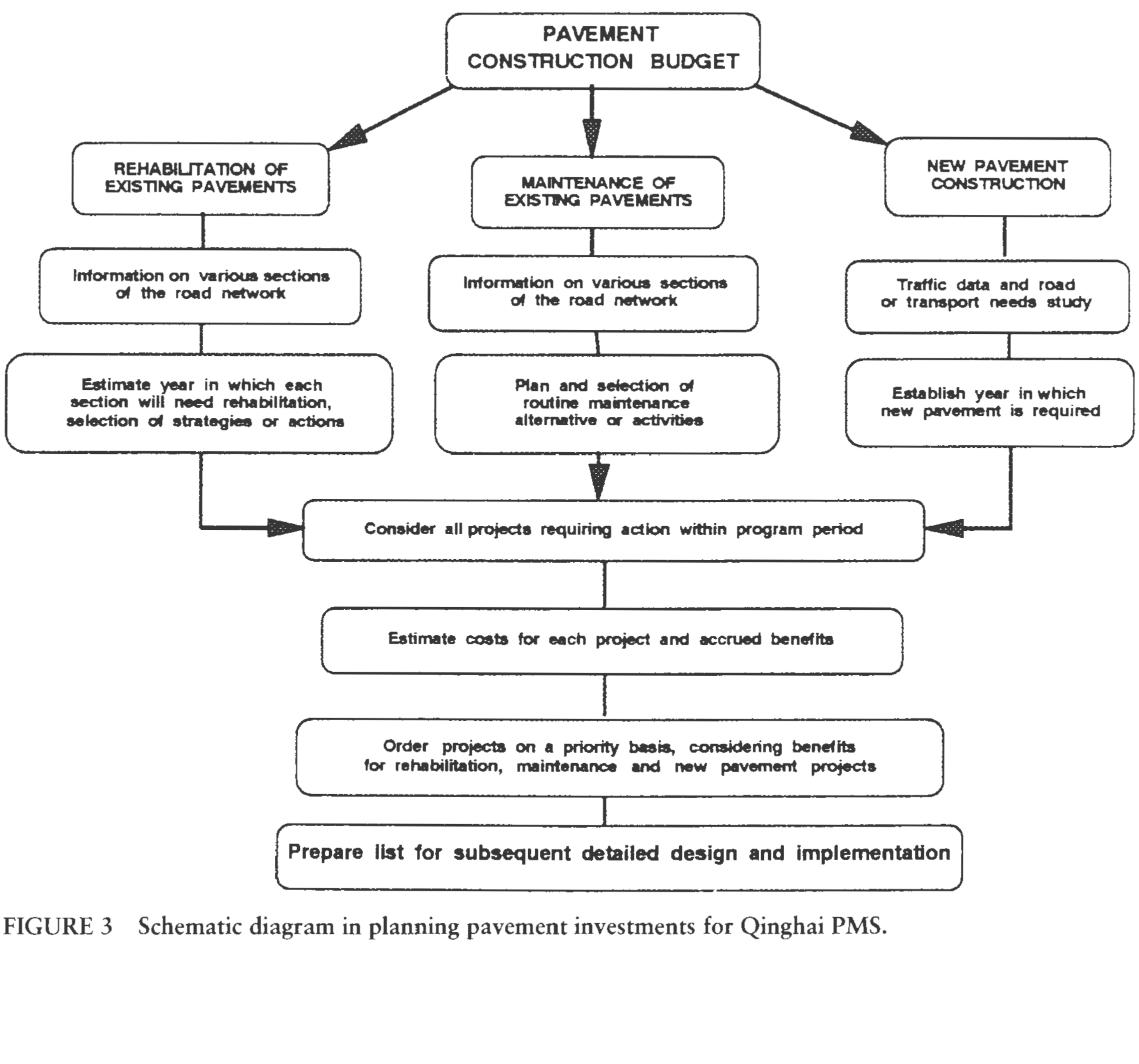


FIGURE 3 Schematic diagram in planning pavement investments for Qinghai PMS.

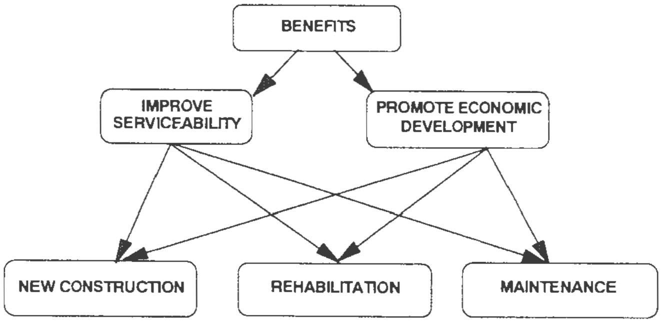


FIGURE 4 Structure of analytical hierarchy model.

diction level (central government, provincial, municipal), budget-planning or decision-making level for various general departments, and detailed budget-allocation level for specific projects. The result of pavement investment analysis can be expressed as a vector that represents the proportion of investment in different levels of construction activities. For example, the vector (0.30, 0.40, 0.30) includes suggestive values of investment rate of new construction, rehabilitation, and maintenance, respectively.

Review of Available PMS

Basic Requirements

A complete PMS should have at least the following main functions or characteristics:

1. To operate efficiently at both the network and project levels and to make good decisions regarding network programs and individual projects;
2. To be equally applicable and effective in large agencies as in those of medium or small size;
3. To have sufficient flexibility that modifications or upgrading can be carried out in terms of operational models, components, and methods; and
4. To make good use of the existing and new technology and to make effective use of available funds.

In order to fulfill these requirements, a generic structure and staging modules for pavement management were outlined (*4*). The major component activities and decisions to be executed for the management are given in Table 1. Any actual system used by a particular agency would cover part or all of the components of Table 1. The rate at which these modules are developed and implemented varies widely, depending largely on resources, size of the agency and its special needs, and the people involved.

Since they were originally developed in North America in the 1960s, PMS have been widely used both in developed countries where a sound road network has been established and in developing countries where the road network is still being expanded. PMS activities are directed toward achieving the best value possible for the available funds in providing and operating pavements (*5*).

Features and Limitations

A number of PMS have undergone at least partial implementation in some developing countries (*1,6*). Choosing the best alternative from the economic point of view and establishing the priority of works under given budget revenues have been taken as the two major optimization considerations when the road network development plans of an area are to be carried out. To meet these two basic considerations, a large number of interacting parameters and existing pavement condition data base analyses have to be executed, which involves a great quantity of data collection, road tests, surveys, and complex calculation. Therefore, a series of comprehensive computer programs have been developed. The most widely used are programs for the developing countries established by the World Bank. Most of the programs focus on the study of the feasibility of long-term investment strategies based on the simulation of pavement performance in connection with traffic and maintenance action alternatives during the entire lifecycle. Some of the programs deal with the investment strategies under the overall predicted costs during a given project period.

Better and positive pavement management, when it means improving current pavement activities or the beginning of a PMS, must recognize the organizational structure of the agency and be suitable to this situation. Experience suggests that major factors in the successful implementation and improvement of PMS are staging, preimplementation planning, and strong top management support. For the first stage and often for subsequent stages of PMS implementation, experienced consultants have been very useful. They have also been useful to PMS improvements and in helping to maintain a strong interest by agency managers through periodic technology consultations and seminars. In essence, financing and consultant expertise can play a key role in development, implementation, and ongoing improvement of a PMS.

Application and Improvement of a PMS in China

Background

Highway transportation has become one of the four key areas of development in China since 1985. Huge investments have been scheduled to effect new highway con-

TABLE 1 Pavement Management Decision Levels and Activities

Basic Blocks of Activities	Network Management Level (Administrative and Technical Decisions)	Project Management Level (Technical Management Decisions)
A.Data	1 Sectioning 2 Data acquisition a)Field inventory (roughness, surface distress, friction, b)Other (traffic, costs) 3 Data processing	1 Detailed data (structural, materials, traffic, climate, and unit costs) 2 Sub sectioning 3 Data processing
B. Criteria	1 Max. serviceability, friction, and structural adequacy, max. distress 2 Min. user costs, maint. costs 3 Min. program costs 4 Selection criteria (benefit max.; cost-effectiveness)	1 Min. as-built roughness;max. structural adequacy and friction 2 Min. project costs 3 Min. traffic interruption 4 Selection criteria (least total costs)
C. Analyses	1 Network needs(now) 2 Perf. predictions and future needs 3 Maint. and rehab. altern. 4 Tech. and econ. evaluation 5 Priority analysis 6 Evaluation of alternative budgets	1 Within-project alternatives 2 Testing and technical analyses (performance and distress predictions) 3 Life cycle economic analyses
D. Selection	1 Final priority program of capital projects 2 Final maintenance program	1 Best within-project alternative (rehab, or new pavement) 2 Maintenance treatments for sections in networks
E. Implementation	1 Schedule, contractor 2 Program monitoring 3 Budget and financial planning updates	1 Construction activities, contract control and as-built records 2 Maint.activities, maint. management and records

struction projects plus rehabilitation and maintenance of the existing network. Two major implementation stages were planned to increase highway network links and improve the existing highway network, the objective being to establish a sound national highway network. The vital role of highway transportation in the economic prosperity of developed countries has been clearly recognized in China (2).

There are many approaches to finding resources and funds for carrying out such highway expansion. These include budgets from the various levels of government, foreign investment, loans from the World Bank, and so on. As a result, the total length of highways in China has increased from 0.96 million km in 1985 to 1.04 million km in 1992. Freeways and some high-speed expressways have now begun to appear in many provinces of China.

The initial aim of PMS development was to assist with decisions on preservation of the investment in the more important roads up to late 1990. However, fast deterioration of the existing pavements on the remainder of the network appears to be the biggest problem after the first 5 years of the original implementation plans, which focused on new highway construction. The concept of pavement management systems was introduced into China in the early 1980s, and some practical management systems had been developed in the mid- to late 1980s.

Technology transfer, consultations, and guidance of developed countries have played a significant role in assisting and accelerating the development and implementation of PMS in developing countries. Major benefits have been received from utilizing technical development from various countries such as Australia, Japan, Canada, and the United States. In addition, a 2-week series of seminars on pavement management in China by Haas and Hudson in 1989 generated a great deal of interest, to the extent that PMS have been encouraged from ordinary technicians to engineers to top managers or administrative leaders. For example, in late 1992, a senior delegation led by Deputy Minister Zhanyi Wang of the Ministry of Transportation of China made a special trip to Canada and the United States for a 2-week official visit. The aim was to observe and study the technology development of PMS and the corresponding implementation. In addition, a number of senior managers, engineers, researchers, and technicians from different provinces of China were sent to North America to study or make contact with some agencies and companies that developed the PMS technology.

Experience suggests that major factors in the successful implementation and improvement of a PMS are strong top management support, in addition to the staging previously noted. Very important steps are to convince top management of the value of a PMS, illustrate to them what a PMS can do, and describe what is required to develop such a system.

In Qinghai Province, the Ministry of Transportation directly manages the principal road network, including planning, design, construction, and management. This includes about 9500 km of highways, with bituminous surfacing in 36 percent. There are an additional 8500 km of local roads in Qinghai that are directly managed by local government and municipal regions. Improvement of and investment allocation for the highway network in Qinghai over the last 7 years is shown in Tables 2 and 3, respectively.

Most of the existing pavements were constructed with different thicknesses of asphalt or surface treatment. It may be noted that new construction, both in absolute terms and as a percentage of the total budget, increased substantially from the mid- to late 1980s. At the same time, rehabilitation and maintenance as a percentage of total budget dropped somewhat. Consequently, substantial rehabilitation work will be required to preserve the investment during the new-construction boom of the late 1980s. It can be seen from Table 2 that the total length of highways in Qinghai has increased 1200 km from 15 490 km in 1980 to 16 691 km in 1992. A third of the original, unpaved highways have been reconstructed and paved, including a large amount of special highways that are used for transportation in new resource-developing areas such as oil fields, areas with mineral or coal resources, and landscape or scenic areas. Reduced investment in rehabilitation and maintenance will result in fast deterioration of the existing pavements. A reasonable and consistent allocation of the investment among the different activities is imperative. Selection of proper rehabilitation alternatives and fulfilling a required level of performance or serviceability are the primary tasks for the decision maker and the goal of the implementation plan.

Pavement Evaluation

A systematic approach to a pavement management data base has been recommended since 1988 by the Ministry of Communications of China for application to the national

TABLE 2 Change in Total Mileage of Highways in Qinghai, 1980–1992

Year	Total Length (km)	Provincial & National	Local & Rural	Special Highways	Paved	Unpaved
1980	15490	8580	6040	870	11620	3870
1982	15614	8624	6120	870	11744	3870
1984	15798	8690	6163	945	12039	3759
1986	16078	8788	6203	1087	12319	3759
1988	16147	8802	6258	1087	12470	3677
1990	16505	9104	6269	1112	13411	3094
1992	16691	9254	6325	1112	13700	2991

TABLE 3 Budget Allocation for Different Activities

Year	Total budget (million $)	New Construction		Rehabilitation		Maintenance	
		Cost	%	Cost	%	Cost	%
1980	14.6	2.77	19	6.57	45	5.26	36
1982	14.9	3.43	23	6.56	44	4.92	33
1984	15.8	3.95	25	6.79	43	5.06	32
1986	17.4	5.39	31	7.13	41	4.87	28
1988	19.8	6.34	32	8.12	41	5.35	27
1990	24.2	7.26	30	10.16	42	6.78	28
1992	26.4	6.6	25	11.88	45	7.97	30

and provincial highway networks. Pavement condition survey and performance evaluation can be carried out from three aspects: structural condition, functional condition, and safety condition. Structural condition surveys include structural capacity and surface defects. The former is evaluated by use of the Benkelman beam to test the surface deflections on each chosen homogenous section, and the latter is assessed by measuring the quantity of cracking (alligator, transverse, and longitudinal), distortion (rutting, heave, and consolidation settlement), and other conditions (patching, potholes, etc.). Pavement function condition is assessed by its riding quality or serviceability. Safety condition is marked by the skid-resistance coefficient.

A special pavement evaluation methodology has been developed for Qinghai's PMS. Pavement condition evaluation of each section on the network is finally described in terms of strength index, distress ratio, riding quality index, and skid-resistance coefficient, which represent the results of evaluation on the pavement conditions mentioned earlier, respectively. For the purpose of evaluation, the paved road network is divided into "homogeneous subsections." The sampling segment system for network survey is described in Figure 5.

The following sequence of procedures was applied to define segments, where deflections were measured, and assessment areas, where detailed condition surveys were carried out:

1. Division of a section of highway into a number of homogeneous subsections by the district engineer according to the type of pavement structure, condition of the surfacing, and the traffic volume.
2. Identification of sample segments that were considered representative of each homogeneous subsection; a minimum length of homogeneous subsection is 1000 m.
3. Measurement of deflection on the sample segments; the Benkelman beam was adopted to measure deflection in outside wheel tracks at certain intervals of each sample segment.
4. Roughness testing on homogenous subsections by using a bump integrator because it relates to safety, the overall economics of the road, rider comfort, and performance.
5. Investigation of pavement condition—determining the types and extent of pavement defects is of great importance for planning road maintenance and rehabilitation.

In summary, the pavement evaluation includes a survey of pavement condition and deflection measurements on a sampling basis and of roughness on the whole network. Data

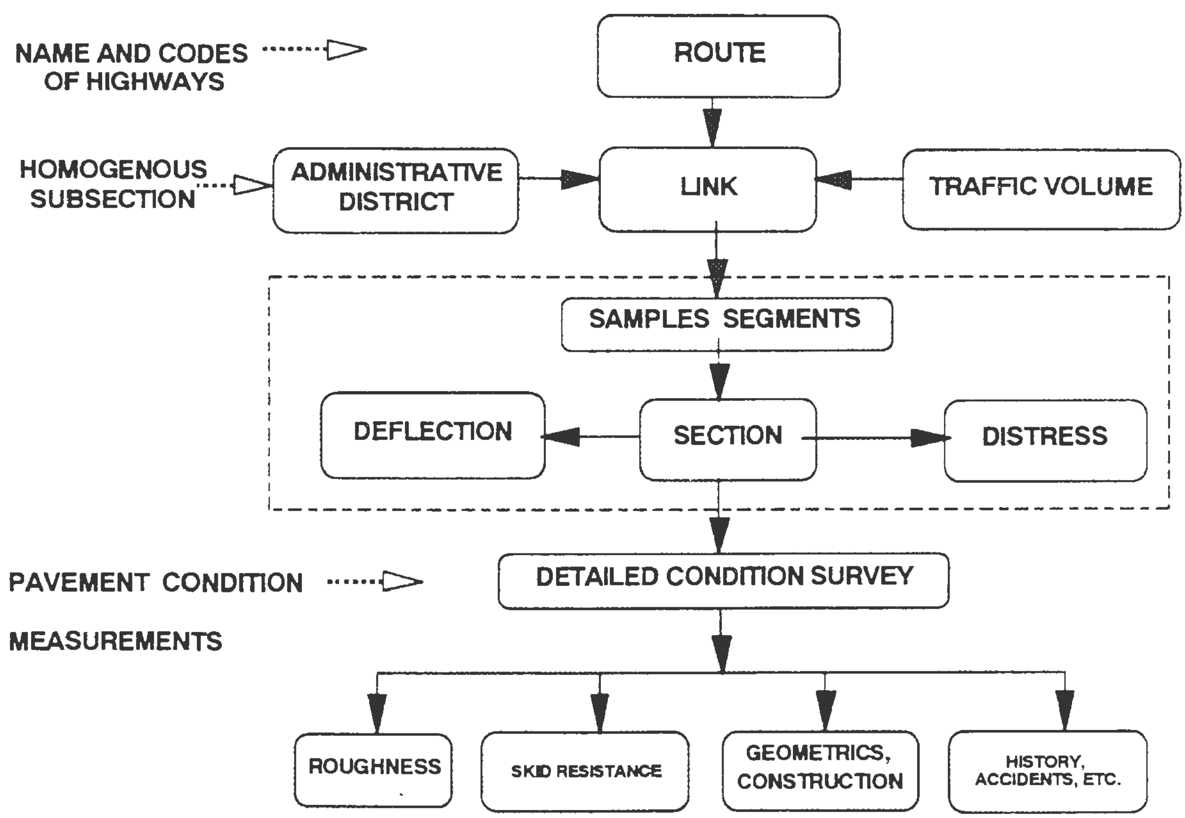


FIGURE 5 Measured attributions for network survey.

for this case study were obtained on about 4500 km of the provincial and national paved network located in the southeast region of Qinghai. The surveyed pavements were divided into 950 homogeneous subsections and 1500 sample segments. Pavement structural capability is measured by strength index (ratio of tolerable deflection under certain conditions over the actual measured deflection by Benkelman beam). The pavement distress index is calculated by using the following formula:

$$PDI = 100 - \sum_i \sum_j DP_{ij} * W_{ij}$$

where DP_{ij} is a deduct value for distress type i and severity j and W_{ij} is an adjustment factor for multiple distresses that varies with the proportion of the deduct value to the total summed deduct value. Riding quality index is measured by vehicle-mounted bump integrator. Skid-resistance coefficient is measured by the sideways-force coefficient route investigation machine. For data collection and analysis, see the technical report by Li (6).

Present Status of the Highway Network

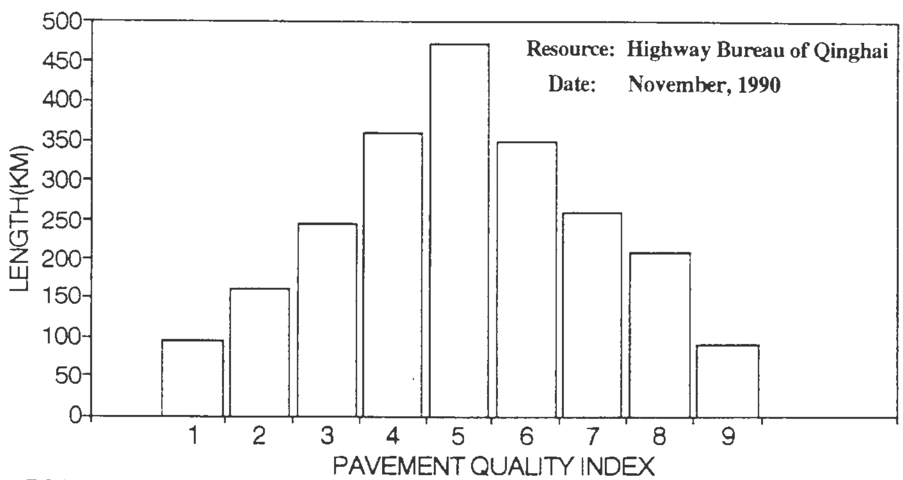
A 2-year detailed data investigation for the southeast region, which is a recently developing economic area of Qinghai, was carried out in 1990, as shown in Figure 6. The pavement condition evaluation of the highway network includes strength index (structural adequacy index), distress ratio (visual condition index), roughness (riding comfort index), and skid-resistance coefficient. Detailed records of these measures for each section, in tabular form, along with such other data as geometric and traffic volume, were generated. Each of the measured results can be converted to a scale of 0 to 10 and eventually expressed as a combined pavement quality index (PQI) (7). For instance, the strength index (SI) mentioned here is

$$SI = \frac{D_{\max}}{D_{\text{act}}}$$

where $D_{\max}$ is the maximum acceptable deflection for the expected traffic loads and D_{act} is the actual deflection measured on site. The results of the calculated SI range from 1.0 to 0.5 for asphalt concrete pavement. The relationship to convert SI into a 10-point structural adequacy index (SAI) is given in Table 4.

TABLE 4 Conversion of Strength Index to Structural Adequacy Index

Strength Index	Structural Adequacy Index
>0.9	9--10
0.85--0.9	8--9
0.80--0.90	7--8
0.75--0.80	6--7
0.70--0.75	5--6
0.65--0.70	4--5
0.60--0.65	3--4
0.55--0.60	2--3
0.50--0.55	1--2
<0.5	0--1.0



PQI INTERVAL	1-1.9	2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9
LENGTH (KM)	96	160	247	360	471	350	260	210	90
NO. OF SECTIONS	56	76	82	126	141	132	133	40	19

FIGURE 6 PQI distribution for the southeast region, Qinghai.

Figure 6 shows the distribution of the composite PQI of each road section in the network. About 34 percent of the total road sections of the network are below a pavement quality index of 5.0, which amounts to 863 km in length. Moreover, most of these road sections were rehabilitated in the form of different thicknesses of asphalt overlay or surface treatment approximately 10 years ago. Therefore, on the basis of this experience and research, those sections with a PQI between 3.0 and 3.9 will deteriorate very quickly in the next few years because of the lower-quality rehabilitation material, long service, and greatly increased traffic. Normally, when the PQI of a road section drops below 2.5 or 3.0, the section will be reconstructed with a new base layer and new paving materials, particularly when the section has been rehabilitated more than once over the last 8 to 15 years. Those sections with a PQI level over 8.0 are new highways and freeways built about 3 years ago with relatively high paving quality and standards. The life-cycle was designed to be 12 to 17 years, and these sections are not expected to experience any major rehabilitation within the next 8 years on the basis of both traffic and environment analyses, which indicates that little emphasis will be put on these sections when needs analysis and rehabilitation priority programming of the whole network are studied. There are 59 sections involved, with a total length of 300 km.

Needs Analysis

The needs year is the point in time when the performance curve for a particular road section reaches its terminal acceptable or "trigger" level. Before the needs distribution of a highway network is worked out, pavement performance prediction models have to be identified and the different minimum acceptable levels have to be designated.

Performance is a general term to describe changes in the basic functions or serviceability of pavements with accumulating effects of traffic and environment. Development of performance prediction models is a most important requirement because the identification of future needs years depends on them. Development of these models involves a large quantity of work related to classification and performance prediction analysis of each section in the road network. Because each section of pavement has its own particular characteristics, its performance is based mainly on the following factors: pavement type, material and structure, construction and rehabilitation history, and traffic and environment. One of the most useful approaches, particularly in developing countries where data collection on pavement condition has just started or is very limited, involves the development of a model based on the current state of the road. This could be done by applying the Markov chain model analysis, which relies on the knowledge and experience of local engineers, researchers, and technicians to predict the change in road condition with time for various combinations of traffic volume, pavement type and detailed structure, base strength, and subgrade condition.

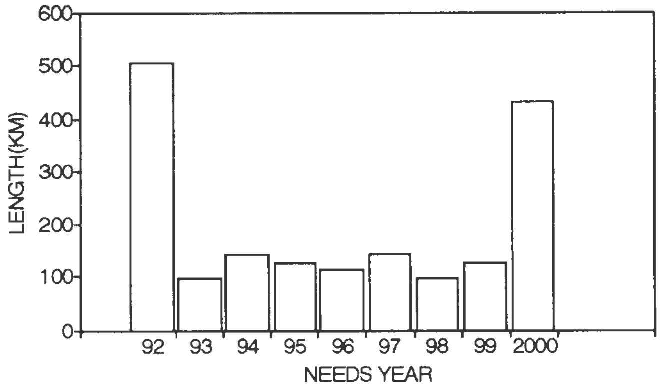
Another available and simple approach is the application of existing models used in other agencies or even in other developed countries provided that the pavement type, traffic and environment, and other factors are similar. In the case of Qinghai, both of the approaches have been adapted to real applications. Although desirable models for performance prediction of the highway network have not been developed for each type of pavement structure, the performance prediction methods used are practical and comprehensive. They are a combination of pavement condition history and theoretical life-cycle analysis. For each section, the following information is needed:

1. Type of pavement structure (asphalt concrete, rigid, or composite);
2. Recent traffic volume and classification, future increase rate and rank analysis or calculations;
3. Environment factors that affect pavement deterioration in terms of time and extent (climate, temperature, precipitation, ultraviolet rays, etc., for which a meteorological map is provided by the local meteorological bureau);
4. Present pavement condition data as described previously; and
5. History of pavement construction and future maintenance and rehabilitation programming.

An example application of needs analysis to the network of the southeast region of Qinghai is shown in Figure 7. It is based on a minimum PQI level of 4.0. The performance prediction models used are not shown. The high level of needs for the first year of the programming period is typical for many provinces of China. Normally, those needs in the first year cannot be met because of limited financial support. Also, some of rehabilitation projects cannot be carried out in the year in which they are required, but may have to be deferred to the second year and so on, depending on the funds available.

Priority Programming

Selecting a length of program period for rehabilitation is not necessarily the same as that for life-cycle economic evaluation. In fact, it would be less because the latter commonly covers 20 or more years. Certainly, the length of program period for maintenance would generally only be 1 to 5 years. A very practical approach is to develop a 5- or 10-year program. The priority assessment methods vary from simple subjective ranking to sophisticated mathematical programming. Each has specific features in



NEEDS YEAR	1992	1993	1994	1995	1996	1997	1998	1999	2000
LENGTH (KM)	503	96	140	124	110	141	95	125	430
NO. OF SECTIONS	206	39	56	31	47	69	65	51	97

FIGURE 7 Needs distribution of the southeast region, Qinghai.

terms of the pavement rating parameters, type of economic analysis applied, and so forth. An alternative approach to priority programming is to specify a standard or requirement and then determine the funding required to meet this standard. Such standards could be a minimum average serviceability for the network.

For the real application of Qinghai pavement management, after one prepares the needs distribution of the road network for a planning and programming period, knowledge of what sections will become needs in what years does not, however, indicate which sections should be rehabilitated and which should be deferred under the usual budget constraints, or what the optimum rehabilitation strategy should be for each section. In order to make a final selection and to make maximum use of the economic analysis results, not only the economically optimal strategies but also a number of nearly optimal strategies should be listed. The expected availability of funds has a major impact in strategy selection. Some major factors that have been considered in the rehabilitation priority programming of the Qinghai PMS are pavement types and lifecycle, traffic volume and rank, and present pavement condition (structural capability and distress ratio). The process of priority ranking follows:

1. The existing pavement rehabilitation alternatives are determined in terms of pavement service life, potential structural capability, and visual distress ratio. Strength index is used in determining whether a section is to be rehabilitated or reconstructed.
2. Any chosen rehabilitation candidate should have at least 5 years' service life.
3. Traffic and distress (PQI) are two major factors in ranking. Traffic is ranked higher than distress; that is, the project with a higher level of PQI is ranked higher than the project with a lower traffic level.
4. In the same rank group (each section candidate has the same traffic volume and similar distress), the project with lower riding quality is ranked higher than that with higher riding quality.
5. Economic analysis is based on the calculation of the rehabilitation candidate's costs and benefit and determination of which candidates will be selected is made by comparison of the total rehabilitation budget.

The formula for calculation of the priority index is expressed as follows:

$$PI = \sum K_i F_i \qquad (i = 1, 2, 3, 4, 5)$$

where

PI = priority index,
F_i = priority factor (i.e., F_1, daily traffic volume; F_2, distress ratio; F_3, service life; F_4, pavement roughness; F_5, pavement type), and
K_i = weight of corresponding factors, determined by type of pavement structure, traffic rank, and environment condition; it can be adjusted in different regions.

Priorities can be determined by many methods, ranging from simple subjective ranking to the true optimization, by using a mathematical programming model or marginal cost-effectiveness. The techniques for developing a priority program of pavement preservation will assist the pavement manager in selecting sections, treatments, budget-level evaluation, and timing for projects.

Conclusions

The present process of programming pavement projects (including new construction, resurfacing, and reconditioning) in Qinghai is the first step in the implementation of its PMS, and it has been applied in the southeast region developing area of Qinghai. The system provides an objective and systematic means for planning and justifying road improvement expenditures in developing countries. It is being used as a tool to assist in the development and preparation of reasonable annual maintenance and rehabilitation program fund allocation. The major modules or building blocks for implementing the network level of PMS include

1. Detailed pavement condition surveys and measurements, with the aim of establishing a sound data base information system;

2. Needs analysis based on the existing pavement evaluation, cost-benefit economic analysis, technical standards, and other considerations; and
3. Rehabilitation and construction priority programming, by which a list of optimum investment times for all projects is determined with the budgets available.

For investment in new construction, rehabilitation, and maintenance, a number of steps are involved in determining a series of projects for pavement improvement based on the priority programming and the hierarchy of planning levels. The top level of the hierarchy is the administrative jurisdiction (central government, provincial, municipal). Next is the level of the total budget planning in different departments. The final level is that of allocating the road building budget (new construction, rehabilitation, and maintenance). A reasonable proportion of budget allocation among the activities is determined by establishing the module of investment benefit analysis, which is based on the generic structure of decision making for the implementation of a PMS.

The process of priority ranking used in the Qinghai PMS for the selection of rehabilitation strategies as well as for fund allocation of rehabilitation and maintenance activities is practical and objective in terms of grading performance functions and serviceability for various pavements. The major factors such as pavement class, traffic volume, pavement structural strength, and distress ratio are taken into consideration and then ranked in determining the proposed network projects.

Further improvements and adjustments to the implementation include

1. Automated methods of measuring and evaluating pavement condition, widespread use of microcomputers, and available software;
2. Utilization of experience as the implementation of the PMS becomes more widespread; and
3. Long-term, performance-based specifications.

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Implementation of VIC ROADS Pavement Management System

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Toward the end of 1987, the Roads Corporation of Victoria, Australia (VIC ROADS), identified the need for the development and implementation of a pavement management system (PMS). A steering committee was established to guide the development, and by the end of 1988 the PMS had been implemented in each of the eight regions for use on the highway network. The PMS has been in operation for 4 years at a regional level and has recently been extended to cover all major roads under VIC ROADS control but is maintained by local governments. The PMS now operates on a network of over 23 000 km. The process of implementation and the use and impact of the system over the last 5 years were investigated. In particular, the need for clear objectives and ownership of the PMS was essential. Key problem areas include data collection, pavement performance modeling, training, and the need for a more widespread understanding of the concepts underlying the system for all users.

Toward the end of 1987, the Roads Corporation of Victoria, Australia (VIC ROADS), identified the need for the development and implementation of a pavement management system (PMS). A steering committee was established to guide the development, and by the end of 1988 the PMS had been implemented in each of the eight regions for use on the highway network. VIC ROADS is the responsible authority within the state of Victoria for the management of the 23 000-km principal road network and its use.

Organizational Environment

The organizational environment into which the VIC ROADS PMS was born was one of major cultural change, characterized by

- A chief executive determined to introduce commercial management into what was a very strong technically oriented organization,
- Increasing decentralization of authority,
- Rapidly developing computer literacy and capability,
- Major efforts to direct staff attention to customer-oriented outputs rather than internal processes aimed at input management,
- Significant loss of experience and skill because of retirements of a number of senior engineers,
- A road network that had a significant proportion of pavements approaching 20 to 30 years of age, and
- A change in emphasis from new road construction to road maintenance.

Each of these characteristics had a major effect on the method that was adopted for developing and implementing the PMS and on its eventual form and capability.

Objectives

Five objectives were developed for the PMS, which are to

1. Provide road users with the optimum road conditions for a given budget;
2. Predict pavement conditions and user costs for a given budget;
3. Assess the effect of different management strategies on a statewide, regional, and road section basis;
4. Provide a means of objectively reporting on asset preservation needs; and
5. Relate pavement performance to past investment levels.

These were ratified by the Statutory Board of the Road Authority before further work commenced. The members of the board were representatives of major road user groups and of state and local governments.

System Development

From the outset, ownership by those who were to use the system was the major guiding principle. In particular, the statement that the desire for a PMS has to come from the very top of the organization proved to be true and represented the catalyst for the project to develop and to implement the PMS.

Ultimate responsibility was given to the director of operations, who chose to form a steering group consisting of four of the five directors who reported to the chief executive, representatives of local government engineers, and a senior pavement research manager from the Australian Road Research Board. This ensured the ownership and commitment of the corporation's most senior management group.

The group to work on the project was chosen from one of the operational regions with assistance from experts in computers and pavement performance monitoring as required. The decision to develop the PMS in the operations area assisted in obtaining the support of the managers of the eight regions throughout the state, and ultimately of local government.

The system was derived from that developed for the Arizona Department of Transportation (DoT) Network Optimization System (*1*), which uses probabilistic models (Markov transition matrices) for performance prediction and a linear programming-based technique to determine optimum treatment strategies.

It is not the purpose of this paper to describe the system in detail. Suffice it to say that the system was chosen because it was capable of satisfying the organization's objectives for pavement management, and 10 years of condition data were available to derive reliable performance models. The value of the probabilistic modeling approach proved to be that the results were seen as reasonable across the network. The alternative model, using deterministic predictions of performance, could have been subject to accusations of unreliability when compared with the actual performance of particular road sections. The cooperation of the Arizona DoT during the development phase was generous and invaluable.

Pavement Performance Criteria

In keeping with the principle of ownership and to ensure that objectives 3–5 were achieved, it was decided to use a Delphi questionnaire (*2*) approach for two purposes: to identify relevant pavement performance criteria for decision making and to "calibrate" the performance models with the best judgment of expert pavement managers who were working in or had recently played a significant role in the organization.

The aim was to try and model the decisions about managing pavements that had been previously made using the same criteria but at the same time to improve consistency, reliability, and optimizing benefits and costs.

The initial choices of performance criteria were *roughness* as measured by the NAASRA roughness meter (*3*) and *cracking, rutting,* and *surface texture* as rated using a manual system that had been used annually for about 10 years (*4*).

These criteria were seen to reflect both the road user and the agency perspectives of pavement surface and structural characteristics as follows:

	Pavement Characteristic	
Perspective	*Structural*	*Surface*
Agency	Rutting	Cracking
Road user	Roughness	Texture

In hindsight this was useful in interpreting the PMS outputs in a manner that is understood by politicians, pavement engineers, road user groups, and management within the Roads Corporation and local governments.

Marketing and Initial Implementation

During the development, a marketing approach was adopted. This involved not only the frequent meetings with the steering committee including 80 percent of the corporate management group and key stakeholders, but also monthly reports to and consultation with regional managers and key operations staff who would ultimately become the principal users of the system.

The benefit of this activity was that the system could be fine-tuned to suit the organization's operational needs and the potential users could maintain an involvement and influence, thereby gaining an understanding of the way in which they would eventually use the system for management.

As a consequence, when the system was ready for implementation, only minimal effort was required to train regional managers and regional maintenance engineers in its use. Training for each region was completed in about 2 days.

Initial implementation included developing business rules for the collection and input of condition data and producing guidelines for the use of the PMS in developing annual pavement management strategies and budget bids by regions and on a statewide basis.

From the beginning, all regions were given access to each other's data and PMS files. Therefore, they could, if they wished, run optimization trials for other regions and for the state as a whole. Many availed themselves of this opportunity, and in doing so not only learned more about the sensitivity of PMS to a wider range of pavement conditions but also developed confidence that the system was treating them fairly from the point of view of obtaining funds for pavement maintenance.

This concluded the development phase, ensuring that as far as possible the VIC ROADS PMS satisfied corporate objectives, was owned by corporate management and operational regions; and was compatible with the organizational culture and technology. Therefore, it had a good chance to be useful and to improve the efficiency and effectiveness of pavement management well into the future.

Local Government Implementation

Following the successful implementation of the PMS on the 9000 km of major highways throughout the state of Victoria, implementation proceeded to cover the remaining 14000 km under the management of local governments. The scale of implementation and the issues involved were significantly different in many respects.

There are over 200 local government authorities, and for virtually all roads there were no historical road condition data to form the basis for the performance models. Consequently, extensive input was sought from expertise in the local government area to calibrate the known performance models for the major highways onto the lesser trafficked local-government-maintained road network.

Implementation into local government was left to each of the VIC ROADS regional managers. This was done very well in some areas and not so well in others, but it did help develop ownership of PMS throughout VIC ROADS. Importantly, the push for development and use of a uniform PMS statewide is being recognized by many local government authorities, because they see the potential benefits that may follow. As discussed later, the use of a network-level PMS at this local level is not ideally suited. Local governments are more interested in using the raw pavement condition data, and this approach has been encouraged to focus users on road needs rather than on funding.

Using the Pavement Management System

Organizational Structure

VIC ROADS PMS is used at three levels within the organization. At the lowest level, local governments are required to submit PMS analysis and results in support of funding applications for roads that they maintain on behalf of VIC ROADS. The eight regions coordinate the use of the PMS at the local government level and use the submissions to assist in distribution of funds to each local government authority. In turn, each region uses the PMS to support funding applications for maintenance and rehabilitation works to the central operations group, which ultimately uses statewide optimization for the final distribution of funds. Figure 1 shows this three-level approach.

The PMS Process

The PMS forms an integral part of the annual development of the works program for each VIC ROADS region. The process begins with the condition survey during September to November and ends in June the following year. The process is shown in Figure 2. The PMS is operated by the central operations group at all levels, providing regions with guidelines on condition standards and analyzing the road network as a whole.

At a regional level, the PMS is used for network analysis in support of maintenance and rehabilitation requirements on individual roads. Although statewide standards are set centrally and essentially based on traffic volumes, local conditions and factors provide input into justifying the adoption of condition standards for specific roads. The raw condition data are available to support the funding of individual projects, and it is left up to each region to use and analyze the data at this project level.

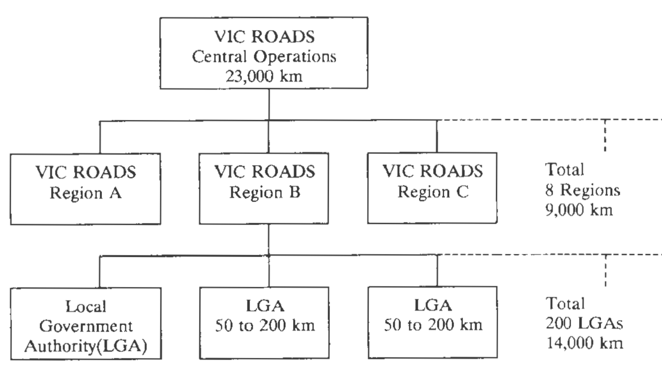

FIGURE 1 Organizational use of PMS.

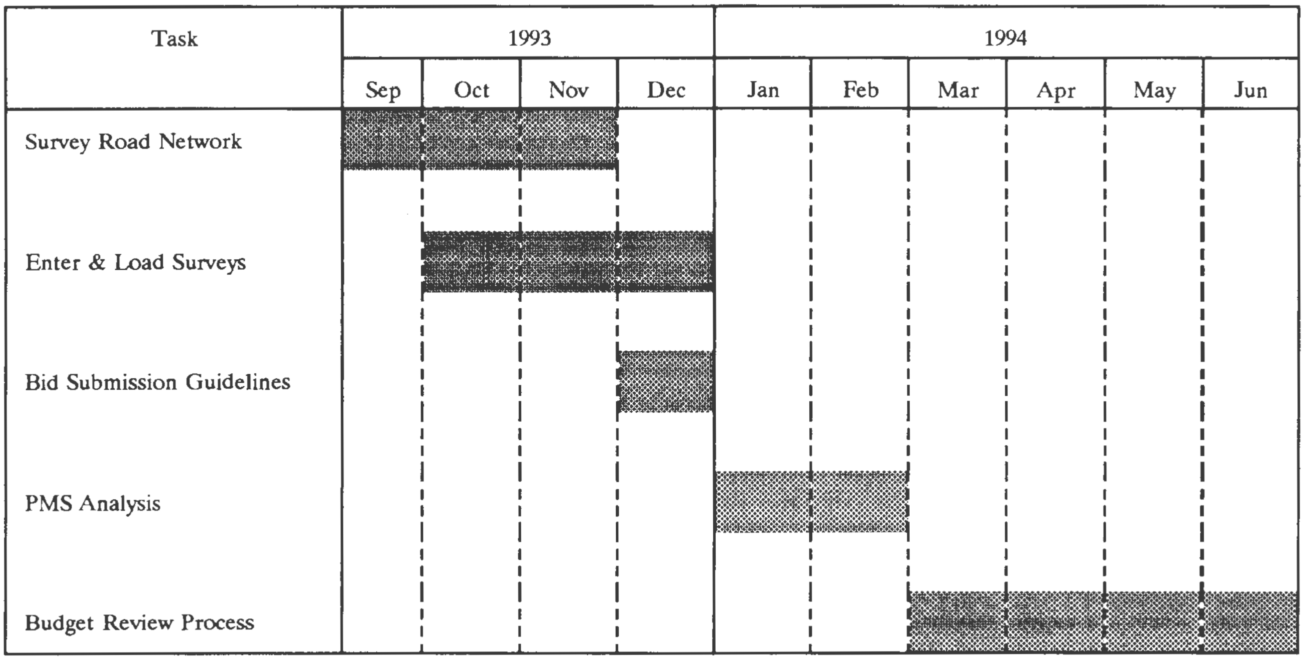

FIGURE 2 PMS process.

The steps involved in using PMS at the regional level are detailed in VIC ROADS *Business Planning Guidelines* (5) and can be summarized as follows:

1. Determine the budget required to maintain the current road conditions across the whole region,
2. Determine the budget required to achieve and maintain the statewide standards set for each road category,
3. Decide on appropriate road condition standards across the region and then determine the budget required to achieve those standards, and
4. Use the road condition data base to provide support for each of the individual road projects being considered.

Given the significantly smaller network of major roads in each of the local government areas (50 to 200 km), it has been found that a network analysis using PMS does not provide a meaningful result unless local government areas are grouped together. This is undertaken at the regional level, and it is left to local government to use the road condition data base to provide the necessary objective support of maintenance and rehabilitation treatments. In many cases, this can simply take the form of a ranking of road sections based on road condition.

At both the regional and local government levels, users are encouraged to make comparisons outside their areas of responsibility to encourage standardization. However, the tendency is still to consider road conditions and needs only within their own area, and the analysis of the most effective distribution of funds is done at the next higher level.

Part of the difficulty in encouraging use of the PMS is in redirecting thinking away from a budget-driven approach to a needs or standards basis. The setting of statewide standards for different road categories was developed to address this problem and provide a base for the determination of appropriate road condition standards for each road.

Data Collection

The collection and maintenance of road condition data each year are by far the greatest expenses in implementing and using a PMS. Even so, the cost represents only 1 percent of VIC ROADS' total maintenance and rehabilitation budget and forms the basis for decisions that have been estimated to improve the effectiveness of funding by up to 20 percent.

Initially, regional and local governments were required to collect the majority of road condition information using a visual survey. It was soon discovered that, despite extensive training and spot audits, comparability between regional and local government authorities was not sufficiently accurate. In addition, the repeatability of visual surveys from one year to the next is highly dependent on the individual concerned and relies on that same individual's performing the survey each year.

The pavement performance model associated with the PMS highlighted the need for an accurate, objective, and repeatable measurement of road conditions. In 1992, a firm commitment was made by VIC ROADS to start using machine-based road pavement condition measures with the acceptance of a 3-year contract on all 23 000 km of major roads throughout the state of Victoria. This was a significant step, taken to enhance the quality and reliability of pavement condition data and therefore improve user acceptance of results from the road pavement condition survey. This was particularly the case with users from the local government level who were skeptical of the consistency of pavement condition measures across the state following the 1991 survey.

Although ownership of the PMS at regional and local government levels was important during implementation, it was soon discovered that centralization of the data collection functions is essential to ensure the ultimate acceptance and ownership of the PMS. The survey is now 75 percent automated using vehicle-based laser technology with the intention to automate fully when a technical solution is found for the reliable measurement of cracking.

Pavement Condition Standards

In 1992, considerable work was carried out by VIC ROADS on the development of pavement condition standards (6). This work comprised two main thrusts. The first was an extensive survey of what customers considered the most important aspects of pavement condition in judging whether a road was in good condition or not. This was carried out in urban and rural areas, with car drivers, truck drivers, and motorcycle riders being the main customer groups. Roughness (or smoothness) appeared the most often as the critical factor in customers' judgments about road condition. This customer survey also attempted to establish the threshold values of pavement condition that signaled when a road pavement had deteriorated to an unacceptable level from the customer's viewpoint.

The second thrust of the work was an economic analysis of the user benefits obtained when road pavement conditions were improved by carrying out some rehabilitation work, for example, the savings in road user costs realized by placing an overlay on a rough road pavement. Both aspects of this work have helped to establish some strategic guidelines for statewide road pavement condition standards for use in PMS analyses and to help with the development of road asset preservation works programs.

PMS Outputs

The reports and output from the PMS optimizations have been kept as simple and straightforward as possible. This was due mainly to the network-level approach and also to the apparent complexity of the optimization. A number of issues have stemmed from users' interpretations of the PMS outputs. The most significant was for users to come to grips with the logic behind the analysis and the probabilistic nature of pavement performance across a network of roads.

Although a probabilistic-based system provides a clean and simple solution to the problems of predicting pavement performance, there are few persons in the organization who understand the detailed workings of the PMS. This inevitably leads many users to interpret outputs wrongly and to apply the results inappropriately. It is important that the tools used to assist in managing the road network be fully understood. In order to facilitate this understanding, VIC ROADS intends to target three areas by

- Stimulating technical discussion on aspects of pavement management and using the PMS to illustrate these concepts,
- Opening the system up to make the workings of the system more transparent, and
- Initiating formal training on concepts and mechanics of the system including interpretation of input and output.

Impacts of the Pavement Management System

General

PMS has great potential to affect road maintenance funding levels. To date, the impact on total levels has been limited by the overriding effect of political decisions on state and federal budgets. Until PMS forecasts are given greater status at these levels, they will continue to have the most impact at the regional and local government levels in the appropriate distribution of available maintenance funds.

Ideally, reductions in funding would only have an impact on the road improvement program. In practice, it is difficult to reduce funding for improvement projects with a political commitment. Furthermore, in the declining funding situation of recent years, it is inevitable that pavement condition standards together with community expectations will be reduced.

Redirection of Funding

Funding targets for road maintenance and rehabilitation are set centrally for each of the eight regions. Target statewide condition standards are defined by the central operations group for each class of road. The distribution of funds between regions is based on PMS analysis that attempts to achieve target standards over a 5-year period.

A redirection of funding is required at both regional and local government levels because of a significant variation between existing conditions and target conditions.

These largely insupportable variations were prime catalysts for the need to develop a PMS. Redirection will require a 5- to 10-year period to be achieved in a funding-neutral sense that is, without requiring an overall increase in funding levels. This variation is a result of a tendency to maintain higher- and lower-trafficked roads to a similar standard and to maintain historic levels of funding to regional and local government authorities. Redirection of funding is a sensitive issue that requires sufficient time to avoid political repercussions.

Supporting Regional Funding Bids

Distinct from the central approach to funding redirection is the impact of regional and local government bids that use the PMS for support. Considering that the PMS is still in a relatively early development phase, regional factors and local knowledge can have a marked effect on appropriate road condition standards. These standards may, in fact, vary significantly from the centrally set statewide condition targets. The potential to have an impact on funding in this way using an objective approach to justifying standards has been slow to evolve. Again, the emphasis has remained on historical funding levels and resources, and it is likely to remain so until regions perceive that the distribution of funds is actually being influenced by such an approach.

One of the major problems hampering the user acceptance of the potential impacts that use of the PMS can afford relates to the current overall funding levels for maintenance and rehabilitation. In most instances, the PMS suggests a far higher funding requirement than is currently available, and, hence, users are seeing little influence on these overall funding levels. Unfortunately, this has clouded the benefits that can be obtained by using the PMS to use the existing funds more efficiently.

Supporting Submissions to Government

An annual PMS report is submitted to the state government describing (*a*) the 5-year forecast of pavement conditions based on the current and proposed levels of funding, (*b*) funding levels over time, and (*c*) condition variation over time. Another corporate report now being prepared annually compares maintenance expenditure with asset value and roughness condition over time. Initially these reports were not favorably received when they indicated an increased need for funding. However, the information had greater effect when it was presented in a manner that illustrated the adverse effects on road users in terms of, say, travel time, safety, and vehicle operating costs.

An annual report is submitted to the federal government providing pavement condition data on the national highway network as requested. PMS is used in determining appropriate maintenance funding levels for submission.

Altering the Funding Mix

Maintenance funding allocations are grouped by type—routine, periodic, and rehabilitation. The distribution of funding among these types can be adversely affected by factors other than need, such as current resources or previous funding. The appropriate levels can be determined using PMS, given accurate pavement performance data.

This area is seen as having the greatest future potential for the PMS to have an impact on funding given the current funding constraints. At this time, the pavement performance models have not been developed to this level of accuracy. However, the commitment to machine-based road condition measurement is an essential first step in a necessary system improvement.

Conclusions

A number of issues have been tackled during the 4 years of implementation and use of the VIC ROADS PMS. The following summary reflects VIC ROADS' experiences during that period:

- Establishing a clear set of objectives for the PMS is essential for a successful implementation.
- Ownership of the PMS must be established at all levels, but most importantly at the top of the organization. Formation of a steering committee was key to acceptance at the top level.
- Initially, a PMS should be compatible with the culture and technology of its user. As confidence is gained in its ability to provide "reasonable" predictions of pavement performance and investment needs, more sophisticated development can be accommodated.
- Road pavement condition measurement is the single most important part of the PMS, and accurate, repeatable machine-based measurement is essential to gaining acceptance of the PMS.
- Ongoing support, training, and development are essential because most systems are evolutionary in nature and must cope with changes and improvements in computer and condition measurement technology.

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Organizational Implementation and Application of Alaska's Pavement Management System

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The Alaska Department of Transportation and Public Facilities (DOT/PF) implemented its pavement management system (PMS) formulated as a dynamic problem using the Markov decision process. Four technical and management committees were established in headquarters and three regions. Planning, design, materials, construction, and maintenance are represented on these committees. Technical committees provide and review data and help delimit rehabilitation projects on the basis of PMS recommendations. Management committees, which include directors, deputy commissioners, and commissioners, establish target pavement conditions and budgets. Alaska's PMS projected an annual savings of $3.9 million compared with the average previous 10-year budget of $28 million. Although the committees require much of the PMS engineer's time, it provided a very successful vehicle for implementing PMS. Ninety percent of initial project recommendations were implemented in the 6-year plan. In 1988 the department increased the tandem axle legal load limit to 38,000 lb, reducing the average structural pavement life 28 percent and increasing roughness and rut depth 7.5 percent. PMS showed that the long-term annual cost would increase $3 million, as opposed to $12 million based on structural life alone. Urban rutting and rural roughness were found to control the scheduling of pavement rehabilitation projects rather than pavement fatigue. Because of this, pavement structural design lives were reduced from 20 to 10 years for rural Interstate and principal arterials and to 12 years for urban Interstate and principal arterials. Alaska's PMS shows the preventive maintenance is more cost-effective than corrective maintenance and that rehabilitation is more cost-effective than corrective maintenance.

The field of operations research has long recognized that management systems must function within the system of a human organization. Rarely does a new method fit harmoniously within previous management methods and organizational cultures. People automatically resist change. "A truly successful implementation of an operations research system must apply behavioral as well as mathematical science, because the resultant system must interact with human beings" (*1*, p.8).

This paper presents experiences of the Alaska Department of Transportation and Public Facilities (DOT/PF) in creating and implementing a pavement management system (PMS). The development history of the system is presented from 1981 with the decision to create a PMS, hiring of a consultant in 1985, and delivery of the system in 1988. The system characteristics are discussed briefly to provide a framework for the rest of the paper. In 1988 the department hired a PMS engineer. Organizational issues are discussed as is information learned during implementation. Applications of the system other than those related specifically to project selection are also presented. These helped demonstrate the system's capabilities and sell the system to the department. Full implementation of pavement rehabilitation project recommendations was completed in 1991 with maintenance recommendations implemented in 1992.

Development of Alaska's PMS

Development of Alaska's PMS began in 1981 as part of a transportation improvement programming system (TIPS). TIPS was divided into three parts: the PMS, the Highway Analysis System (HAS), and the Highway Improvement Programming System (HIPS). Airports and marine systems were not included.

PMS provides input for planning, design, construction, maintenance, evaluation, and research of pavement structures. The HAS coordinates data entry and retrieval for all data bases required by HIPS and PMS. HIPS assists in the management of all highway improvement activities including pavement, bridge maintenance and rehabilitation, and geometric improvements.

A statewide committee was established for each of the systems. The chairperson of each committee served as a member of the other two committees. The remainder of the committee members represented planning, design, construction, and maintenance. These committees ensured that the department's needs were met by focusing on the technical merits of the systems.

A steering committee was also established to oversee the overall development of TIPS and ensure that management needs were met. This committee was composed of the commissioner and directors of planning, design, construction, and maintenance, and the committee chairpersons of the other three committees. Their focus was on integrating the systems into the budgeting cycle and how the systems would affect policy.

It is interesting that there were three different commissioners during the development of PMS, HAS, and HIPS; however, the committee structure provided the continuity to complete all three projects.

Three consultants were selected to develop the systems. Although the contracts were independent, each contract contained a coordination task to ensure continuity between the systems. The contract for PMS was awarded to Woodward-Clyde Consultants.

The first task under the PMS contract was to become familiar with Alaska's budgeting and design processes and its unique physical environment. The contractor was then required to educate the PMS and steering committees on the various types of pavement management systems, focusing on how each would suit Alaska's program and including advantages and disadvantages of each. This task proved to be one of the most valuable efforts of the contract. Through this education, not only was a system selected, but the participants were also convinced of the value of a PMS. Consequently, support for the PMS throughout the department was quickly established.

Three PMS models were considered: a priority ranking model, a static decision model, and a dynamic decision model. Alaska chose a dynamic decision model because of its flexibility. The model is complex, but its computerization makes the system practical.

Once the committee had selected the decision model, the contractor was given specifications for the pavement management system. The development was divided into nine steps:

1. Divide the highway network into uniform road segments;
2. Define road categories on the basis of factors that do not change with maintenance actions;
3. Define distress states and conditions for each of the road categories;
4. Select appropriate maintenance actions;
5. Develop performance prediction models;
6. Develop cost estimation models;
7. Develop the optimization model;
8. Develop computer software; and
9. Develop documentation and training materials and train department personnel in the use of the system.

The PMS committee was kept informed of the progress. Whenever decisions were required, input from the committees was obtained. Consensus was obtained before continuing with the project.

The contractor completed the project in 1986. The system was turned over to the pavement management engineer, who was thoroughly trained.

Description of Alaska's PMS

The Alaska PMS includes a formal optimization model that can be used to meet two basic pavement management objectives:

- Maximize pavement performance for a fixed pavement preservation budget and
- Minimize life-cycle costs to achieve specified pavement performance standards.

Details of the optimization model can be found elsewhere (*2,3*).

The optimization model is formulated as a Markov decision process that captures the dynamic and probabilistic aspects of pavement management. The dynamic aspect refers to the fact that pavement rehabilitation decisions are not simply one-point-in-time decisions. Instead, they represent a sequence of decisions over a specified planning horizon. Furthermore, future rehabilitation decisions depend on rehabilitation choices made at the present time, future pavement conditions, and rehabilitation budgets available in future years. The probabilistic aspect of pavement management refers to the uncertainty in forecasting future pavement conditions given the rehabilitation actions implemented now. The Markov decision process addresses these uncertainties by estimating the "transition" probabilities (i.e., the probability that a road segment will move from its current condition to each of several possible future conditions if a particular rehabilitation action is implemented now).

For computational convenience, the statewide highway network is divided into road categories of different traffic and environmental factors. Within each road category, 1-mi road segments are identified and grouped into condition states. A condition state defines a particular combination of specific levels of the variables relevant to evaluating pavement performance. For example, if pavement roughness and fatigue cracking were the only relevant variables, one condition state might be defined as the combination roughness = 65 in./mi and fatigue cracking = 5 percent. Note that the definition of a condition state retains descriptions of individual pavement distresses; hence, rehabilitation actions are better matched with pavement condition than combing all relevant distresses into an overall condition score or index.

For the optimization model, decision variables are the proportions of road segments within each road category that should be maintained in different condition states and the rehabilitation action that should be applied to the road segments in each condition state. The optimal values of decision variables are found by specifying the appropriate objective function (i.e., minimize cost or maximize performance) and relevant constraints (e.g., fixed budget and desired performance standards for different road categories).

Assignment of a specific rehabilitation action to each condition state within each road category defines a rehabilitation policy for the entire highway network. The model provides both short- and long-term optimal rehabilitation policies. The long-term policy maintains the highway network in steady state (i.e., the proportion of road segments in each condition state and expected budget requirements remain constant over time). The short-term policy is formulated to bring the network from its current condition to the optimal steady-state condition over a specified period (such as 5 or 10 years).

Besides identifying the optimal short- and long-term rehabilitation policies the model also provides (*a*) estimates of current and future budgetary requirements, (*b*) projected network performance (i.e., the proportion of road segments in good, fair, and poor conditions), and (*c*) lists of specific road segments selected for rehabilitation actions in each year of the planning horizon.

IMPLEMENTATION

Organization

To implement the pavement management system, an organization of committees was created. Alaska DOT/PF has three regions and a headquarters section. Technical and management committees members were appointed by the directors. The PMS engineer first presented the theory and operation of the pavement management system to each of the committees. Implementation, from the time of delivery of the system from the consultant to the first list of pavement rehabilitation projects, took 3 years. Biannual presentations to the committees were made throughout the implementation period to update the committees and solicit feedback.

Technical Committees

In the regions, technical committees consisted of representatives from design, planning, maintenance, materials, and construction. At headquarters, the committee also included representatives from groups responsible for the statewide relational data base and the highway performance monitoring system. These committees reviewed all technical data and provided input into the implementation.

The technical input included regional design, construction, and maintenance costs. The committees also provided suggestions on how the system should handle permafrost settlement areas and how the various roadway categories should be delineated. Alaska has more than 70 categories that vary the basis of equivalent single-axle load (ESAL) level, climatic zone, frost susceptibility, functional class, and foundation code. On completion of the first implementation rehabilitation project recommendations, the technical committees provided input to define project limits. Alaska's PMS is based on 1-mi sample sections that do not necessarily coincide with logical project termini.

Management Committees

At the headquarters level, the management committee consisted of the commissioner, deputy commissioner, and the headquarters directors. Regional management committees included planning, maintenance and design, and construction directors. It was originally envisioned that these committees would receive only an executive summary, but questions asked during the presentations dictated that the full technical briefing be given.

The management committees selected long-term optimal steady-state pavement target conditions. As a starting point the average existing pavement condition was presented for each roadway category. Once the permafrost settlement area data were separated from the pavement condition data, most categories were at acceptable levels. Only rural, low-volume minor collectors and local roads and urban primary routes fell considerably below acceptable levels. By selecting the pavement target conditions, the management committees committed the department to a specific budget level for pavement rehabilitation. The regional budget split closely approximated historical budgets, probably because PMS is based on pavement area and ESAL level whereas historical budgets were based on lane miles and vehicle miles of travel.

The management committees selected a transition period from the current pavement condition to the long-term steady-state optimal condition. A transition period of 6 years was shown to cost approximately 20 percent more than a 10-year transition period. The committees chose 10 years.

System Verification

During implementation, the two largest roadway categories, one urban Interstate and one primary Interstate, were selected for research into the annual rehabilitation cost for the past 10 years. This cost was apportioned over the remaining roadway categories on the basis of performance models, then compared with the long-term optimized steady-state pavement condition recommended by the PMS. The PMS showed an annual savings of \$3.9 million over previous rehabilitation on a total annual budget of \$32.2 million, or 12.1 percent. Most of the savings probably result from the linear programming optimization selecting the optimum rehabilitation timing. In the past, the department rehabilitated entire previous projects, because they had been constructed at the same time, rather than the individual mile segments that truly deserved rehabilitation.

Implementation Summary

The management and technical committee structure requires much of the PMS engineer's time, but because of extensive communication, acceptance of the PMS recommendations was almost unanimous. By addressing concerns over the 3 years, while collecting historical data and developing the models, almost all problems were solved. Approximately 90 percent of a statewide list of federally funded projects selected in the first implementation list for the 6-year planning cycle were programmed. It is believed that by intimately involving the committees in the implementation phase, the department invested in the system and was ready to embrace the results when they arrived. Because knowledgeable people at all levels of the department had the opportunity to be heard and educated, many of the barriers that could have blocked the implementation of PMS were removed.

Applications of Alaska's PMS

Unstable Foundation Areas

Alaska's PMS makes recommendations for releveling unstable foundation areas caused by melting permafrost, peat settlement, and other embankment instabilities. Most of Alaska's unstable foundation areas are caused by permafrost thaw settlement. Permafrost is permanently frozen material, which can be mostly ice. Paved embankments over permafrost have settled up to 4 ft/year. The unstable foundation areas are not considered pavement structure problems, correctable by surface rehabilitation, and are treated separately in Alaska's PMS. Those mile segments with greater than 15 percent unstable foundation areas are set apart from the rehabilitation optimization; rehabilitation costs are assumed to be driven by the foundation problems. Only 3.4 percent of Alaska's total paved area is affected by unstable areas, but about 500 mi of Alaska's approximately 2,800 centerline-mi of pavement have unstable areas, and 210 mi have greater than 15 percent area of permafrost instability.

Material borings, maintenance supervisors' experiences, and visual observation were used to estimate the frequency of releveling for each unstable area. Previous releveling budgets were then apportioned over the settlement areas to determine the total annual cost for releveling unstable foundation areas, which is \$5.5 million. With the data from PMS, a designer can look at the releveling cost for a specific length of roadway and compare it with the cost of mitigating the settlement with insulation, thermal probes, or other alternatives. For a further discussion, see the work by Johnson (*4*).

Effects of Increased Legal Axle Loads

Just before implementing PMS, the state of Alaska raised the tandem axle load limits on trucks from 34,000 lb to 38,000 lb. Using the distribution of Alaska's trucks, this amounted to an approximate increase in ESALs of 28 percent. This increase will result in a reduction in fatigue life of the pavement. If the life of all Alaska's pavements were reduced 28 percent this would translate into an increased annual budget of \$12 million/year in additional asphalt concrete to maintain the same design life. PMS was used to include the effects of increased roughness and rutting. By comparing the models for different levels of ESALs, it was estimated that both the roughness and rutting would increase only 7.5 percent. The ESALs on much of Alaska's rural paved roads are low enough to require a minimum 2-in. pavement with considerably more fatigue life than required. The roughness lives for these roadway categories are shorter than the design life for fatigue. Hence, the additional ESALs reduced the service life only 7.5 percent instead of 28 percent. Taking into account rutting and roughness, PMS then demonstrated that the actual increase in the annual budget was only $3.1 million.

Pavement Design Lives

Before PMS, Alaska's pavement design life for all pavements was 20 years. Alaska's PMS analyzes various thicknesses of hot asphalt pavement and overlays. The system selects the optimum alternative on the basis of its predicted average performance and cost. The output includes the average frequency of rehabilitation; the inverse is average pavement life. The design life is selected to give a 95 percent confidence level based on pavement life distributions determined during research performed for Alaska's excess fines design method. (These distributions will be updated from annual PMS pavement condition surveys.) The following table shows Alaska's recommended pavement design lives:

Recommended Design	*Life (years)*
Rural Interstate and principal arterials	10
Urban Interstate and principal arterials	12
All other routes	20

Fatigue controls the high-volume rural Interstate and principal arterial design lifes; rutting rarely exceeds 0.5 in. during the life of the project. Roughness controls the low-volume rural Interstate and principal arterial design lives. PMS recommends recycling or replacing 2 ins. of hot asphalt pavement on the average for both these categories. The urban Interstate and principal arterial design lives are controlled primarily by rutting (5 to 11 years) and secondarily by roughness. For urban principal arterials and Interstates with curb and gutter, PMS recommends an average of 5 in. of hot asphalt pavement, milling and replacing the upper 2 in. until fatigue occurs. For urban principal arterials and Interstates without curb and gutter, the PMS recommends a 3-in. overlay. All other routes require only Alaska's minimum pavement thickness of 2 in., because of low ESALs, and therefore were left at the original 20-year design life. The aforementioned design lives are recommended for new construction as well as rehabilitation projects.

Preventive Versus Corrective Maintenance

On the basis of Alaska's performance models, Alaska's PMS recommends no corrective maintenance or seal coating but does recommend preventive maintenance. Preventive maintenance is defined as crack sealing with hot rubberized sealant. Alaska's performance prediction models are assumed to vary on the basis of climatic zone for preventive maintenance. In a wet maritime climate, the design life is assumed to be reduced 50 percent if no preventive maintenance is performed; in the transitional zone the reduction is 35 percent; and in the drier continental climate the reduction is 25 percent. These data are based on estimates of engineers and maintenance supervisors. Using an annual cost equal to resealing all cracks each year, the benefit cost ratio for the maritime zone from Alaska's PMS is 3.5; the transitional zone, 2.5; and the continental zone, 1.0. Alaska is currently reanalyzing these assumptions, including reducing the annual cost of crack sealing assuming a service life of up to 5 years. This should make crack sealing more attractive. Research is needed to verify this experience.

CONCLUSION

The full creation and implementation of Alaska's PMS started in 1982 and finished in 1992. The experience of Alaska shows that including department representatives from both the technical and management levels in all phases of the decision process will lead to a successful implementation of a PMS. By holding regular committee meetings, presenting interim results, and receiving feedback and concerns, all resistance can be addressed and the system will be embraced rather than rejected or ignored by the organization. Demonstration of the results of various applications of PMS also helped sell the system to the department.

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Strategic Tools in Finland

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The Finnish National Road Administration (FinnRA) has been developing pavement management systems (PMSs) since the late 1970s. By now, the following systems of the pavement management process have been implemented and are in use: the Highway Investment Programming System is used for strategic decision making by the central administration (FinnRA). Recommendations for budget levels and maintenance measures from the model have been transferred to nine highway districts to their project-level PMSs for capital programming. The condition register contains all relevant information on road condition needed in both PMSs. Basic information on, for example, traffic and construction history is retrieved from the road data bank. As in many other road agencies around the world, the development and implementation of these systems has appeared to be time-consuming, laborious, and even sometimes difficult; significant resources, both human and financial, have been used in the development. The most significant problems have been organizational, institutional, and human, whereas technical problems are currently minor. The systems developed and implemented in Finland are first evaluated mainly according to the outlines defined by the PMS literature. Discussion concentrates on the pros and cons as well as new solutions faced during the development and implementation process. Finally, some recommendations for improving this process are presented. Second, experiences of application of management tools in the Lapland highway district are presented. Because of the economic recession, Lapland is facing severe budget cuts. To fully comprehend the implications, the district initiated a study on the impacts of different strategies concerning the allocation of funds between maintenance, rehabilitation, and investments. It turned out that the different road-keeping actions are not independent of each other and that their simultaneous optimization is necessary.

The Finnish National Road Administration (FinnRA) is the central administrative body for nine highway districts. FinnRA is responsible for making policy for the whole country, developing standards and guidelines, evaluating the districts' efficiency and productivity, and relating with the Ministry of Transportation and Parliament. The districts execute the program and policies independently within a given budget framework.

FinnRA has been developing pavement management systems (PMSs) since late 1970s. The first systems operational in microcomputers were put into use around 1985. As in many other road agencies around the world, the development and implementation of these systems in Finland has appeared to be a time-consuming, laborious, and sometimes difficult task; significant resources, both human and financial, have been used in the development. Despite these, many problems have hampered the process.

Evaluation of pavement management implementation process has been widely discussed in the literature. In 1987, at the Second North American Conference on Managing Pavements in Toronto, this topic was discussed in several papers [Clark (*1*), Jackson and Grauberger (*2*)]. In 1991, the Conference on Pavement Management implementation was held in Atlanta, Georgia. In this conference, Paterson and Robinson (*3*) listed parameters for technical evaluation and ranking of PMSs. Other topics, such as benefits of these systems and the most common institutional barriers of PMS implementation, were also discussed in this conference.

PMS Implementation in Finland: Experience Gained Since 1985

PMS Overview

The FinnRA's PMS contains three parts:

1. Network-level PMS, Highway Investment Programming System (HIPS);
2. Project level PMS (PMS91); and
3. Road condition data register (KURRE + RDB).

The network-level system, HIPS, is used for strategic-level decision making by the central administration of FinnRA located at Helsinki. It analyzes the condition state distribution of all paved roads and predicts its change in the long term. The objective of HIPS is to find the optimal condition level of roads by minimizing total costs to the society; this includes road maintenance and rehabilitation costs as well as road user costs. More detailed information on HIPS is found elsewhere (*4*).

Recommendations for budget levels and maintenance measures from HIPS are transferred to the nine road districts to their project-level systems PMS91, for yearly capital programming. In the districts, the goal is to find the right rehabilitation actions and timing for each road segment. PMS91 also contains tools for follow-up of quantities of the actual paving work and determination of the improvement after paving.

The condition register contains accumulated up-to-date and historical condition data for each 100 m of the paved road network. It produces comparisons of condition states in different districts or road classes and shows the trend for condition changes. It also produces all condition data needed in both pavement management systems. The system is decentralized: districts are responsible for updating the data and the central administration maintains its version of the register for strategic level data needs. Other data needed in analysis are retrieved from the road data bank.

Technical Evaluation

A set of evaluation criteria has been defined by Paterson and Robinson (*3*) in which more precise definitions of the parameters can be found. Evaluation of the Finnish systems according to these 15 criteria is given in Table 1.

Completeness and Resources Required

All three decision-making levels and two monitoring levels are included in the Finnish systems. Implementation and quality control are being monitored, and all systems are completed but development work is continuous.

User Interface

System efficiency is a problem because the running of all programs is still time-consuming, even in 486-level microcomputers. User-friendliness is high in all systems, although understanding the HIPS structure is difficult. All programs are interactive and produce sensitivity results. Reports are mainly ready-made numerical reports; ad hoc

TABLE 1 Technical Evaluation of Finnish PMSs

COMPLETENESS AND RESOURCES REQUIRED		Maximum score	Finnish scores
1.	Completeness of System for:		
	a. information sub-system	8	8
	b. strategic network planning	8	8
	c. tactical network-level programming	10	10
	d. project design and analysis	8	8
	e. implementation and quality monitoring	6	6
2.	Need for system development or customization		
	a. information system	5	4
	b. Decision-support modules	15	14
USER INTERFACE			
3.	System efficiency	10	6
4.	User-friendliness	10	7
5.	Interactive capability	5	5
6.	Quality of reporting	10	8
7.	Software robustness and security	5	3
MODELS			
8.	Technical analysis	10	8
9.	Validity and calibration	10	8
10.	Sectionization	5	5
11.	Economic evaluation	5	4
12.	Prioritization and optimization	10	9
DATA MANAGEMENT			
13.	Data item requirements	10	9
14.	Data collection and processing procedures	15	13
15.	Data storage, retrieval and communication	15	13
SUBTOTALS			
	Completeness and resources required	60	58
	User interface	40	29
	Models	40	34
	Data management	40	35
TOTAL		**180**	**156**

reports and graphical outputs require extra skills. Program robustness has not yet been fully tested, and security questions are open.

Models

Full empirical deterioration and cost models are in use in both PMSs. A sample road network was established in 1987 to collect information for deterioration model updating. Sectionization is done by various parameters and is flexible. Economic evaluation includes a comprehensive economic analysis of road agency and user costs. Optimization is implemented at full scale in HIPS; simple prioritization is used in PMS91.

Data Management

Data collection and management are well developed. Road surface condition (roughness, rutting) is measured by high-speed vehicles. Structural condition is measured with FWDs and pavement distresses are inspected visually. All data are stored in a road data bank and KURRE and can be reported and viewed easily.

Conclusions of Technical Evaluation

The earlier technical evaluation confirms that the Finnish pavement systems contain most of the features needed in an advanced package. The main features to be further improved are (*a*) system efficiency, (*b*) user friendliness, (*c*) reporting, (*d*) deterioration and cost modeling, and (*e*) bearing capacity and distress data validity. However, all these development needs are minor: the development of pavement management systems is, in any case, a continuous process.

Pavement Management and the Organization

The organizational structure of pavement management is twofold: development organization and user organization. There have been many stages in the organization of this management system. The first idea was to distribute all programs to both the central administration and all districts. Currently, the organization is well formalized. The development organization, a special PMS-group in FinnRa's Research Center, is developing the model independently of the user organizations both in the central administration and district agencies. The PMS group is responsible for all programs, development of the models, and training of users. FinnRA's management, strategic planning, and financial planning departments are interested in strategic-level information produced by HIPS. Road districts use PMS91 for their planning and capital programming.

Problems of Pavement Management Implementation

Hall (*5*) and Smith (*6*) have listed major PMS implementation problems. In their conclusions, problems center much less on technical aspects than on human questions. In the following, the authors' experiences reflect these barriers, and solutions are presented.

Resistance to Change

Traces of resistance to change are found in Finland. In 1980s, FinnRA started to develop two totally separate systems because decision makers were not able to decide how to proceed. District engineers have resisted PMSs because they think that new systems will decrease their decision power by cutting down annual budgets. Road data bank staff were not willing to store huge amounts of road condition data in their registers; this led to the creation of a separate condition register. Another barrier in Finland is the so-called not-invented-here syndrome.

Long Time Frame

The long development period has occasionally been frustrating, and the short-term benefits of the system have been questioned. On the other hand, this period has also been extremely important and fruitful because the necessary learning process has taken place simultaneously.

Black Box Effect

Both HIPS and PMS91 are theoretically advanced and complex systems. To reduce the "black box" effect, the use of the system is left for a small group of experts, who are also responsible for marketing the results to decision makers. Training and data quality improvements have improved the situation, but the highly mathematical nature of these systems still causes resistance, especially when HIPS is implemented.

Data Reliability and Validity

Data reliability and validity have appeared to be significant questions in Finland. During the development process, the need for more objective road condition information became essential and the evaluation procedures had to be designed. This led to purchasing of five high-speed road condition measurement vehicles, which, after regular calibration measurements, produce valid and accepted information.

Bearing capacity and distress measurements are still problematic. They are slow and expensive, and the reliability of the samples is considered low.

Other sources for prejudice are road deterioration and road user cost models. To overcome the problem, a sample road network was founded to collect objective data for empirical deterioration models. Finland has a long history of estimating road user costs, but the effect of road condition on these costs is unclear; this is still causing obstacles.

One-Person Show

In the case of PMS91 and KURRE, the importance of organizational structure has been well understood by FinnRA, and the problem of the one-person show has been avoided. For HIPS the situation has been worse.

The importance of adequate, skilled personnel for the use, training, and development of the systems is currently better valued. Wide support from upper management is, however, limited.

Experiences from Lapland Case Study

General

In the beginning of the 1990s with the economic recession, opinions began to differ between FinnRA and the regional Lapland district concerning the development of the northern part of the Finnish road network. FinnRA suggested decreasing resources for investments, rehabilitation, and maintenance whereas the district felt that such a policy would have harmful long-term effects. To fully comprehend the implications of the proposed budget cuts, the district initiated a study of the impacts of different strategy alternatives on the road network condition, agency and user costs, maintenance level of service, and on the regional economy.

In this study, the impacts of different budget levels were first analyzed separately within each component (i.e., rehabilitation, summer and winter maintenance, and investments). In the second phase, marginal benefits and losses due to changes in the budget level were compared. This, however, proved to be difficult because a considerable part of the benefits cannot be measured in monetary terms. This is why only broad conclusions can be presented at this stage of the study.

Lapland District in Numbers

Lapland differs considerably from other regions in Finland. The road network is very long, about 9000 km, whereas traffic volumes are low because of an extremely low population density. The arctic climate puts severe restrictions on the technology used, the amount and quality of winter maintenance, and road standards.

Lapland is covered with forests that are the basic source of the local value added; it is the main tourist attraction in Finland, and its future depends heavily on public funds and investments. There are several schemes for the future development of Lapland. The main factors that were taken into account when evaluating the benefits of alternative strategies concerning road maintenance are given here:

- Wood and paper sectors will be more important in the future for the well-being of Lapland, and it is essential to invest in roads used for transportation on this sector.
- Tourism will increase considerably in the future and the main road network to the holiday resorts in the north toward the Norwegian border, to the northwest and to Sweden, and to the east crossing the Russian border will get a special emphasis.
- The triangular area in the southwest part of Lapland encompass most of the population. In some road sections congestion is already severe and the road standard is not always up to that of the nation in general. Thus, investments are needed.
- The population of northernmost Europe is considerable; thus, increased contact between Norwegian, Finnish, and Russian Lapps is potentially strong, but is dependent on a good west-east road network.
- The potential of commerce and tourism between Lapland and the Kola Peninsula emphasizes the importance of a transborder road network.

For the planning period of 1992–1995, about 450 million marks/year have been allocated to the Lapland road district ($1.00 U.S. = 6 Finnish marks). In 1992, 440 million marks were used. Almost 50 percent of the funds are being used for rehabilitation, 30 percent for summer and winter maintenance, and the remaining 20 percent for investment projects. However, because of the severe economic recession, the budget level will be cut drastically.

Maintenance of Paved Road Network (HIPS)

Input to HIPS Model

FinnRA uses the HIPS mainly to analyze the road network of the whole country and to allocate funds to the nine highway districts. However, HIPS is a practical and efficient tool for gathering more precise results concerning one highway district and for facilitating decisions on how to allocate the rehabilitation funds to different roads. The system used in this study is basically similar to FinnRA's model. The main difference concerns the problematic part of Lapland's road network: the HIPS model was adapted to take into account roads that have extremely low traffic volumes and without national importance but that are essential to the well-being of the local population.

The road network of Lapland was divided into nine subnetworks depending on pavement type, average daily traffic (ADT) volumes, and the functional class. There were three pavement classes: asphalt concrete main roads, soft asphalt main roads, and soft asphalt secondary roads. The ADT classes were chosen to reflect relative low, medium, and high traffic volumes on the respective pavement types just mentioned. For the asphalt concrete main road network, the ADT classes are less than 1,500, 1,500 to 6,000, and more than 6,000 vehicles per day; for the two other classes the boundaries are considerably lower: less than 350, 350 to 800, and more than 800 vehicles per day. The classification made it possible to evaluate different maintenance policies between asphalt concrete and soft asphalt roads and ADT classes.

The HIPS analysis requires the following input data from each of the nine subnetworks:

- Current condition: roughness, bearing capacity, ruts, and defects were produced from the condition register. The time lapse between the last measurements and this study was insignificant (less than 1 month).
- Average daily traffic to calculate the user cost.
- Current budget levels for different subnetworks.
- Condition constraints that were chosen according to the FinnRA's policy.
- Agency costs, allowable states input data, and transition probability models were the same as those used by FinnRA.

The application of the FinnRA's network-level PMS to the case of one highway district is straightforward and there is thus no need to explain it in more detail.

Results of HIPS

The starting point of the HIPS analysis is the current condition of the nine subnetworks versus target condition set centrally by FinnRA. With a given budget framework those rehabilitation actions are suggested that minimize both social cost (i.e., agency and user costs) and deviation from target condition. The optimization period is 8 years.

In Figure 1, user cost savings for the total network are shown as a function of different budget levels. The savings are estimated after 6 years of rehabilitation actions proposed by the HIPS model and are calculated as differences from the current situation where the annual budget is 100 million marks.

There is a steep decline in user costs as a response to rehabilitation actions up to a yearly budget level of 150 million marks. For a 25 million mark marginal increase in the pavement management budget, the user costs decrease about 15 million marks annually. On the other hand, the relative user benefits from a rehabilitation budget of 175 million marks or more are far less striking. A 25 million mark/year increase in pavement management investments benefits the users by only about 5 million marks, implying diminishing marginal returns.

In Figure 2, the development of the road condition following to different budget levels is presented for the subnetwork of "soft asphalt main roads," the total length of which is 1157 km. The condition (bearing capacity, roughness, ruts, and defects) is presented after 8 years. The different budget levels used were 14 million, 31 million, and 45 million marks, whereas the current budget level is 25 million marks. Similar analyses were performed for all nine subnetworks.

As to bearing capacity and roughness, the actual budget level is satisfactory whereas the amount of ruts and defects would increase in comparison to the target condition. The target condition would be reached or exceeded in 8 years only with a considerable increase; in fact, almost a doubling would be necessary (from 25 to 45 million marks) in the funds allocated for this pavement class.

As a summary covering all the nine subnetworks, the following conclusions concerning pavement maintenance can be obtained:

- The current budget level (130 million marks) is satisfactory because the main road network can be main-

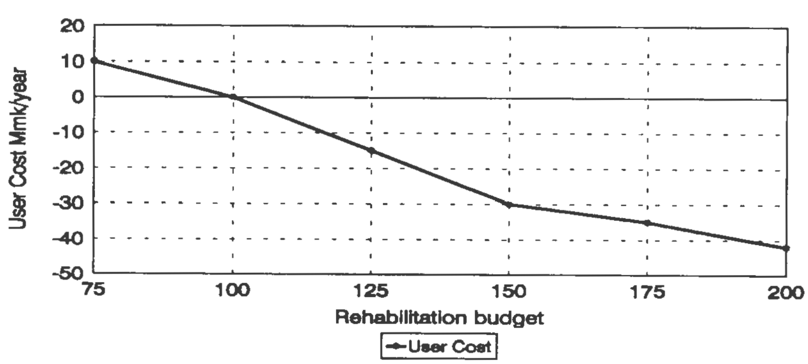

FIGURE 1 User cost difference after 6 years (MmK = million marks).

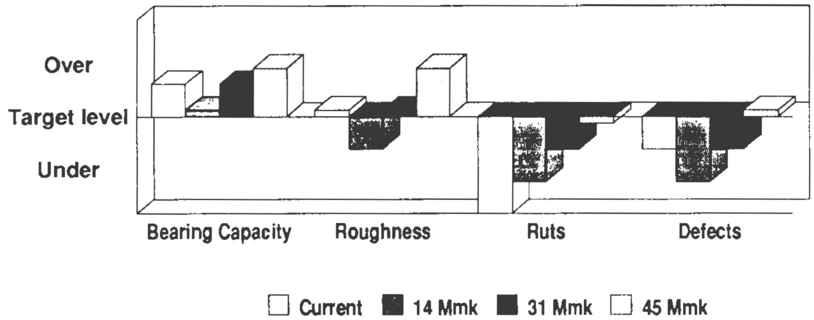

FIGURE 2 Condition development with different budget levels.

tained in good condition and the other subnetworks approach the target condition although they do not reach it within the study period.

- It is unacceptable to decrease the budget level to 80 million marks because this would mean that the condition of all subnetworks deteriorates.
- The economic depression Finland is facing does not allow for an increase in the current budget level, although the optimal budget resources should be increased to 160 million marks to meet the pavement condition targets set by FinnRA.

Presentation of Results

The results of the HIPS analysis were presented to the management personnel of Lapland district in three 1-day seminars. The seminar program covered the following topics.

- Theoretical foundations of the model: definition of agency and user costs, optimization procedure, and subnetworks.
- Presentation of aggregate results for the nine subnetworks: actual versus optimal budget level, and development of the road condition due to proposed budget cuts.
- Analysis of the concrete rehabilitation actions suggested by the HIPS model subject to different budget levels.

Summer and Winter Maintenance (AHP)

For the allocation of summer and winter maintenance budget, the Analytical Hierarchical Process (AHP) was chosen as a comprehensive maintenance management system and is still under development in Finland. AHP is a method involving pairwise comparisons that allows the selection of best action or alternative among different policy options [for theory see work by Saaty (7)]. AHP was used to evaluate the appropriateness of the level of funds allocated between different actions of summer and winter maintenance assuming, however, that the total budget is optimal. The respondents consisted of district management and operation staff; road users were not interviewed at this stage.

The hierarchy consisted of two levels. In the first stage, road users were classified into four functional classes: commerce/distribution, local inhabitants, industry, and tourism. The respondents agreed that the most important classes were the two last ones. These classes were given a more important weight implying that maintenance actions on the road networks serving these two user groups were valued more than on other subnetworks irrespective of, for instance, total traffic volumes. The second level consisted of four subnetworks: asphalt concrete roads, soft asphalt main roads, soft asphalt secondary roads, and gravel roads. The results of summer maintenance are summarized in Figure 3.

Major divergencies were found in funds used and funds needed to accomplish actions related to the level of service standard, which represent 12 percent of the total maintenance funds. Maintenance personnel appear to prefer construction-based actions, as opposed to providing services to road users. According to their preference setting, it would be possible to save up to 6 million marks annually in summer maintenance activities such as mowing, cleaning, putting up signs, and painting. On the other hand, dust removing, grading, and forestry actions need more funds than they are currently allocated. However, were the road users included in the hierarchy setting, the results would probably have been different in this respect.

Investments

The average yearly investment budget level of Lapland has been about 100 million marks. This represents a considerable amount of the total demand or the gross regional product of Lapland's economy. To analyze the effects of the aggregate level of investments on the regional economy, it was assumed that the investment budget would be decreased to 70 million marks or increased

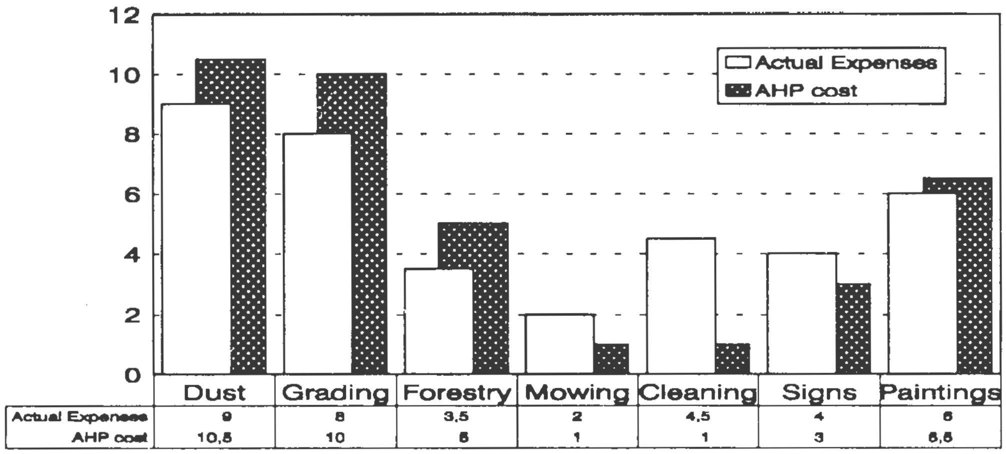

FIGURE 3 Summer maintenance, actual expenses versus AHP weighted budget.

to 130 million marks. The calculations were made with a regionalized input/output model and the results are summarized in Table 2.

The monetary multiplier effect presented in Table 2 makes it possible for the companies of Lapland to hire 600, 720, or 950 additional employees for the three budget levels, respectively. On the other hand, if the investment budget of Lapland is cut from 100 million marks to zero, as suggested, the region's enterprises lose almost 200 million marks as direct and indirect income and the number of unemployed increases by more than 700 persons.

In the second stage, different investment projects were compared. In addition to conventional cost-benefit analysis, further information about each project was obtained by calculating the indirect multiplier effects of user cost savings. It turned out that the heavier traffic there was, the more benefits the project would yield in terms of productivity gains and increased sales and employment.

Road keeping is not market-driven in Finland but is financed through general taxation, so the long-term effects, direct as well as indirect, should be taken simultaneously into account by the government when allocating funds for road upkeep. If the highway investment monies are cut, it would be necessary to increase the unemployment funds or to stimulate the regional economy by other means.

TABLE 2 Multiplier Effects of Road Investments (million marks)

Yearly budget level	70	100	130
Multiplier effects / sector			
Agriculture	3	3	5
Industry	53	75	98
Transports	53	77	100
Services	27	38	50
Total	***136***	***193***	***253***

Summary of Results

Comparison of user cost savings from highway investments and pavement management actions showed that allocation of funds between these two subcomponents was not straightforward. Depending on traffic volumes and the composition of traffic, total benefits from investments in urban areas appeared to exceed those of pavement maintenance on rural gravel roads. In economic terms, this means that the marginal benefits of 1 mark invested in congested areas exceed the marginal benefits of 1 mark used for rehabilitation of rural gravel roads. It is thus probable that rehabilitation and investments are, mathematically speaking, nonseparable and that a simultaneous optimization model for the two subcomponents is essential for maximizing the welfare of the society of Lapland.

Presumably maintenance is also nonseparable from rehabilitation and investment. This being the case, it is of primary importance to develop a comprehensive model to cover all road keeping actions, as nonseparability implies that optimization or decision making cannot be made separately for different actions but the allocation of funds must be done centrally and simultaneously.

Conclusions

In this paper, the most significant issues and problems in the implementation of pavement management systems in Finland were presented. The major implementation problems were related to human issues and the implementing agency. Yet successful implementation depends heavily on the agency's confidence that the system is well supported by the organization and that the development process will be continued and enhanced in the future.

On the other hand, following to the results of the Lapland case study, it is evident that rehabilitation, summer and winter maintenance, and highway investments cannot be viewed independently of each other. Road keeping must be seen as a whole and the optimization of its subcomponents has to be done simultaneously. Mathematically speaking, this means that pavement maintenance, summer and winter maintenance, and highway investments are nonseparable from each other and that the optimization function has to cover them all.

ACKNOWLEDGMENTS

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All opinions and conclusions reported in this paper are strictly those of the authors and do not necessarily represent the view of FinnRA or the district agency.

Implementation of Pavement Management System in Spanish State Road Network

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The Spanish Ministry of Public Works and Transport has begun to implement a pavement management system for its road network. Studying the experience of other authorities has been extremely important in selecting a method. The aim was to adapt the system to the circumstances of the network. The system is being implemented in stages in order to produce results as soon as possible and to not lose the advantages of a rigorous approach. The existing requirements and resources available have been considered in selecting the data to be collected. Some of the problems that have arisen during the work have been solved, and it is hoped that others will be solved in the future. The first stage has been implemented, and work is under way on the second stage.

The road network managed by the Spanish Ministry of Public Works and Transport covers 20 000 km, of which 2000 km are toll motorways, 4000 are expressways, and the remainder are single-lane highway. The 2000 km of motorways are managed under concessions by private companies that are responsible for their maintenance. In geographical terms, Spain is divided into provinces, in each of which is a head of maintenance. These provincial heads report to regional heads, who in turn report to the director general for roads.

Although there are more than 300 000 km of roads in Spain, the majority of road transportation uses the Ministry of Public Works' network. In addition, 85 percent of land transportation in Spain uses the roads, and 70 percent of truck traffic is supported by the state roads. This network therefore is of fundamental importance to the country's transportation system. In other words, the state network, which accounts for 7 percent of the roads, carries more than 70 percent of the truck traffic of the entire country. The average annual daily truck traffic (AADTT) of the entire network is 1,390 per road. For this reason, bearing in mind that the maximum axle weight permitted is 13 tons, the network withstands considerable loads. Concern was therefore expressed by those responsible that the method of road rehabilitation be improved as effectively as possible. To this end, it was decided to develop a pavement management system (PMS) (*1*).

Few governments in Europe have fully developed PMSs; many of them are still in the early stages of implementation (*2*). In Spain, the Ministry of Public Works and Transport commissioned the CEDEX Road Research Center in 1991 to draw up a PMS for its road network. The first phase of the system is being implemented now. The experience of other authorities, especially in North America, has been extremely useful in choosing the methodology to adopt.

The rest of this paper deals with the problems that arose during the development of the system. From the experience observed in other countries' systems (*3*), problems that often arise in operating systems happen because either the data have not been properly selected or the system is so complicated and sophisticated that it is difficult to adapt it to varying circumstances. The process that was adopted and the decisions reached, taking into account the effects that they would have when the system entered operation, are analyzed in the following.

Although it is true that the first results of the PMS were available in 1992 and experience in operating the system is very recent, an explanation of why one method was chosen over another could prove of interest.

General Description of System

As mentioned, the experiences of other authorities were considered when the system was designed. Special consideration was given at this stage to various AASHTO guidelines (*4, 5*).

Several possibilities were examined during system design. The first of these involved whether to make a new design from scratch or to buy a ready-made system. To this end, several systems were analyzed and special attention was also paid to the methods and means already available. Pavement management had been carried out for several years using a certain methodology and particular means, and for this reason it was decided to take maximum advantage of this whenever possible. This ruled out all commercial systems and left the possibility of changing the methods and means. The ones already in use generally appeared to be effective, and it was not thought necessary to make any major changes. It was therefore decided to adapt the system chosen to the existing circumstances, rather than the other way around (*6*).

One alternative was whether to implement a system that covered all requirements, one that would cover a long period of time, or one that was simpler. The fact had to be taken into account that no data base was available in which information had been stored in the past; for this reason, a compromise solution was reached, consisting of implementing the system in three stages. These stages could be characterized in terms of implementation of the three analysis methods proposed in the *AASHTO Guidelines on Pavement Management Systems* (*5*), in other words pavement condition analysis, priority assessment models, and network optimization models. Doing this would avoid the use of prediction models not adapted to the pavements in the Spanish network, which could have led to considerable errors. Furthermore, it would be possible to use a simpler system while the models continued to be studied.

In the first stage, therefore, indexes were assigned to each road section. Action was assigned in accordance with traffic levels, pavement distress, and pavement type. For this purpose, it was assumed that the useful life of the road works would be equal when attempting to resolve similar problems. A priority was assigned to each item of action and was costed. This meant it was possible to take a given budget and select road work actions to be carried out or to ascertain the means required to maintain the network in a particular condition.

User costs were not considered during this first stage and may not be considered in future stages. It is very difficult to assess them, and it is not usual to take into account high levels of roughness that would considerably increase these costs. Loads are high and traffic is intense, in general, in Spain, so pavements have a considerable thickness of asphalt concrete or cement-treated layers and are therefore fairly rigid (Figure 1). Pavements with more than 15 cm of asphalt concrete plus rigid and semirigid pavements amount to 61 percent of the total, whereas flexible pavements with less than 7 cm of asphalt concrete only make up 13 percent. The authors' experience is that surface evenness does not vary much over the life of Spanish pavements and hardly affects users. For example, Figure 2 shows a surveyed section of the road N-501, which has 12 cm of asphalt concrete over a granular base. Roughness is good, fluctuating from an international roughness index (IRI) of 1.2 to 2.7, while cracked areas reach 50 percent. In other words, there comes a time when it is necessary to rehabilitate pavements before users are affected to any substantial extent.

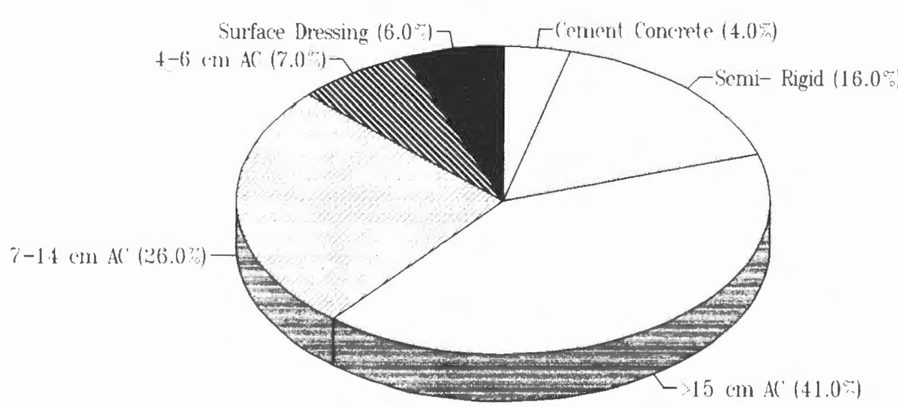

FIGURE 1 Types of pavement, Spanish network.

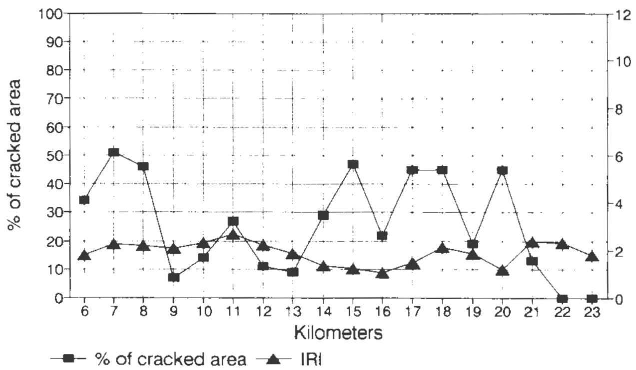

FIGURE 2 Cracked area, roughness (Road N-501).

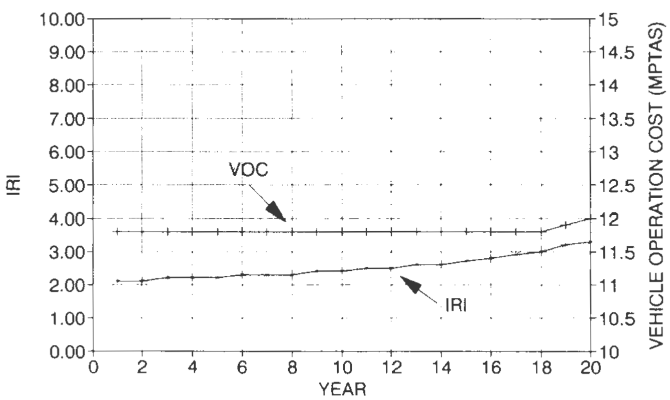

FIGURE 4 HDM-III run for IRI and vehicle operation cost for 1-km section of Spanish network.

Figures 3 and 4 show the results of running the World Bank HDM-III program, for a typical section of the Spanish network designed for an average daily truck traffic (ADTT) of 180, with 15 cm of asphalt concrete over granular base. It was assumed that traffic does not grow, so that the evolution of vehicle operation cost could be related only with the evolution of roughness. Although the model uses asphalt concrete with lower moduli than those used in the Spanish network, it confirms the authors' experience. The same does not happen with more flexible pavements, but these are less common and carry less traffic.

This first phase is already in operation. For the second phase it will be necessary to develop prediction models that enable different courses of action to be allocated to each road section and the most appropriate ones to be chosen over a particular period of time. It is to be hoped that with the information already gathered, model design can begin. Some sections have borne different numbers of axles and are in a differing condition, although they have the same pavement types. In other cases it will be necessary to wait.

During the third stage it will be possible to choose the most suitable courses of action, not for each road section but for the entire network as a whole.

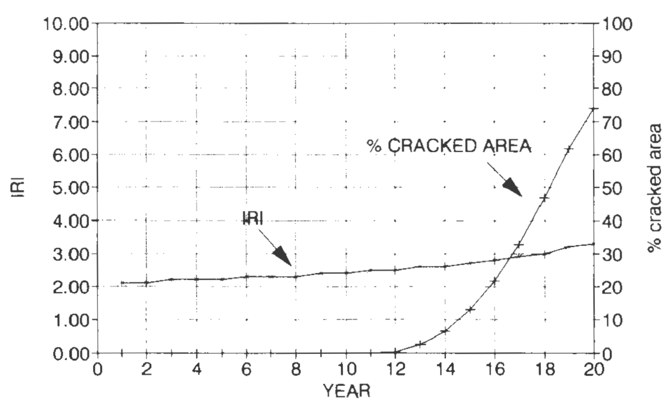

FIGURE 3 HDM-III run for IRI and percentage of cracked area for 1-km section of Spanish network.

Information to be Considered

Reference System

Each road in the network has a name, and each road section is referenced according to the distance from the last post. Throughout the system are posts at 1-km intervals. Occasionally, when modifications are made to the horizontal alignment, this distance between posts can vary. As a result of the inventory of the geometrical characteristics, carried out at set intervals and using vehicles, the distance between the posts is known and each point can be properly located. In addition to the vehicles taking this inventory and obtaining other information, global positioning systems have been brought into operation that enable coordinates to be assigned to each point with a high degree of accuracy. From the outset, prime importance was placed on the reference system since, without this, it would be impossible to proceed.

Inventory

Many roads in Spain were built on older roads, even on old Roman roads. Over the years these roads have been modified on many occasions. Preparing an inventory that contained full details of all pavement layers was not an easy task. Modifications have been made not only along their length but also in their cross section. If the highway personnel directly responsible had been asked to carry out a detailed inventory, there would have been a risk of nothing being done, as the task was almost impossible. A method was therefore chosen by which the personnel responsible described the composition of the pavements along their section of road, which could be considered as a single homogeneous unit.

The information included highway width, shoulder width, type of surface, type of layers and their thicknesses, and details of past rehabilitation work done. The only information obtained for the subgrade was whether or not it had been treated with cement, given the difficulties involved. Details were also provided as to whether the pavement was uniform in a transverse sense (7).

Equipment is being studied that, using radar, can check the thicknesses and some of the characteristics of layers. The use of falling weight deflectometers (FWDs) together with backcalculations will also enable the moduli of different layers to be ascertained.

Traffic

The figures for the average annual daily traffic (AADT) and the AADTT were taken into account, the latter to provide information on loads and the former to ascertain how the condition of pavements affected road users. The weights of vehicles are measured using weigh-in-motion equipment. Up to now, only the AADTT has been considered in each road section, but soon details of the distribution of the loads on them will be available.

Pavement Condition Surveying

Two types of information were examined in establishing the condition of the road network: information on distress and on the coefficient of friction. The former was mainly used to establish the degree of fatigue and rutting; the latter is fundamental for vehicle safety.

To establish the structural capacity on various sections, deflectometers such as the Lacroix, the Curviameter, and the FWD were used. The Lacroix and the FWD performed poorly. The Curviameter takes measurements at 18 km/hr but its use is still in the study stage. Although there is considerable experience in Spain in designing rehabilitation work using deflections, it has not been used in the PMS because it is a lengthy and costly process. It is hoped that better-performing equipment will be used in the future.

Ride quality is another parameter being measured on roads, but it has still not been incorporated into the PMS. The IRI has been adopted as a measure of roughness and will soon be incorporated into the system.

Distress

To assess the condition of pavements, a visual pavement inspection method was designed. It was necessary to distinguish between distress caused by fatigue and that caused by other wear. For this purpose, each lane was divided into five zones, and fatigue was considered only in the wheelpath zones. Within the latter, a distinction was made between longitudinal cracking, crazing, alligator cracking, and potholes. Distress was also considered away from the wheelpaths, along with other types of wear such as rutting. The severity of the distress was not taken into account; in other words, it was a question of keeping the system as simple as possible with minimum reliance on individual personal assessments. This meant that although there was less information, that which existed was more objective and different sections could be compared reliably. Earlier experiences had proved that detailed inspections in which personal assessments weighed heavily led to problems.

These inspections were carried out mostly on foot, but in some cases vehicles were used to obtain video images. It will be necessary to improve the resolution of the videos to be able to use them in a general way in the future. They have the advantages of being more objective, accurate, and easy to repeat, and in the longer run it will be possible to process the images automatically. This subject is undergoing study and will constitute a considerable advance in the PMS.

Safety

To measure the friction factor that is so important for safety when pavements are wet, the Sideways-Force Coefficient Routine Investigation Machine (SCRIM) is used. This equipment has been used for some years on the network with good results. Texture is also measured using vehicles equipped with laser-operated measuring devices, but these devices have not yet been incorporated into the PMS.

Although there were problems some years ago with rutting it hardly exists now with the current way that asphalt mixes are designed. Nevertheless, rutting is one of the distresses measured during the visual inspection process.

INDEXES

To select indexes, the possibilities were to use several similar indexes or one combined index. Many authorities combined roughness with distress, but experience on the road network in Spain, as mentioned does not enable the use of these combinations because current information suggests that roughness develops in a different manner from the other forms of distress. In addition, no information was available on the evenness of the pavements on initial construction; consequently, surface evenness and other forms of distress were treated separately.

Combining a distress index with an index with an index for the friction coefficient was ruled out because different treatment is required to solve these problems. In other words, different indexes were selected with respect to each problem that could require a separate type of treatment. During the first stage, a structural index was chosen, consisting of the percentage of the length of a lane showing distress as a result of fatigue, from 0 in the best case (with no distress) to 100 in the worst case.

As far as the friction coefficient was concerned, a somewhat more complicated value was adopted as the index, one that basically consists of taking the value exceeded by 95 percent of the measurements.

Actions

Actions have been divided into two types, one relating to the structure and the other to the surface, depending on the index involved. Structural actions were the pavement type, the heavy traffic rate, and the index. Action is assigned as a function of combinations of these factors. It is assumed that in each case the structural rehabilitation work will last for 10 years. A financial cost is assigned to each action. Surface actions were the overall traffic, the road type, and the index. In this case, the problem can be resolved in a similar manner in all instances. The financial cost of the action is also examined, as in the previous case.

Thresholds are set in both cases, below which no action is assigned apart from routine maintenance.

Prioritization

For structural actions, priority is given to sections with a higher density of heavy traffic and increased distress. Where these factors are equal, priority is given to the less flexible pavements. Considering the heavy traffic density, distress, and pavement type, each section is allocated a degree of priority and, where two sections are similar, priority is given to the one with the highest AADTT. The aim of this ranking is to give preference to roads in which more resources have been invested, which are usually those with the greatest traffic. This criterion also benefits road users.

For actions to improve the friction factor, priority is given to roads with a higher AADT and a lower index. Single-lane roads are given preference over dual-lane roads, because a higher coefficient of friction is usually more important on them. In short, preference is given to the sections where there is a greater effect on road user safety.

Implementation

The main problems before implementation were the inventory and visual pavement surveying. It was difficult to know the thicknesses of the layers and the times when they were constructed because of the lack of records at the time. Surveying many kilometers of road was also hard, and a new, faster method was provided to reduce the amount of and accelerate the work. For the next campaigns a new method has been developed and is ready for use.

At present the system has been run only for first time, therefore experience with it is not great. Nevertheless, this short experience appears to be good and convincing for obtaining funds for road rehabilitation. Contrast between the system results and the provincial manager's opinion has been fulfilled in most cases. Table 1 gives action costs calculated with the system and the real project cost. Although in some cases differences are large, the average is good.

All the actions proposed by the system were ordered with the prioritization criteria and show the cost and accumulated cost (Table 2).

TABLE 1 PMS Costs of Actions Versus Project Costs.

			COST MPTAS/KM	
ROAD	START	END	PMS	PROJECT
N00002	464.80	465.90	13.83	21.19
N00004	52.70	58.75	33.07	27.73
N00004	58.75	59.35	33	27.73
N00006	407.00	407.10	11.75	12.23
N00006	407.10	408.00	21	12.23
N00006	408.00	420.00	14.70	12.23
N00006	421.80	424.00	14.68	12.23
N00006	424.00	424.50	9.20	12.23
N00006	427.30	427.60	16.67	12.23
N00006	427.60	432.00	13.73	12.23
N00110	189.70	189.73	6.19	17.46
N00120	426.00	426.65	21.08	14.81
N00120	426.65	427.00	21.14	14.81
N00120	427.00	429.50	14.72	14.81
N00122	458.00	458.06	16.83	11.92
N00232	405.90	411.60	15.85	34.86
N00234	28.90	31.00	14.24	8.13
N00234	31.00	33.70	13.19	8.13
N00234	33.70	36.00	17.17	8.13
N00240	118.40	118.44	11.50	6.99
N00260	476.00	477.90	9.89	4.53
N00260	477.90	478.00	3.30	4.53
N00502	20.60	20.70	11.75	10.33
N00502	77.40	77.50	4.40	17.76
N00620	192.99	193.00	17.64	18.28
N00625	40.90	62.00	10.64	25.42
N00625	115.14	121.70	10.08	12.15
N00625	130.00	131.00	9.90	12.15
N00630	152.00	153.00	21	13.98
N00634	148.40	149.30	8.85	3.38
N00634	154.00	172.00	10.72	3.38
N00634	172.00	173.70	5.06	3.38
N00004	53.00	58.80	27.62	27.73
N00004'	58.80	59.35	22	27.73
N00004	81.72	81.88	14.38	23.63
N00004	250.00	250.60	14.50	21.33

AVERAGE OF DIFFERENCES	: -0.09
STANDARD DEVIATION	: 6.93
AVERAGE OF ABSOLUTE VALUE OF DIFFERENCES	: 5.51
STD OF ABSOLUTE VALUE OF DIFFERENCES	: 4.20
MAXIMUM DIFFERENCE	: 19.01
MINIMUM DIFFERENCE	: 0.09

TABLE 2 Prioritization Table

PRIORITY	ROAD	CARRIAGEWAY	STARTING KM POINT	ENDING KM POINT	TYPE OF	COST	CUMULATIVE COST
1	N-538	Single	965.6	970.7	A-2	177.6	177.6
2	N-679	Single	330.8	334.0	A-3	101.0	278.6
3	N-287	Right	4.0	9.5	S-3	115.5	394.1
.	..		..	..	.	..	..

As the budget was not large enough for all actions, the top manager decided to select sections until the budget was completed. All the other actions were postponed for future years. One-third of the total cost of the structural rehabilitation proposed by the system was accepted. In the case of surface rehabilitation, two-thirds of the total cost was accepted. The reason for this larger acceptance is that costs are lower than in structural actions and that safety concerns exist.

Conclusions

During the first stage, the work necessary to implement a PMS has been carried out. The aim has been to adapt the system to the means available and to the requirements of the network.

An effort has also been made to implement a simple but rigorous system as soon as possible. The complicated systems used by other authorities were ruled out because of the difficulties in adapting them and because they did not solve the problems of the Spanish network. It was also decided not to wait for a complicated system of special design to be made available. Preference was given to implementing the system to achieve results as quickly as possible.

Although there were difficulties over gathering data, it has already been possible to use the system to prepare network rehabilitation plans. Proposals for the PMS have been compared with the requirements of each province in Spain and with the projects carried out. The results of this comparison have been satisfactory.

Difficulties have arisen in this work, some of which have partly been overcome; others still need to be solved. The inventory needs to be improved to provide more details of pavement characteristics. It will also be necessary to adapt the visual inspection process so that it can be automated, if possible, or simplified. Information on roughness and deflection also needs to be incorporated.

Work on the subsequent stages is under way, and it is hoped that prediction models will be available soon for comparison with actual circumstances.

Considerable benefit is expected to result from the PMS. In addition to more effective management, there will be increased knowledge of the performance of pavements and construction techniques.

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Pavement Management System Implementation in the Transvaal Provincial Administration

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A brief background is given to the implementation of a pavement management system in the Transvaal Provincial Administration in the Republic of South Africa. The system has been in place for 8 years and provides valuable information in terms of the overall condition of the road network and its deterioration over time. The pavement management system primarily utilizes visual inspections to assess the network condition and to prioritize resealing and rehabilitation. The current visual inspection procedure is described briefly, and the various changes that have been made and problems that have been experienced with this procedure over time are described. In view of the fact that reseals are prioritized on the basis of road condition, the poorer roads have been sealed during periods of severe budget constraints. This has led to neglect of the better-quality roads, which in their turn have deteriorated significantly. More recently the approach to resealing has been changed so that resealing is prioritized on a cyclical basis for each road, with condition playing a smaller role. The current intention is to try and maintain the better roads and to abandon the very poor roads because of severe budget constraints. The road network condition is deteriorating, and funds have been reallocated from other sources to prevent the deterioration. A combination of user operating costs and road maintenance costs is used to prioritize the rehabilitation and reconstruction work. The problems in carrying out rehabilitation work in the past and with present procedures in a period with decreasing budgets are described.

The Roads Branch of the Transvaal Provincial Administration (TPA) administers the planning, construction, and maintenance of 44 000 km of road in the Transvaal Province of South Africa. These roads include roughly 200 km of freeway and 20 000 km of blacktop roads; the remaining roads have a gravel wearing course. A pavement management system (PMS) for the surfaced road network was initiated in 1982 and fully implemented in 1985. The system has gradually been refined over the last 8 years while funds for road maintenance and rehabilitation have dwindled. More recently, funds have been reduced significantly and the adoption of the most cost-effective rehabilitation strategy has become a primary goal of the system.

The current system is described briefly and some of the changes that have had to be made during the above period and problems experienced with system implementation are examined. In addition, some of the current issues being addressed and changes envisaged are described.

BACKGROUND

The PMS forms one part of a reasonably comprehensive road network management system that includes, among other elements, a

- Geometric management system (*1*),
- PMS,
- Maintenance management system, and
- Gravel road management system.

Several other information systems such as a traffic counting system and collision reporting system are also included.

Environment and Pavement Performance

In view of the high cost of the bituminous materials in South Africa and the relative abundance of reasonable to good-quality natural gravels, most pavements consist of granular layers with thin bituminous surface dressings. The granular layers range from natural gravels through cement-stabilized gravels to high-density crushed stone layers.

The climate in the Transvaal varies from dry areas with rainfall of approximately 300 mm/year to extremely wet areas with annual rainfall figures of over 2000 mm/year. However, these latter wet areas are extremely limited; most of the province has a rainfall of less than 600 mm/year. Most of the rainfall occurs in the form of short thundershowers during the summer rather than long soaking rains.

In view of the environment, most pavements perform satisfactorily when constructed from granular materials provided that the surfacing is kept well sealed and surface runoff is adequately accommodated. In places, subsoil moisture occurs, and this is kept out of the pavement by using either deep side drains or subsurface drains.

Daytime temperatures range from 16° to 30°C, and night-time temperatures range from 0° to 18°C. Frost occurs at night in some of the higher areas, but no freeze/thaw situation needs to be catered to.

Pavement distress normally occurs in the form of gradual rutting or other permanent deformation due to densification of some of the granular layers, followed by crocodile cracking of older surfaces, water penetration into the granular layers, and further shear failures of the wet materials. The PMS is primarily aimed at ensuring a watertight surfacing layer by means of regular resealing and at providing some minor rut filling and smoothening using coarse slurries. In the extreme situations where the riding quality has deteriorated significantly, reconstruction or the addition of one or more pavement layers, followed by resealing is normally considered as a rehabilitation option. In view of the fact that much of the Transvaal is at an altitude of more than 1000 m, hardening of the bituminous material because of ultraviolet radiation and oxidation is common, and diluted emulsions are generally applied between resealing operations to improve the waterproofing of the surfacing and to extend its life.

Organization

The province is divided into four regions, and the responsibility for road maintenance in each region is assigned to the regional engineers. They obtain support with respect to materials, pavement design, and pavement management from a centrally located materials directorate. However, the regional engineers are not obliged to carry out any work in accordance with the outputs of the PMS, and they have a significant input into the final treatment selected and the prioritization of projects within the region. The staff within the materials directorate attempt to ensure some degree of uniformity with regard to priorities across the regions and are responsible for combining the regional priorities into an overall resealing program for the province.

Funding

In view of the current status of political developments in the country, the decision makers are reducing all capital expenditure on the infrastructure in favor of expenditure on social upliftment. The maintenance of the existing road network therefore receives priority and even then funds are severely restricted.

IMPLEMENTATION

The PMS was implemented in phases, with associated problems, as follows:

- *Departmental visual evaluations of the entire surfaced road network:* This had the advantage that all roads were inspected on a link-by-link basis by two engineers with the result that reasonably uniform visual inspections were achieved, but severe strain was placed on the inspectors. This strategy could only be kept up for 1 year, after which only part of the network was inspected. This made it difficult to present details of overall network condition over time.
- *Visual evaluations by seven consultants on a regional basis:* This facilitated the inspections but led to some nonuniformity between inspectors. Detailed documentation of inspection procedures and training, including "test" inspections on selected links to prove competency prior to carrying out network inspections, has improved the situation.
- *Implementation of a detailed network inventory of all surfaced and gravel roads:* This is to ensure consistent link descriptions and to add traffic information to the PMS.
- *The inclusion of pavement structure data, resealing history, and riding quality measurements of the entire surfaced road network in the PMS.*
- *Modification of procedures and algorithms:* This previously only considered visual inspection data to determine resealing needs, to also utilize traffic, riding quality, pavement structure, and resealing history in a more

comprehensive algorithm that also identifies rehabilitation needs.

Traditionally, the PMS in the Transvaal has been aimed at optimizing periodic resealing of the road network. This is primarily carried out using annual visual evaluations of the entire surfaced road network, followed by panel inspections of selected projects. Limited additional riding quality data and other information on the pavement are currently also used to select rehabilitation options. As indicated above, the network has now deteriorated in places to the extent that surface treatments are no longer adequate, but funds for major rehabilitation are not available. The past procedures and adaptations thereof and the present strategy being implemented to address this problem are set out in the following sections.

Components

The TPA PMS has the following major components:

- *Inventory:* A fairly detailed inventory exists within the province and selected information is extracted for the PMS. This mainly involves items such as the kilometer distances and descriptions of each individual road link, the road type (i.e., whether it is a freeway, dual carriageway, or conventional two-lane road), and the surfaced width of the road.
- *Traffic:* Traffic information is obtained from short-term traffic counts carried out at all intersections on a 3-year cycle, as well as from axle weight analyses carried out at selected locations.
- *Pavement structure:* Fairly detailed information on the pavement structure exists on the PMS that relates to the thickness and material classification of each individual pavement layer.
- *Surfacing:* Surfacing details involve the start and end kilometer position of each surfacing layer placed over the life of the structure and a type code describing each layer.
- *Visual evaluations:* Formal network level visual evaluations are carried out on the entire surfaced road network on an annual basis.
- *Riding quality:* Riding quality measurements are carried out using response-type devices on a 3-year cycle.

More details about these phases of implementation and the associated problems follow.

Inventory

It was initially decided to carry out visual evaluations on a link-by-link basis, where a link is defined as a road section stretching from one intersection to another. The data are stored per road number and kilometer position. On the face of it, defining these links and carrying out the visual inspections would appear to be simple, but in practice it has proved to be extremely difficult. Links were not numbered, because this was expected to become complicated due to renumbering when new intersections were built.

The major obstacle encountered involved the kilometer position of the intersection and the need to maintain a fixed value for this kilometer position to compare visual inspections for successive years on the link. Many arguments arose between the materials directorate and the regions as to the exact kilometer position of intersections, with the result that the start and end kilometer distances of links often changed in successive years leading to a lot of manual work in attempting to redefine equal links in successive years in order to compare historical data over that link. The problem was eventually solved by carrying out fairly accurate measurements of the road network with vehicle-based electronic distance measuring equipment and by installing node point markers at each intersection identifying the road number and the kilometer position of that intersection. The various regions are responsible for installing and maintaining these node point markers and all the various management systems now use a common inventory. Visual inspections in successive years are carried out on forms which are preprinted with the road numbers, kilometer distances, and descriptive information. Where node point problems are observed in the field these are noted on the form and action is taken in the following year to rectify this problem.

Traffic

In the early stages of implementation of the PMS the type of work to be carried out and its priority was primarily based on network-level visual evaluations and subsequent project level inspections by a panel of engineers and technicians. Traffic volumes are taken into account during these inspections and influence the decision on the type of seal and the priority of the work. More recently, the need for more substantial rehabilitation has increased and the selection and prioritization of these projects is largely based on excess user costs which are incurred on these roads relative to user costs on roads with a reasonable riding quality. Traffic counts are required to compute the excess user costs and these are obtained from the comprehensive traffic information system (2).

Heavy vehicle volumes and axle loads are primarily used at the project level and not at the network level. Further work is being contemplated at the network level in which the expected number of E80's relative to the overall pavement structural strength will also be used to assess the type of project being contemplated on poor roads. If the road is weak relative to the traffic load some form of strengthening is considered.

Pavement Structure

Pavement structure information has been collected from as-built information and is stored per layer for each uniform section of road. At this stage the information is primarily used at the project level although some network-level investigations have been carried out, by dividing the pavements into categories using the basecourse type, pavement age, and visual inspection details, to assess the long-term performance of different pavement types. The accuracy of the information is often suspect and it is gradually being improved with time as more information comes to hand.

Resealing History

The details of every seal and treatment with diluted emulsion are stored by kilometer distance, with a code indicating the type of seal. This information is extremely useful at the project level to assess the performance of the past seals and the likelihood of good or bad performance of future seals. It is also fairly useful in the identification of rehabilitation projects as the excessive costs of placing seals with short lives can also be used to justify rehabilitation actions.

No work has been done yet at the network level to assess the lifespan of different types of seals and their cost-effectiveness, but such an analysis is being contemplated in the medium term.

Annual Visual Evaluations

In the early stages of implementation, all project identification and prioritization was based on the visual evaluations. Initially, visual evaluations were only carried out on parts of the network, but since 1985 this has been expanded to include all roads, every year. The form used for the visual evaluations is shown in Figure 1 and the procedures used have largely been standardized throughout all rural road authorities in South Africa (*3*).

Visual evaluations were initially carried out on a link basis, where a *link* is defined as a road section between intersecting roads. Some of the links were as short as a few hundred meters while others were up to 50 km long.

The degree and extent of 21 different distress types were noted and used to show the overall visual condition of the link. This entails the calculation of a visual condition index (VCI) by weighting and combining the attributes of distress. The evaluation data are also used to calculate several other indices to identify possible resealing projects and to determine the repair measure that would be likely to improve the road condition.

Some problems were experienced in that long links would be shown to have erroneous conditions, because distress might only occur in isolated areas. The inspection links were subsequently redefined and long links were subdivided into two or more segments if the overall link length exceeded 7.5 km. This has largely eliminated the above-mentioned problems. However, it is felt that the visual inspection procedure may now include several unnecessary details and too many types of distress. For example, recording the extent of some of the distress types may be irrelevant on such short links as it invariably occurs over the entire link.

The inspections are carried out by consultants and are paid for on a kilometer basis. Each consultant is allocated a region and some inspections across the boundaries of regions are carried out to compare the results of the different inspectors and to ensure uniformity.

Riding Qualities

Riding quality measurements are carried out using a linear displacement integrator (LDI). This is a device similar to a Mays meter mounted in a vehicle that measures the displacement between the rear axle and the vehicle body. The results are converted to present serviceability index (PSI) and the latter value is stored per 100-m length of road on the database. Measurements are currently carried out by in-house personnel and a cycle time of approximately 3 years is aimed for.

In retrospect, it is generally felt that it would be preferable to have annual riding quality measurements, particularly on the more heavily trafficked roads and on roads that are nearing the end of their lives and where the riding quality is deteriorating fairly rapidly. The cost associated with this work would, however, be fairly significant. Furthermore, although significant effort was put into the establishment of several calibration sections and the LDIs are calibrated on these sections regularly, organizational problems led to a delay in the resurvey of the calibration sections with a result that all of the more recent riding quality measurements differ fairly significantly from those measurements made prior to the resurvey. Some adjustment of the measurements taken immediately prior to the resurvey are being considered.

The riding quality measurements are used, together with vehicle operating cost functions, to identify possible rehabilitation projects on a network level. They are also used at the project level to assess past performance and whether strengthening and smoothing of the road is required, and to justify these improvements in economic evaluations.

Procedures

Apart from the normal data collection and storage procedures, several further procedures are carried out annually to identify problems, define projects for solving these problems and prioritize them, and to produce overall net-

TPA ROADS BRANCH
DIRECTORATE MATERIALS
NETWORK PAVEMENT EVALUATION

FORM LM3
11/91

ROAD NUMBER	: 836		RECORDER	:JdW
SECTION	: P3/5	-KMPOST	DATE	:28-01-93
KM	: 14.40 - 20.00		KM PROBLEMS	:| Y | N | N
REGION	: WEST-TRANSVAAL			| SUBSIDY | HOMELAND | URBAN |
DISTRICT	: KLERKSDORP	GEK. VERKEER : 619	AVE ROAD WIDTH	:7.4 (m)
CLIMATE	:	ROUTE NO. :	TERRAIN	:R

SURFACING

TYPE 13/6

F1	TEXTURE	~~VARYING~~	1: FINE	2: ~~F~~-M	3: MEDIUM	4: M-C	5: COARSE
F2	VOIDS	~~VARYING~~	1: NONE	2: ~~N~~-F	3: FEW	4: F-M	5: MANY

SURFACING DEFECTS			DEGREE (SMALL) 1	2	3	4	(SEVERE) 5	EXTENT (RARE) 1	2	3	4	(MANY) 5
SURFACING FAILURE/PATCHING	F3	~~0~~										
SURFACING CRACKS	F4	~~0~~										
STONE LOSS	F5	0			X					X		
BINDER: DRY/BRITTLE	F6	0			X							X
BLEEDING	F7	0			X			X				

STRUCTURE

				DEGREE (SMALL) 1	2	3	4	(SEVERE) 5	EXTENT (RARE) 1	2	3	4	(MANY) 5
CRACKS													
BLOCK	N M L	F8	~~0~~										
LONGITUDINAL/SLIP	~~N~~ M L	F9	0			X					X		
TRANSVERSE		F10	0			X			X				
CROCODILE		F11	0			X				X			
PUMPING		F12	~~0~~	1	2	3	4	5	1	2	3	4	5
DEFORMATION				1	2	3	4	5	1	2	3	4	5
RUTTING		F13	0			X				X			
UNDULATION/SETTLEMENT		F14	0	X						X			
PATCHING		F15	0	1	2	~~3~~	4	5	~~1~~	2	3	4	5
		OCCURANCE		STRUCTURES		VALLEYS		GRADIENTS		CUTTINGS		GENERAL	
FAILURES/POTHOLES		F16	0	1	2	~~3~~	4	5	~~1~~	2	3	4	5
		OCCURANCE		STRUCTURES		VALLEYS		GRADIENTS		CUTTINGS		GENERAL	
EDGE BREAKING		F17	0	1	2	~~3~~	4	5	1	2	~~3~~	4	5

FUNCTIONAL EVALUATION

RIDING QUALITY	F18	0: VERY GOOD	1: GOOD	~~2~~: FAIR	3: POOR	4: VERY POOR	
	PROBLEM		POTHOLES	~~PATCHING~~	~~UNDULATION~~	CORRUGATION	
SKID RESISTANCE	F19	0: VERY GOOD	1: GOOD	~~2~~: FAIR	3: POOR	4: VERY POOR	
	PROBLEM				BLEEDING	~~POLISHED~~	
SURFACE DRAINAGE	F20	0: ADEQUATE	~~2~~: WARNING	4: INADEQUATE			
	PROBLEM		ALIGNMENT	SHOULDERS	RUTTING		
SHOULDERS	F21	0: SAFE	~~2~~: WARNING	4: UNSAFE			
	PROBLEM	ERODED	~~FROSTING~~	~~TOO HIGH~~	NARROW	STEEP	O. GROWN / L. GRAVEL

SUMMARY

TYPE OF ATTENTION NEEDED	0: NONE	1: ROUTINE			2: ~~RESEAL~~			3: STRUCTURE		
PRIORITY		C	B	A	~~C~~	B	A	C	B	A
GENERAL PAVEMENT CONDITION	0: VERY GOOD	1: GOOD	2: FAIR	3: ~~POOR~~	4: VERY POOR					

FIGURE 1 Visual inspection form.

work conditions statistics with time. These procedures are described in more detail in the following subsections.

Visual Condition Index

A VCI is computed from all of the defects identified during visual inspections. The formula for the condition index is as follows:

$$\mathrm{VCI} = 100(1 - C * F_n)$$

where

$F_n = (D_n \times E_n \times W_n)$,
$C = 1/F_{n\max}$,
VCI = visual condition index,
D_n = degree of defect n,
E_n = extent of defect n,
W_n = weight of defect n, and
$F_{n\max} = F_n$, where degree and extent of each defect are set to the maximum possible value.

Each defect is weighted and the combined index attempts to provide an overall rating of the road condition in general terms. Various index limits have been established for different condition categories and the all road segments are grouped into these categories and their condition reported as very good, good, fair, poor, or very poor. Three other condition indexes, namely, a functional index, a structural index, and a resealing index, are also computed using different weights and selected defects. These indexes are used to identify problems reflected by the name of the index.

Printouts are produced in order of descending visual condition category and statistics in respect of the distribution of condition per region and per road class are produced annually to assess the trend of the network condition with time and to identify areas with greater rehabilitation needs. An example of the overall deterioration of condition with time for the Transvaal road network is shown in Figure 2.

The overall statistics of network condition have been extremely useful for assessing the trend in the network condition over time. Some minor problems were experienced when small changes were made to the visual evaluation procedures and when the formula for the index was modified. These adjustments normally resulted in changes in the network condition statistics and resulted in some conflicting statistics over time, which were difficult to justify to decision makers. However, the statistics have proved to be extremely valuable when informing political decision makers of the need for funds for road rehabilitation. It is of interest to note that the road network deterioration rate has been very gradual in spite of the fact that only very few roads are rehabilitated annually. Many pavements are exceeding their design lives significantly, which

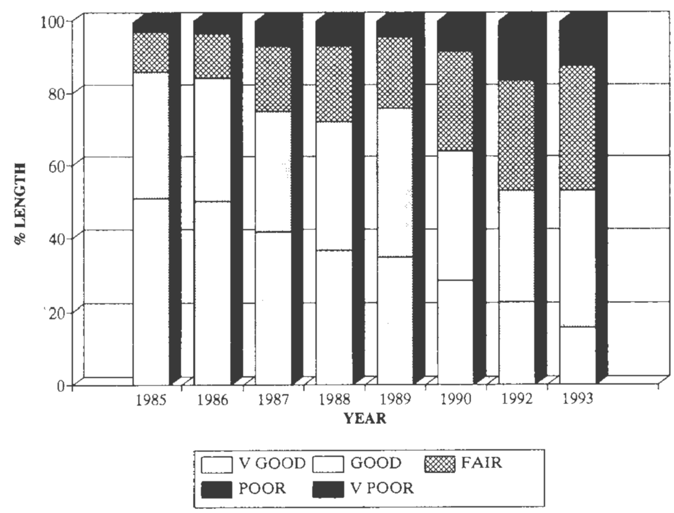

FIGURE 2 Transvaal network condition statistics.

attests to the benefits of timely routine maintenance and periodic resealing.

A further problem with this approach is the question of whether the general condition of a road can adequately be described by a single index. There are so many different defects resulting in loss of condition and so many different causes and remedial actions that it is doubtful whether these can all be reflected in a single condition index. Nevertheless, the resulting condition categories have been calibrated repeatedly with panel inspections, and they do provide a very good indicator of overall network condition and trends. The use of a single condition index in problem identification and prioritization, however, would appear to be somewhat limited. To a certain extent this is overcome by utilizing other indexes and algorithms as indicated above.

Repair Algorithm

An algorithm has been produced to provide an initial indication of the repair measure that is likely to be required for each individual road to improve its condition. These measures include the following:

- Diluted emulsion,
- Reseal using conventional binders,
- Slurry seal, and
- Reseal with modified binders such as bitumen-rubber.

The algorithm is fairly detailed and is extremely useful for estimating the likely resealing action required. However, it will be noted that the algorithm does not identify rehabilitation projects, and these are normally identified during panel inspections on the problem roads, and more recently using vehicle operating cost models as described below.

Problem List

After all the visual evaluations in a particular year have been carried out, all the various indexes are computed and a list of road segments is prepared by descending visual condition category and, within each category, by road number and kilometer distance. The list also shows the likely resealing measure required to address the problem, computed using the above-mentioned algorithm.

Panel Inspection

Inspections are carried out annually on all roads on which problems are identified by the above procedures and that are not already included on a current resealing program.

Staff from the Materials Directorate and the region normally carry out the inspection. The priority of each reseal and the type of reseal is normally selected during these inspections by the panel, with the regional staff attempting to maximize their allocation and the Materials Directorate attempting to ensure uniformity across the regions.

The reseal program is drawn up after these inspections and the projects are sorted in order of descending priority for the entire province. The total resealing budget allocation then determines the cutoff point on the list, and all projects above the cutoff are carried out.

In the early stages of implementation this procedure produced satisfactory results. However, as funds have dwindled and as road conditions have deteriorated, the procedure has led to a "worst first" approach, and the application of expensive seals with modified binders on roads in a poor condition, where some form of rehabilitation may have been more cost-effective. In addition, as competition for the available funds becomes fiercer, it becomes more and more difficult to ensure reasonable uniformity between the regions, particularly as the Materials Directorate's staff involved are less senior than the regional engineers.

Rehabilitation

Most rehabilitation projects were initially identified during panel inspections and were added to the overall list of capital projects for the province. However, funds have diminished to the extent that none of these projects are being carried out. This has led to a significant rethinking of the present maintenance and resealing policies with the following inputs from the various management systems:

1. All resealing funds were being concentrated on poorer roads and more expensive types of seals were being applied, of which many were ineffective;
2. The condition of the surfaced road network is deteriorating steadily while other service levels such as capacity are not deteriorating as rapidly;
3. The condition statistics of the primary, secondary, and tertiary road networks are similar;
4. The gravel road network is roughly equal in length to the surfaced road network but only carries 7 percent of the total vehicle-kilometers. It absorbs a major portion of the overall maintenance budget and such expenditure could probably be reduced without a major effect on user costs;
5. Currently, roughly 10 percent of the surfaced road network is in a very poor condition and repairing these roads for a 20-year design life could significantly exceed the budget expectations over the next 5 years;
6. The maximum realistic long-term budget amount for rehabilitation will only allow an average rehabilitation cost of R200,000 ($60,000)/km if all current and accruing problems on the network are to be attended to over the next 5 years.

Although the TPA PMS does not currently include any sophisticated predictive models for evaluating future rehabilitation strategies subject to budget constraints, a few simple calculations based on the current network condition and trends, likely budget allocations, and possible rehabilitation alternatives within the limits of the likely budgets, indicate a need for a review of current resealing and rehabilitation policies and also the need for a revised strategy to limit network deterioration. Detailed predictive models may assist in optimizing this strategy but until these are available, a strategy that concentrates on retaining the condition of good roads while at the same time attempting to improve the condition of the more important roads which are in a poor condition, at minimum cost, is likely to go a long way toward arresting network deterioration.

The above considerations have led to the adoption of the following strategy for road rehabilitation over the medium term.

1. Prioritize the work by classifying the road network into primary, secondary, and tertiary, depending on the importance of the road, and by aiming at achieving higher levels of service on the more important roads than on the less important roads;
2. View resealing and light rehabilitation as maintenance and increase the total funds for this work by reducing maintenance expenditure on gravel roads and by reducing the costs of some capital works by scaling down of standards;
3. Carry out preventive resealing on all roads which are currently in a good to fair condition in order to retain these conditions on these roads. The amount allocated for this work will allow for inexpensive reseals at roughly 10-year intervals on these roads. Carry out this work based on the results of the panel inspections, but prioritized per region;

4. Divide the total resealing and rehabilitation funds between the regions in proportion to the blacktopped area within each region, with some adjustments for road type and climate. This effectively eliminates manipulation of the reseal funds between regions. Some inter-regional transfers can be considered depending on road network conditions;

5. Commission consultants to evaluate roads in the primary network that are in poor and very poor condition and to come forward with rehabilitation designs with a 10-year life and with a limit on the average cost per kilometer of all rehabilitation actions. Alternative designs for a longer period are considered in exceptional circumstances.

6. Use all funds remaining from the increased allocation, after deducting the amount required for preventive resealing, for this work;

7. Carry out heavier rehabilitation on selected primary roads only;

8. Abandon less important tertiary roads in a poor condition if funding constraints become more severe.

In addition to the above, a further algorithm is used to evaluate roads on which rehabilitation is likely to be economically justified in view of the user benefits that would accrue from reducing the roughness of the road. The algorithm uses the latest roughness measurement on the road, and the traffic volume, in a vehicle operating cost model to compute the likely vehicle operating cost saving resulting from rehabilitation. In addition, the algorithm also adds the annual routine maintenance cost and the equivalent annual cost of the most recent reseal measure to the above vehicle operating costs to compute the total likely annual savings that will accrue from the rehabilitation project. A printout showing all roads where these costs exceed a selected cutoff value is produced for use in the evaluation of rehabilitation projects.

The use of the system and current problems have highlighted the need for more objective mechanical measurements in addition to the current visual evaluations. In particular, the need for reasonable predictive models that can show expected network conditions subject to various rehabilitation strategies and budget allocations has been highlighted. Significant work in this respect is being contemplated in the near future using computer programs such as HDM-III and the current database to develop predictive models and rehabilitation strategies.

Conclusions

Several lessons have been learned from the implementation of the PMS in the Transvaal that could be of use to other agencies in evaluating the implementation of their systems.

1. The road network should be divided into reasonably uniform links which are clearly marked in the field and which facilitate obtaining historical data. When the links have been established, efforts must be focused on keeping them constant and avoiding unnecessary changes to road numbers and kilometer distances.

2. The importance of good riding quality measurements can never be emphasized enough and calibration requirements should be reviewed annually.

3. Visual evaluations are a valuable tool for identifying roads in a poor condition and for assessing the condition of the road network over time. Visual evaluations are also a valuable tool for assessing resealing needs, but rehabilitation needs should be assessed in the context of road functional classification, overall budget allocations, network condition trends, economic evaluations, and a viable rehabilitation strategy.

4. Funds should not be allocated for resealing and rehabilitation based on pavement condition only as this will focus attention on the poor parts of the road network to the detriment of the roads which are in good condition. This is particularly relevant when the available funds are severely curtailed.

5. If a regional road network is large enough, fund allocation for road maintenance and light rehabilitation between the regions can be based on network length as it is likely that each region will have an adequate spread of road conditions to use the funds effectively and various strategies can be adopted within each region to eventually achieve reasonably equitable conditions over time.

6. If funds become extremely severely curtailed an optimal policy will probably entail the abandonment of some roads.

7. A 10-year design life for rehabilitation options is probably the most cost-effective method of extending the life of the network in the light of current budget constraints. Over time, however, it is expected that road conditions will again deteriorate and eventually more funds will be required or parts of the network abandoned.

8. Reasonable performance models and optimization systems are required to show likely future network trends subject to budget constraints and to enable decision makers to take early actions where required. The models should however be credible and should produce results that are consistent with actual performance.

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ANALYSIS

Development of United Kingdom Pavement Management System

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The United Kingdom Pavement Management System (UKPMS) is a computer system currently being designed for the economic management of the structural maintenance budget of a road network. It is being promoted and funded by most highway authorities in the United Kingdom, representing owners of all classes of roads, from congested city streets to narrow rural roads. It will incorporate a new system of visual data collection, data analysis, and budget allocation for all paved areas within the highway boundary and will combine data from different types of condition surveys. Other significant features include the ability to project condition data into the future; this enables the user to take account of the economics of alternative maintenance treatments when deciding where and what treatments should occur. Because the economics of alternative maintenance strategies are considered, UKPMS is, in essence, prioritizing the solutions to structural road maintenance rather than, as many systems do, prioritizing the problems. To test the innovative principles of UKPMS, and to test the new data collection techniques, prototype software has been written. It is being used by highway maintenance practitioners themselves during the current design stage. The core philosophy of UKPMS is to defer treatments where it is cost-effective and safe to do so and to give priority instead to preventive maintenance.

There are more than 360 000 km of road in the United Kingdom, of which about 270 000 km are in England. The most heavily trafficked routes in England—the national roads—are looked after by the Department of Transport (DoT). The national road network includes about 2000 km of superhighways and some 8000 km of all-purpose trunk roads. Although they represent only 4 percent of the network, the national roads carry about 30 percent of all traffic and about 55 percent of heavy goods vehicle (HGV) traffic.

The remainder of the network in England—the local roads—is the responsibility of the local highway authorities: the county councils and metropolitan councils. Together they look after nearly 260 000 km of roads, which vary from small, lightly trafficked country lanes to densely trafficked urban routes.

Central and local governments spend a significant amount of money each year on the maintenance and management of the road network. The following table presents the level of road maintenance expenditure in England in 1991–1992:

	Expenditure (£ millions)	
Maintenance Type	*National Roads*	*Local Roads*
Structural	400	480
Routine (cyclic) and winter	160	320

Pavement Management Before UKPMS

To control expenditure and ensure the best value for money, highway authorities have designed various systems for maintenance management. For example, the DoT has introduced a management system for the routine (cyclic) maintenance of the national roads in England. It enables inventory data—road, footpath, and shoulder width and type; drainage provision; road markings; and so on—to be collected using hand-held computers and subsequently transferred for processing onto mainframe or personal computers.

However, the need for structural, or noncyclic, maintenance on British roads is assessed by highway authorities in different ways. For example, the DoT uses a two-level system. The first level—a coarse assessment—is carried out using the High-Speed Road Monitor (HRM). The HRM, developed by the Transport Research Laboratory (TRL), makes use of contactless laser technology to measure, among other things, longitudinal profile and permanent deformation (rutting) of the road surface. These measurements are taken at up to 80 km/hr and are recorded automatically for later computer analysis. The entire national trunk road network is covered by one machine every 2 years, without inconvenience to the road user. The HRM provides a quick and relatively inexpensive method of assessing the serviceability of the national road network.

The second level of assessment—the detailed assessment—is carried out at the time of scheme design using a combination of machine measurement and visual assessment. The machine surveys are carried out using the deflectograph, which measures the transient deflection of pavements under a known wheel load. It is used both to assess the structural condition of the pavement in terms of the residual life and to provide information for use in the design of strengthening treatments.

Visual assessment methods are also used to record defects. Measurements of the surface condition are recorded using hand-held computers and automatically analyzed to provide needs-led priorities and recommendations for treatment.

A Sideways-Force Coefficient Routine Investigation Machine (SCRIM), which travels at 50 km/hr, is used to measure the wet skidding resistance of the road surface; it covers the national road network on a 3-year cycle.

As good as all the current systems are, they produce data sets that are not coordinated. All the systems are separate; they are related, for the department's roads, by a common referencing system, but data are not combined in any way. An engineer may be faced with several survey results for the same section of road; some in paper form, some computerized. Deciding on priorities in these circumstances is difficult.

A particular problem for local highway authorities arises because not all the survey methods are relevant to all classes of road. A county with an extensive rural network may not wish to use expensive laser technology; similarly, techniques used on these roads may not be relevant to an authority with a large urban network with many service provider openings, such as those for water and electricity supply, in the highway.

Pavement Management with UKPMS

History of Project

The Local Authority Associations (LAA) and the DoT established a joint initiative in the mid-1980s to consider a new pavement management system (PMS) that would replace the various existing methods of visual road condition assessment and be able to combine this visual data with machine-based assessments. But it was important that any PMS should manage the maintenance of all roads: from heavily trafficked trunk roads to little used local roads, both in towns and on interurban routes. In short, the need was for a national PMS, now known as UKPMS.

The total project is being managed in three stages. Stage 1 was a feasibility/design study that established draft user requirements and delivered to sponsors a preliminary design for a UKPMS. It concluded that there were significant benefits to be gained by taking UKPMS forward.

All parties therefore decided to proceed with a full-scale system design and prototype testing program—Stage 2. Fifty percent of funding is provided by DoT, and the rest by 91 local authority sponsors from England, Scotland and Wales, and the Department of the Environment for Northern Ireland. A contract was established in July 1990 with the aim of producing a logical design for UKPMS together with the testing of prototype software; a logical design being a machine- and data base–independent specification of a computer system.

The final stage of the project, Stage 3—the implementation of UKPMS by each sponsoring highway authority—is being discussed and planned; it will begin in 1994.

Brief Description of System

An engineering view of the structure of UKPMS is shown in Figure 1. It is recognized that UKPMS must protect investment already made in data by the various highway authorities. Standard format interfaces have therefore been specified to enable links to be made to existing systems.

UKPMS is being designed to enable highway authorities to

- Monitor the condition of the existing road network,
- Formulate options for maintenance treatments,

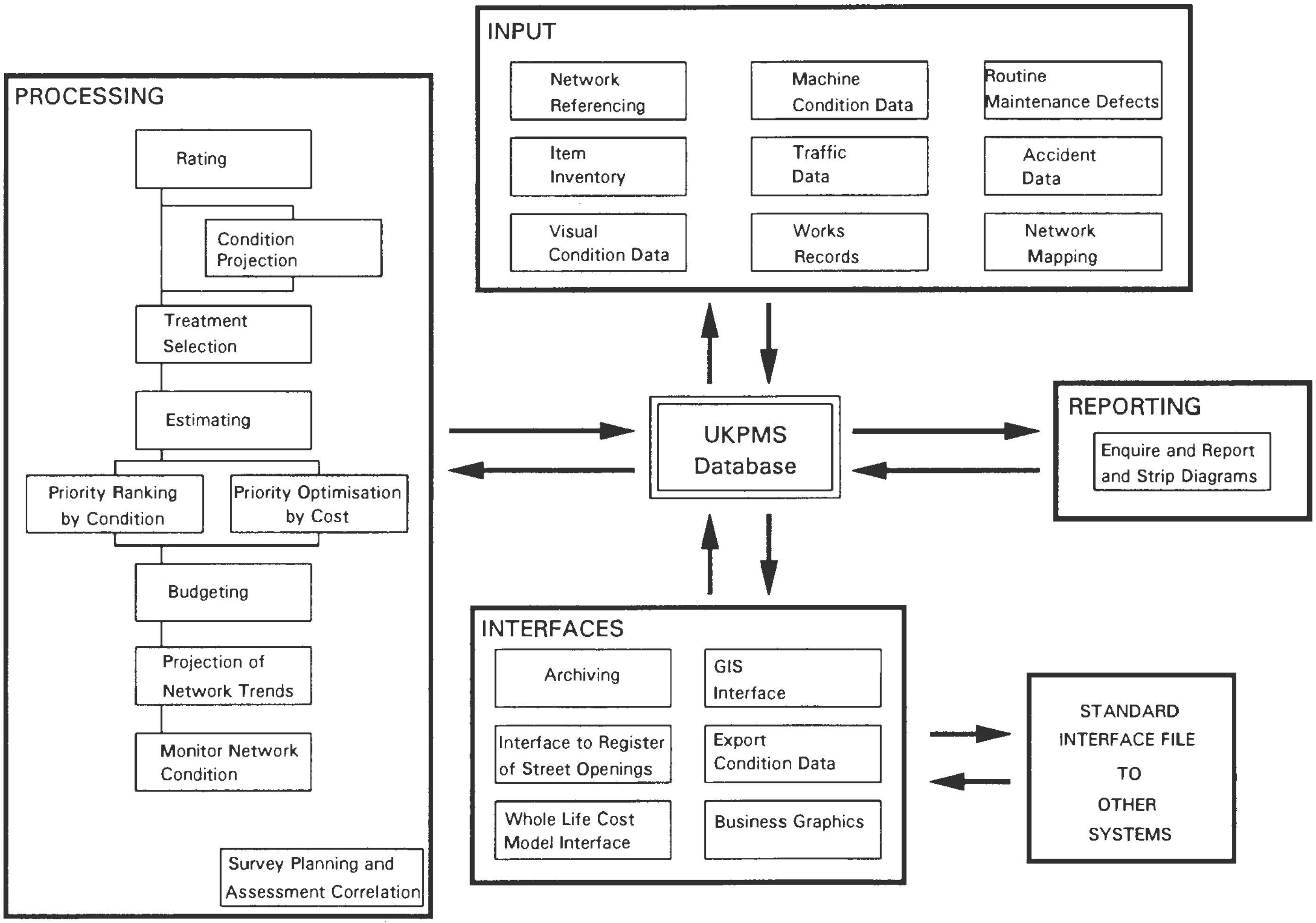

FIGURE 1 Engineering view of UKPMS.

- Manage maintenance priorities, and
- Allocate limited resources on the basis of best value for the money.

It will introduce significant innovations, which include

- A common auditable approach to road assessment nationwide, based on both condition and economic priorities;
- A flexible approach capable of use in all types of highway authority and on all paved areas on all types of road; and
- Cost-effective methods of data collection.

The remainder of this paper discusses in more detail some of the innovative aspects of the system:

- The ability to tailor condition surveys to the needs of a highway authority,
- Network analysis and the creation of schemes,
- Projection of condition data; and
- Priority optimization by cost—that is, economic ranking.

Collection of Condition Data

Condition data used by UKPMS can be described as collection by visual or manual methods or by machine or automatic methods.

Four new visual inspection systems have been designed to take account of both the strengths and weaknesses of current visual inspection systems currently in use in the United Kingdom:

- Annual engineering inspection (AEI),
- Coarse visual inspection (CVI),
- Aggregated visual inspection (AVI), and
- Detailed visual inspection (DVI).

The AEI is essentially a windshield survey to give a rough estimate of pavement condition. The output is aimed at planning further surveys. Both AVI and DVI are detailed surveys carried out on foot.

Machine inspections that UKPMS can use are

- HRM,
- Deflectograph,

- SCRIM to measure wet skidding resistance, and
- Any other machine data whose output can match that of those just given.

The user can pick and choose which survey to use for particular types of road. On a rural network only a coarse visual inspection may be necessary to formulate maintenance schemes. On extensive super highway networks, all the various detailed surveys may eventually be needed; UKPMS can accommodate these extremes and all other situations in between. This graded approach ensures that the demands for data and analysis are kept in proportion to the cost of the works.

Network Analysis and Scheme Creation

General

The highway maintenance engineer, so as to decide the right treatment, strives to ensure that the right amount of data are gathered at the right time. To help this, the operation of UKPMS falls into two distinct passes. The first is the automatic pass, where UKPMS will process data for the entire network automatically to provide a coarse ranking of maintenance schemes for final design or to identify those schemes warranting more detailed investigation before final design is carried out. The maintenance engineer uses the second pass—the interactive pass—with the results of the automatic pass, and other data available within UKPMS, to combine defective lengths of the network to produce maintenance schemes and undertakes the detailed design of the works.

Automatic Pass

The automatic pass is intended to analyze the entire network, or convenient subsets of it, to determine priorities for investment in maintenance works. The central processing functions of UKPMS work as follows:

1. Sections of road are split into lengths of uniform defectiveness known as "defect lengths," which are defined as lengths of a feature (roads, sidewalks etc.) in a single cross-sectional position (e.g., lane) in uniform condition.
2. Defect lengths are rated on a scale of 0 to 100, where
   –0 is "good," or where further improvement would not be of any significance, and
   –100 is "bad," or where further deterioration would not be of any significance.
3. Defect ratings are combined into condition indexes (CIs); those used in UKPMS are
   –Surface,
   –Structure,
   –Edge (bituminous surfaces only),
   –Joint (concrete surfaces only), and
   –Overall.
4. To allow condition assessment to use up-to-date information, the condition is projected on a time basis, to the current date.
5. CIs are input into algorithms to produce treatments for each defect length.
6. Cost estimates are produced by multiplying estimated treatment quantities by unit rates.
7. Priority indexes are produced by comparing CIs with user-defined thresholds. Highest priority is given to those indexes exceeding the thresholds by the greatest amount.
8. Budgets are prepared for treatments under user-specified budget heads.

As a result of extensive research carried out at TRL, rules and parameters have been identified and tested. The starting point of the research was to identify the level of defect that would trigger a change in treatment. Figure 2 shows, for a selection of flexible pavement defects, the level of measured defect required to trigger a particular treatment, together with an example of defects that work in combination to cause particular treatments to be triggered. Defect ratings for a selection of bituminous defects are given in Table 1. (In Table 1, residual life is the number of years until the road becomes critical and requires major strengthening by overlaying; it is calculated from pavement deflections measured by deflectograph and from past and future traffic loading. Whole carriageway major cracking is wide single cracking greater than or equal to 2 mm or multiple cracking and coarse crazing. Wheeltrack rutting is the depression of the wearing surface in the vehicle wheelpaths relative to the rest of the wearing surface. Wheeltrack major cracking is wide single cracking greater than or equal to 2 mm or multiple cracking and coarse crazing occurring within the wheelpaths.)

CI rules define how the various rated defects are combined to give CI values that will identify the need for treatment. Within these rules, precise values of coefficients had to be specified to ensure that boundaries between treatments occur at particular measured defect values. For example, the structural CI for a flexible pavement is the highest rating of

$1.0 \times$ residual life

$0.95 \times$ WC major cracking

$0.5 \times$ residual life $+ 0.6 \times$ WC major cracking

$0.75 \times$ WT major cracking $+ 0.3 \times$ WT rutting

$0.3 \times$ WT major cracking $+ 0.75 \times$ WT rutting

or

$0.8 \times$ failed patching/reinstatement

where WC is whole carriageway and WT is wheeltrack.

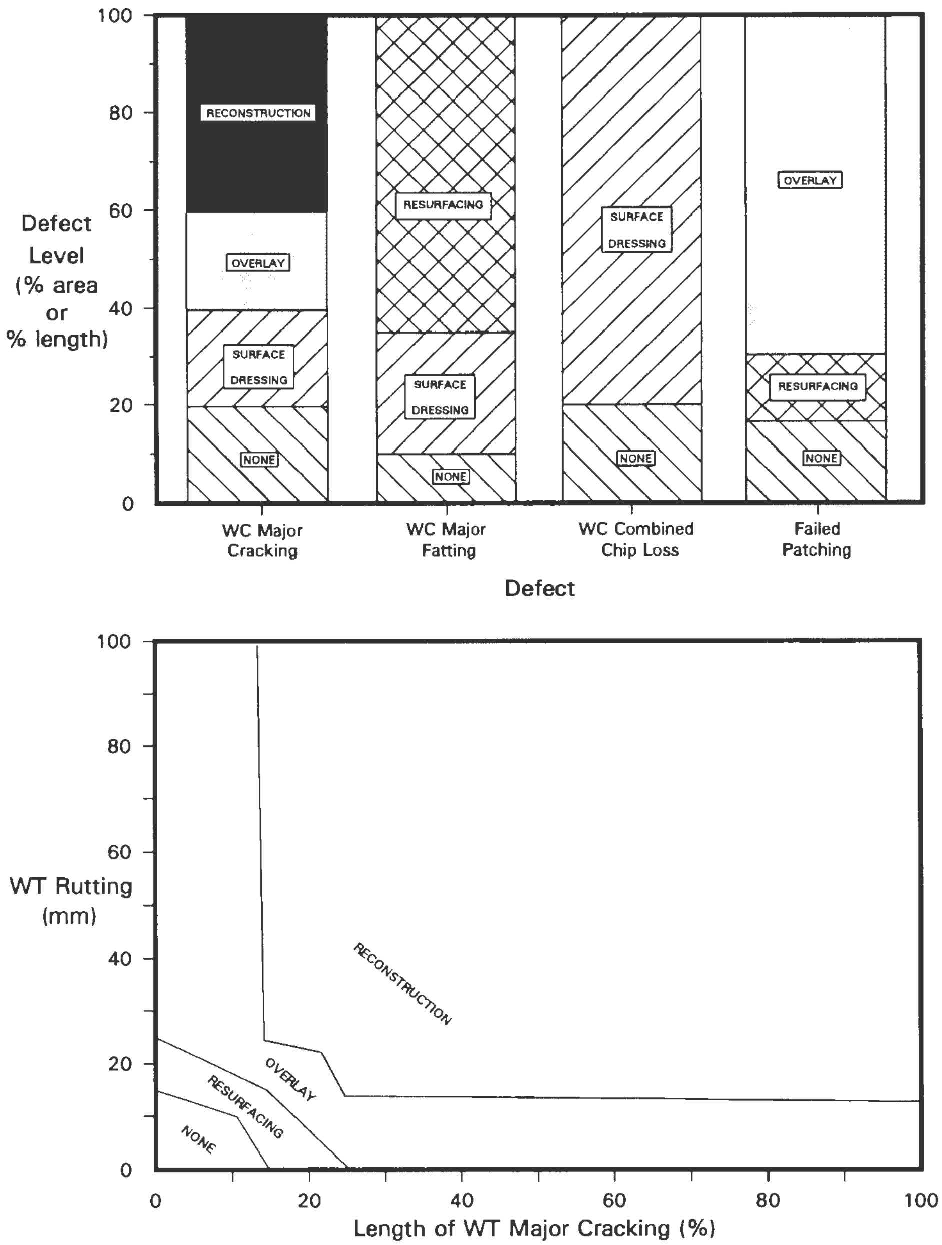

FIGURE 2 **Treatments required for levels of defects on flexible pavements.**

The automatic treatment selection procedure is controlled by sets of rules. Each rule, in a set, defines the values of various CIs—such as surface, structure, and edge—that will trigger a treatment. An example of a typical rule could be

When

Structural CI $\geq$ 70,

Surface CI $\geq$ 40, and

Edge CI $\geq$ 0,

Then treatment is strengthened by bituminous overlay.

However, within UKPMS, the rules use not CI values directly but numbered treatment selection thresholds (TSTs). Each TST rule comprises a set of CI values. These TSTs allow the condition of the road pavement to be compared with a set of CI values. One treatment is associated with each TST. The assignment of TST variables to rule sets within UKPMS is fixed, but the user assigns the CI values to each TST depending on road classification and type of pavement. The TST values proposed for flexible pavements in the DoT road network are shown in Table 2.

For each defect length the treatment selection process tests the CI values against each rule of the appropriate rule set, in turn, until the CI values satisfy a rule. The

TABLE 1 Defect Ratings for Flexible Pavements

Residual Life		Wheeltrack Major Cracking	
Mean Life Years	Rating	% Length	Rating
20	0	0	0
4	50	15	66.67
2	70	25	93.34
0	90	100	100
-10	100		
Whole Carriageway Major Cracking		**Wheeltrack Rutting**	
% Area	Rating	Depth (mm)	Rating
0	0	0	0
20	52.64	15	66.67
40	73.69	25	93.34
60	94.74	100	100
100	100		

treatment associated with that rule is then assigned to the defect length. The treatment selection rules proposed for DoT flexible pavements are given in Table 3.

As an example of how the automatic treatment selection process works, assume the condition of a length of road is

Structural CI = 78

Surface CI = 20

Edge CI = 40

Each rule in Table 3 is tested against these values.

- Rule 1 fails because the structural CI of 78 is less than the TST6 value of 90.
- Rule 2 fails because the edge CI value of 40 is less than the TST1 value of 50.
- Rule 3 passes the test, so the treatment of overlay is assigned to the defect length.

TABLE 2 Treatment Selection Thresholds for Flexible Pavements

Treatment Selection Threshold	Condition Index Value
TST0	0
TST1	50
TST2	40
TST3	70
TST4	90
TST5	80
TST6	90
TST11	90
TST12	80
TST13	70

Although it is possible to use raw defect data to trigger treatments, defects need to be rated so that network condition can be monitored and network trend analyses carried out.

It should be noted that within UKPMS, as well as the definitions of all defects, all the calculations concerned with combining and rating defects, and indeed the CIs themselves, are parameterized. Consequently, any new or different defect or new machine collecting techniques can easily be incorporated into the system. This has been adopted throughout the design of UKPMS to ensure maximum flexibility.

Interactive Pass

It is recognized that the rules embedded in the automatic pass—for example, those for treatment selection—will not match the skill and knowledge of an experienced engineer. The engineer can refine the allocation of the available budget and the details of treatments to be applied using the interactive pass. The interactive pass uses the same processing as the automatic pass, but the user "steps through" the modules and progressively builds up treatments and schemes for possible implementation within next year's allocated budget. It is intended that the priority list of treatments identified in the automatic pass forms the basis of the detailed analyses in the interactive pass, but the user is free to select the schemes to be evaluated and can choose to evaluate the entire network on this basis. When working interactively, the user may access other data held in UKPMS, such as

- Network section data (e.g., length),
- Inventory (e.g., width, surface type),
- Traffic data (e.g., daily flow),
- Accident data (type and number),
- Condition surveys (e.g., raw condition data),
- Results of automatic processing, and
- Construction and maintenance records.

From this information, the user can then define

- Treatment lengths (i.e., lengths over which the treatment is constant and that typically span several of the defect lengths produced by automatic processing),
- Treatment length options (i.e., treatments that could be applied to cure some or all defects within a treatment length), and
- Schemes and scheme options, which typically comprise several treatment length options.

As treatment lengths options and scheme options are created, their priority indexes are calculated (see next section).

TABLE 3 Treatment Selection Rules for DoT Flexible Pavements

Rule Number	TSTs Structural	Surface	Edge	Treatment
1	≥ 6	Any	Any	Reconstruction
2	≥ 3	Any	≥ 1	Edge reconstruction + Overlay
3	≥ 3	Any	< 1	Overlay
4	≥ 1	Any	≥ 1	Edge Reconstruction + Overlay
5	≥ 1	Any	< 1	Resurface by Inlay
6	< 1	≥ 1	≥ 1	Edge Reconstruction + Overlay
7	< 1	≥ 1	< 1	Resurface by Inlay
8	< 1	≥ 2	≥ 1	Edge Reconstruction + S Dress
9	< 1	≥ 2	< 1	Surface Dress
10	< 1	< 2	≥ 1	Edge Reconstruction
11	< 1	< 2	< 1	None

Note: from Table 2, TST1 = 50; TST2 = 40; TST3 = 70; TST6 = 90

Projection of Condition and Priority Ranking

UKPMS can be classed as a third-generation PMS when compared with the more common first-generation systems currently in use in the United Kingdom. (Second-generation systems include basic facilities that enable conditions to be projected so that trend analyses can be carried out.) The important third-generation facility is the ability to carry out optimization of multiple options of treatments for all sections of the network for the budget in the treatment year. This ability to maximize economic benefit under conditions of budget constraint is included within UKPMS. This facility is of particular interest to the DoT because, in the analysis of cost implications for future years, it has been shown to give rise to substantial benefits.

Priority optimization is a method of setting priorities for maintenance expenditures, when budgets are constrained, by minimizing the longer-term costs. In other words, the method requires that in addition to considering the cost implications this year, the implications for future years must also be taken into account. This is a fundamentally different approach to that adopted by many other systems that react to current conditions, rather than looking at the consequences of likely changes in conditions and, therefore, costs with and without treatment.

Condition Projection

For priority optimization to work, the system must have the ability to project pavement condition into the future. This gives immediate benefits, since treatments are not normally undertaken until at least 1 year after condition surveys are carried out, given the time required for relative prioritization and establishing funding. Whereas many systems determine next year's treatment on the basis of this year's condition, UKPMS determines next year's treatment on the basis of condition projected forward to next year from the current condition. This improves the basis for decision making, because decisions on treatments are based on conditions prevailing at the time the treatment is needed, rather than at the time of the assessment.

Prediction of pavement conditions is also required for longer periods into the future so that historical data can be projected forward and future trends in network condition estimated. UKPMS takes a pragmatic approach to this by using standard-shaped curves relating condition to time, which extend between (0,0) and (1,1) in two-dimensional space. The relationships are generalized using five constants (a, b, c, d, and k) to define the curve given by Equation 1.

$$y = k\left[a + (b - a) \times f\,\frac{(x - c)}{(d - c)}\right] \tag{1}$$

where

y = defectiveness,
x = time,
$y = a$ when $x \leq c$,
$y = b$ when $x \geq d$, and
k = 1 (in first implementation).

The relationship is shown diagrammatically in Figure 3.

Deterioration curves for a defect on a particular section of road are user-definable and are specified as a series of discrete points; intermediate values are determined auto-

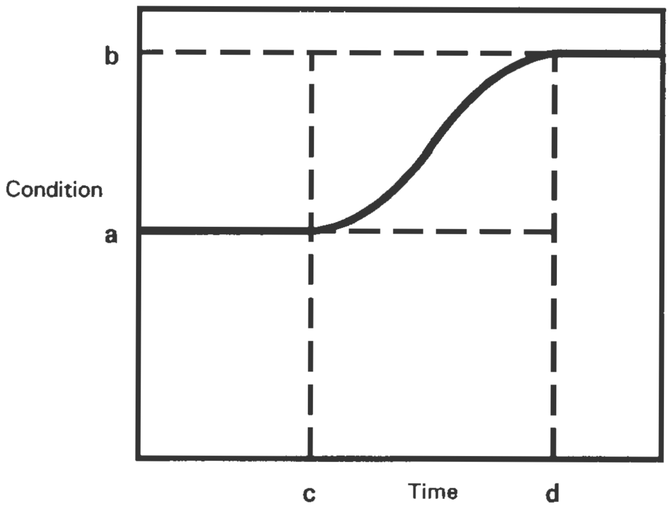

FIGURE 3 Generalized deterioration relationship.

matically by linear interpolation. Alternatively, default curves have been proposed for the first implementation of UKPMS, given that users may not have the data from which to define curves.

Selection of Deterioration Curves

As a result of a comprehensive research study carried out by TRL, the generalized curve form to most appropriately represent the long-term deterioration trend for each of the defects on each pavement construction type was derived in two stages

1. Deterioration trends exhibited by each of the defects were identified; and

2. A standard curve form was assigned to fit the observed trend. Standard curves include linear, exponential, quadratic, and S-shaped curves.

An extract from the catalog of curve types proposed for fully flexible DoT roads is shown in Table 4. (In Table 4, PCV is the proportional change in variance, which is the proportional difference over 2 years in the variance of the deviation from the 3-m moving average of the pavement's profile measured by the High-Speed Road Monitor. WT major tracking is as defined for Table 1. Whole carriageway major fretting is loss of material other than chippings from the wearing surface to the degree that the original wearing surface is no longer discernible. Whole carriageway minor fretting is loss of material other than chippings from the wearing surface although the original wearing surface remains discernible.)

Once the choice of curve function has been made, its shape can be changed by altering the values of *a, b, c,* and *d.* For skid resistance values, for example, *a* is greater than *b* so that the relationship gives decreasing values over time.

To predict future values of defects, it is necessary to fit the curves to existing measurements of condition. For the curves to fit current condition data measurements, they are shifted along the time axis to pass through the current value. Where historical data exist, curves are stretched or shrunk along the time axis to give the best fit to past data but weighted to give more emphasis to recent data.

A comprehensive sensitivity analysis has also been carried out that shows that the projection of defects, for up to about 4 years, is not sensitive to small differences in definition of the base curve. It is considered that reasonable projections can be obtained over the limited number of years necessary for priority optimization to operate.

TABLE 4 Selection of Pavement Deterioration Forms

Carriageway Defect	Measurement Units	Curve Form	Maximum Defect Limit	Duration (Years)	
				Start	Finish
WT Rutting	mm	Cubic	100 mm	0	40
WT Major Cracking	% Length	S-curve	100%	10	30
WC Major Fretting	% Area	S-curve	100%	10	30
WC Minor Fretting	% Area	S-curve	100%	6	20
PCV	%	Exponential	600%	2	40

Setting Priorities

Since maintenance budgets are normally constrained, choices must be made about which maintenance should be undertaken now and which should be deferred for another year or more. Current maintenance systems give priority to remedial measures on those roads in worst condition but do not help the choice between the more expensive treatments and their timing. However, it can be shown that such an approach inevitably leads to a backlog of work building up.

UKPMS can make recommendations with a view to minimizing future, or whole life costs. In particular, the following costs are included

- Future maintenance costs, and
- Costs to the road user: accidents and delay costs at times of maintenance.

Basing priorities on the principle of minimizing longer-term costs overcomes the problem of a backlog of work building up. This is the basis of priority optimization, which defers treatments where there is little immediate cost penalty of doing so. In essence, this gives more priority to preventive treatments, which are more cost-effective over time.

An approach to setting priorities in this way is to use a whole life cost model to determine the net present value (NPV) of each option by comparing the costs associated with carrying out the treatment, the do-something case, with those costs associated with doing either nothing or the minimum treatment possible, the do-nothing or do-minimum case. The option providing the highest NPV should be given priority.

When budget constraints apply, choice of schemes and treatments of schemes, in terms of highest NPV-to-works cost ratio, will ensure that the NPV is maximized within the constraints.

Within the context of UKPMS are several problem areas when applying the NPV test:

- There is a need to make traffic projections for long periods into the future to cover the whole of the evaluation period:
- Capacity problems are likely to occur on major roads if traffic continues to grow through the evaluation period; UKPMS would need a comprehensive traffic model when considering costs and benefits of capacity improvements on new routes.
- The identification of appropriate future maintenance treatment (and road user) costs relies on the projection of pavement condition, both in the do-something and the do-minimum cases, over the whole evaluation period.
- Decisions on future maintenance treatments—as is the case with all long-term evaluations—require assumptions to be made about their economic viability and about the availability of budget for their funding.

The DoT has developed a whole-life cost model, to be known as COMPARE, that addresses these issues, but its data requirements are such that it is inappropriate for use by the smaller highway authorities on their local roads. As a result, a different approach had to be sought.

The alternative method of priority optimization proposed for UKPMS is based on a technique developed during the UKPMS design study. A similar but simpler technique had been used by Rendel et al. (Department of Transport, unpublished document, 1989) in a project they had previously carried out in an overseas country. It involves determining priority rankings, which are based on the benefits derived in the first year of operation only, and on the annualized costs of the first and subsequent treatments. Annualized cost is the "equal annual cost which, when discounted and summed over the life of the treatment, is equivalent to the total cost of the treatment."

In this proposed simplified method, the ratio of NPV to cost, which would be the normal criterion for ranking schemes, is replaced by an economic indicator (EI). This is calculated for each treatment option by considering the costs resulting from carrying out a treatment now and those resulting from deferral of the treatment, as follows:

$$\mathrm{EI} = 100 \times \frac{(T_{\mathrm{dm}} - T_{\mathrm{ds}})}{C} \qquad (2)$$

where

T_{dm} = sum of total annualized costs resulting from deferring a treatment or doing a holding (minimum) treatment (do-minimum case);
T_{ds} = sum of total annualized costs resulting from carrying out a treatment now (do-something case); and
C = cost of do-something treatment minus cost of do-minimum treatment

Annualized costs are calculated for

- Pavement structural maintenance and/or surface maintenance, and
- Routine maintenance costs;

plus, if the user wishes,

- Cost of traffic delays during works, and
- Costs of increased accidents at roadworks.

The value of EI can be considered as a surrogate for the NPV-to-cost ratio; the larger its value, the higher the scheme is placed in the priority list. A negative value of EI indicates that the treatment cannot be justified on economic grounds.

Highest economic cost indicators arise for "doing something" when either

- A more expensive treatment will be needed next year if the treatment is deferred this year, or
- The treatment provides a longer-lasting solution than a minimum holding treatment with a relatively high cost and a short life.

An example of this approach is shown for the scheme in the following table:

Treatment Type	*Year*	*Life*	*Treatment*	*Cost (£ thousands)*
Do minimum	5	20	Reconstruct	27
Do something	0	15	Edge reconstruct	12
	1	8	Surface dress	0.35

The calculations to produce the economic indicator for this scheme are given in Equations 3 through 9, where Equations 3 through 6 show the calculations for the do-something case, Equations 7 and 8 show the calculations for the do-minimum case, and Equation 9 shows the final calculation necessary to produce the EI.

$$AC_1(\text{year } 0) = \frac{(12 \times 0.07)}{(1 - 1.07^{-15})} = 1.32 \tag{3}$$

$$AC_2(\text{year } 1) = \frac{(0.35 \times 0.07)}{(1 - 1.07^{-8})} = 0.059 \tag{4}$$

$$AC_2(\text{year } 0) = \frac{0.059}{1.07} = 0.055 \tag{5}$$

$$AC_{(1+2)} = 1.32 + 0.055 = 1.375 \tag{6}$$

$$AC_1(\text{year } 5) = \frac{(27 \times 0.07)}{(1 - 1.07^{-20})} = 2.55 \tag{7}$$

$$AC_1(\text{year } 0) = \frac{2.55}{1.07^5} = 1.82 \tag{8}$$

$$\text{EI} = 100 \times \frac{1.82 - 1.375}{12 - 0} = 3.7 \tag{9}$$

where AC is the annualized cost and AC_t (year y) is the annualized cost for treatment t in year y.

This approach requires the projection of pavement condition and traffic flow for a maximum of only 2 years beyond the present year. It is anticipated that it can therefore be used by maintenance engineers with greater confidence. In particular, it avoids the complications of considering future capacity limitations on roads when assessing maintenance works.

Benefits

Priority optimization within UKPMS will be provided to enable

- Treatments to be identified that provide a return greater than their cost,
- Most cost-effective treatments to be chosen from a range of possible treatments, and
- Priorities for investment to be determined under circumstances of budget constraint.

Analysis carried out as part of the UKPMS design study has demonstrated convincingly that the priority optimization method proposed leads to not only lower costs for highway authorities, but also improved road conditions over time. The DoT recognizes the significant benefits to be gained in adopting such an approach for determining priorities of maintenance schemes. The availability of priority optimization in UKPMS will enable all highway authorities to take advantage of its benefits.

Conclusions

In essence, the answer to one question will decide both the treatment and its timing. Will the treatment cost any more in real terms if it is delayed until the next year? If it will, and there is sufficient budget, program the work; if not, defer the scheme for 1 year. Under that principle, costly reconstruction schemes will no longer have an automatic first call on the maintenance budget. UKPMS will thus encourage funding of less expensive but more cost-effective treatments than systems that choose treatments on the basis of condition alone. The core philosophy of UKPMS is to defer treatment where it is cost-effective and safe to do so and give priority instead to preventive maintenance.

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Comparing Pavement Performance and Its Effect on Maintenance and Rehabilitation Cost

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Example pavement performance for different maintenance and rehabilitation (M&R) strategies is presented. The effect of the different performances on pavement life-cycle costing is also analyzed. A pavement network of 1.5 million yd^2 was used for illustration. Three M&R strategies were applied to the pavement sections in the network: structurally designed rehabilitation, thin overlay (1 to 2 in.), and thick overlay (3 to 4 in. with or without fabric). Three family curves were developed, one for each M&R strategy, from available data bases. These family deterioration curves were each assigned to the pavement network and a work plan was developed. The results illustrate the economic effect of asphalt overlays compared with structurally designed rehabilitation. The family curve and work planning techniques are procedures incorporated in the MicroPAVER pavement management system. These techniques are also discussed.

An essential component of any pavement management system is condition prediction. Before pavement maintenance strategies and repair budgets can be prepared or evaluated effectively, pavement managers must assess the current and future condition of their pavement network. This information is necessary for effective pavement management. Through years of research, the U.S. Army Construction Engineering Research Laboratory (USACERL) has developed the family curve technique as a method of predicting pavement condition accurately and determining the consequences of different maintenance and rehabilitation (M&R) budgets. The procedure is part of the MicroPAVER system developed by the U.S. Army Corps of Engineers and distributed by the American Public Works Association and the University of Illinois.

The family curve technique relies on the concept that similarly constructed pavements, subjected to comparable traffic and climate, deteriorate at very similar rates. The procedure for family curve development consists of grouping pavements with similar deterioration characteristics, filtering data that are in error, identifying data that are statistically outlier, and then fitting the data with a constrained polynomial curve. The family curves created are used to predict pavement condition at the section level. Predicting pavement condition at the section level assumes that the deterioration of all pavement sections in a family is similar and is a function only of their present condition, regardless of age.

M&R work planning uses the critical pavement condition index (PCI) concept. The point beyond which the rate of pavement deterioration and the cost of applying preventive localized maintenance increase significantly is defined as the critical PCI. The work planning procedure, a feature of MicroPAVER, uses the developed family curves to optimize the type and timing of M&R application. This procedure includes determining the critical PCI, assigning M&R alternatives to the pavement sections, and assigning M&R priorities to pavement sections.

This paper presents an application of the family curve and work planning techniques. During the past 2 years, USACERL has applied these techniques to the pavement networks of many army installations. This application included developing several family curves for each installation and analyzing the consequence of various M&R budgets. The ensuing work plan, developed for all asphalt concrete (AC) roads at a typical Army installation, presents these findings in the most significant fashion. The pavement families that were developed contain sections of comparable characteristics. Several operations, unique to MicroPAVER, produced a work plan report. The work plan report used the family curves and budget constraints to optimally assign M&R. The deterioration rates of the families helped determine optimal M&R scheduling while the budget limits demanded optimal M&R scheduling. A comparison of the resulting work plans outlines the best scenario.

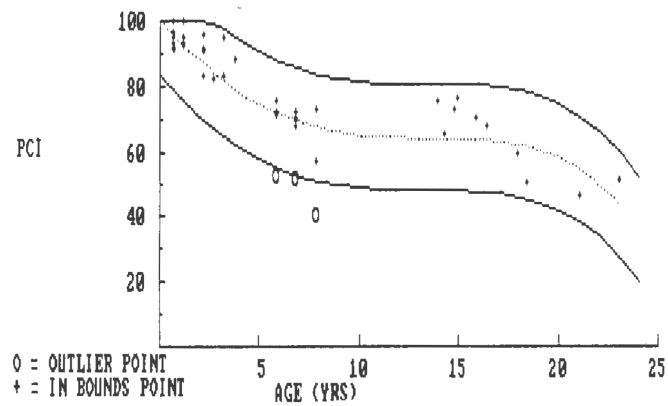

FIGURE 1 Outlier-processed data file, constrained fourth-degree curve.

Pavement Condition Prediction

Accuracy in prediction is essential for budget forecasting and work planning. The family deterioration modeling technique was specifically developed for MicroPAVER. The development of a family consists of four major steps.

1. Grouping pavements with similar material characteristics and traffic conditions,
2. Identifying and omitting the condition data that are obviously in error,
3. Identifying other statistically outlier data, and
4. Fitting the remaining data with a constrained polynomial curve.

Pavement families are based on criteria such as pavement use, pavement rank, surface type, traffic loading, and other factors. The formation of pavement families is dependent on the pavement network. Each network can have several families

A scatter plot of PCI versus age for each family is used to identify and filter data points that are in obvious error. A statistic examination of the filtered data is then used to identify and omit extreme points (outliers). The outlier procedure is based on the finding that the errors between the predicted and observed PCIs (*1*) are normally distributed. A confidence interval identifies the extreme data as outliers. Figure 1 shows an example of outlier-processed data using a 95 percent confidence interval. A constrained polynomial curve (the family curve) describes the remaining data points (minus any outliers). Two constraints are applied to the polynomial curve: the PCI = 100 at age = 0, and the deterioration slope is negative.

Pavement sections in the network are assigned to appropriate families. The PCI prediction for each pavement section assumes that the deterioration of all sections in a family is similar and is a function only of their present condition, regardless of age (Figure 2). The predicted section PCIs are used for the selection of M&R strategies.

Comparison of Family Curves for Different Pavement Types

Figure 3 is an example of two family curves from a typical municipal data base. One family is for AC pavements without overlays (AC) and the other is for surface treatment roads (ST). Figure 4 is an example of two family curves for another network where a 3-in. overlay was applied. One family was created for AC pavements without overlays (AC) and the other was developed for AC pavements with a 3-in. overlay (AAC).

Figures 3 and 4 show the very different deterioration rates of AC pavements than those for ST or AAC pavements. These figures illustrate the considerable differences in pavement life for these three families and the reasons that family curve development is necessary for condition prediction. Since an accurate PCI prediction is so important in determining M&R strategy, family curves are a significant part of the work planning process.

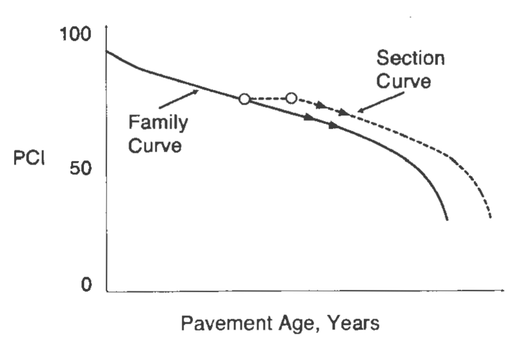

FIGURE 2 Section condition prediction.

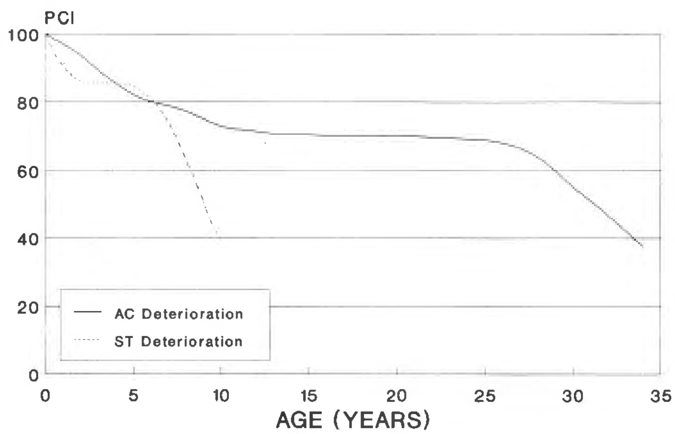

FIGURE 3 **Sample AC and ST deterioration curves, ST (surface treatment roads).**

Development of M&R Work Plans

Work planning must consider both pavement life and cost when selecting the best M&R strategy for each of the pavement sections in a network. The work planning procedure is based on the critical PCI concept (*2*) and consists of the following steps:

- Identify the critical PCI (the PCI below which the condition deteriorates rapidly) for each pavement family.
- Assign appropriate M&R type to each pavement section for each year in the analysis period.
- Rank M&R requirements on the basis of budget limitations.
- Calculate M&R cost, future PCI, and backlog of M&R for each budget scenario.

Identify Critical PCI for Each Family

Annual and long-range work planning operates on the critical condition concept. The critical condition (critical PCI) is the condition beyond which the pavement condition deteriorates rapidly and the cost of applying localized preventive maintenance increases significantly. Previous research results have shown that it is more economical to apply M&R before the pavement deteriorates beyond the critical condition (*4*).

The critical PCI for a family is identified as follows:

1. Visually select the critical PCI range on the basis of the shape of the family deterioration curve (Figure 5).
2. Select a localized preventive distress maintenance policy to be used in the analysis of budget scenarios. Table 1 is an example of such a policy for asphalt roads.
3. Apply the selected preventive distress maintenance policy to pavement sections in the family. This can be done using the MicroPAVER network maintenance report.
4. Plot the cost of localized preventive maintenance per unit area versus PCI for each of the sections. Figure 6 is an example of such a plot.
5. Select the critical PCI from the results of Steps 1 and 4.

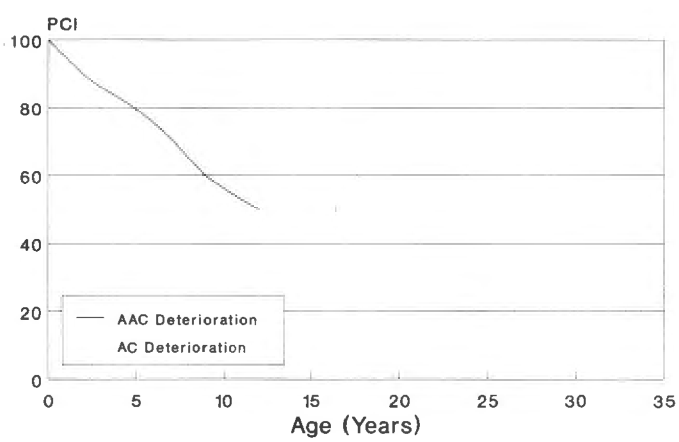

FIGURE 4 **Sample AC and AAC deterioration curves, AAC (3-in. overlay with fabric).**

Assign M&R to Each Pavement Section

There are seven M&R types in the current version of MicroPAVER: localized stopgap, localized preventive, three types of global preventive, and two types of major. M&R types are assigned to each pavement section on the basis of the section's PCI concerning the critical PCI (Figure 7). Following is a description of each of the M&R types:

Localized Stopgap (Safety)

Stopgap M&R is defined as the localized distress that M&R activities needed to keep the pavement in a safe and operational condition. A stopgap policy is different from a preventive policy in that it usually includes only high-severity-level distresses that could be a safety hazard. Stopgap maintenance should be applied only to pavements below the critical PCI.

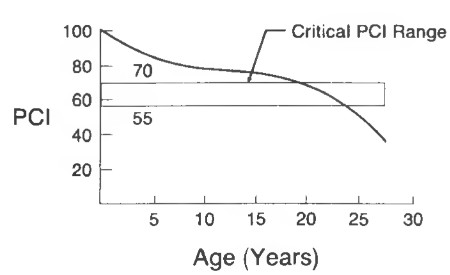

FIGURE 5 **Critical PCI range shown on typical deterioration curve.**

TABLE 1 Example of Preventive Distress Maintenance Policy

Distress	Sev	Work Type & Description		Cost	Unit
1 ALLIGATOR CR	M	PA-AD	Patching - AC Deep	5.00	sq. ft.
1 ALLIGATOR CR	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
3 BLOCK CR	M	CS-AC	Crack Sealing - AC	.60	ft.
3 BLOCK CR	H	CS-AC	Crack Sealing - AC	.60	ft.
4 BUMPS/SAGS	M	PA-AS	Patching - AC Shallow	2.00	sq. ft.
4 BUMPS/SAGS	H	PA-AS	Patching - AC Shallow	2.00	sq. ft.
5 CORRUGATION	M	PA-AL	Patching - AC Leveling	1.00	sq. ft.
5 CORRUGATION	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
6 DEPRESSION	M	PA-AD	Patching - AC Deep	5.00	sq. ft.
6 DEPRESSION	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
7 EDGE CR	M	CS-AC	Crack Sealing - AC	.60	ft.
7 EDGE CR	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
8 JT REF. CR	M	CS-AC	Crack Sealing - AC	.60	ft.
8 JT REF. CR	H	CS-AC	Crack Sealing - AC	.60	ft.
9 LANE SH DROP	M	PA-AL	Patching - AC Leveling	1.00	sq. ft.
9 LANE SH DROP	H	PA-AL	Patching - AC Leveling	1.00	sq. ft.
10 L & T CR	M	CS-AC	Crack Sealing - AC	.60	ft.
10 L & T CR	H	CS-AC	Crack Sealing - AC	.60	ft.
11 PATCH/UT CUT	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
13 POTHOLE	L	PA-AD	Patching - AC Deep	5.00	sq. ft.
13 POTHOLE	M	PA-AD	Patching - AC Deep	5.00	sq. ft.
13 POTHOLE	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
15 RUTTING	M	PA-AD	Patching - AC Deep	5.00	sq. ft.
15 RUTTING	H	PA-AD	Patching - AC Deep	5.00	sq. ft.
16 SHOVING	M	PA-AS	Patching - AC Shallow	2.00	sq. ft.
16 SHOVING	H	PA-AS	Patching - AC Shallow	2.00	sq. ft.
17 SLIPPAGE CR	L	PA-AS	Patching - AC Shallow	2.00	sq. ft.
17 SLIPPAGE CR	M	PA-AD	Patching - AC Deep	5.00	sq. ft.
17 SLIPPAGE CR	H	PA-AD	Patching - AC Deep	5.00	sq. ft.

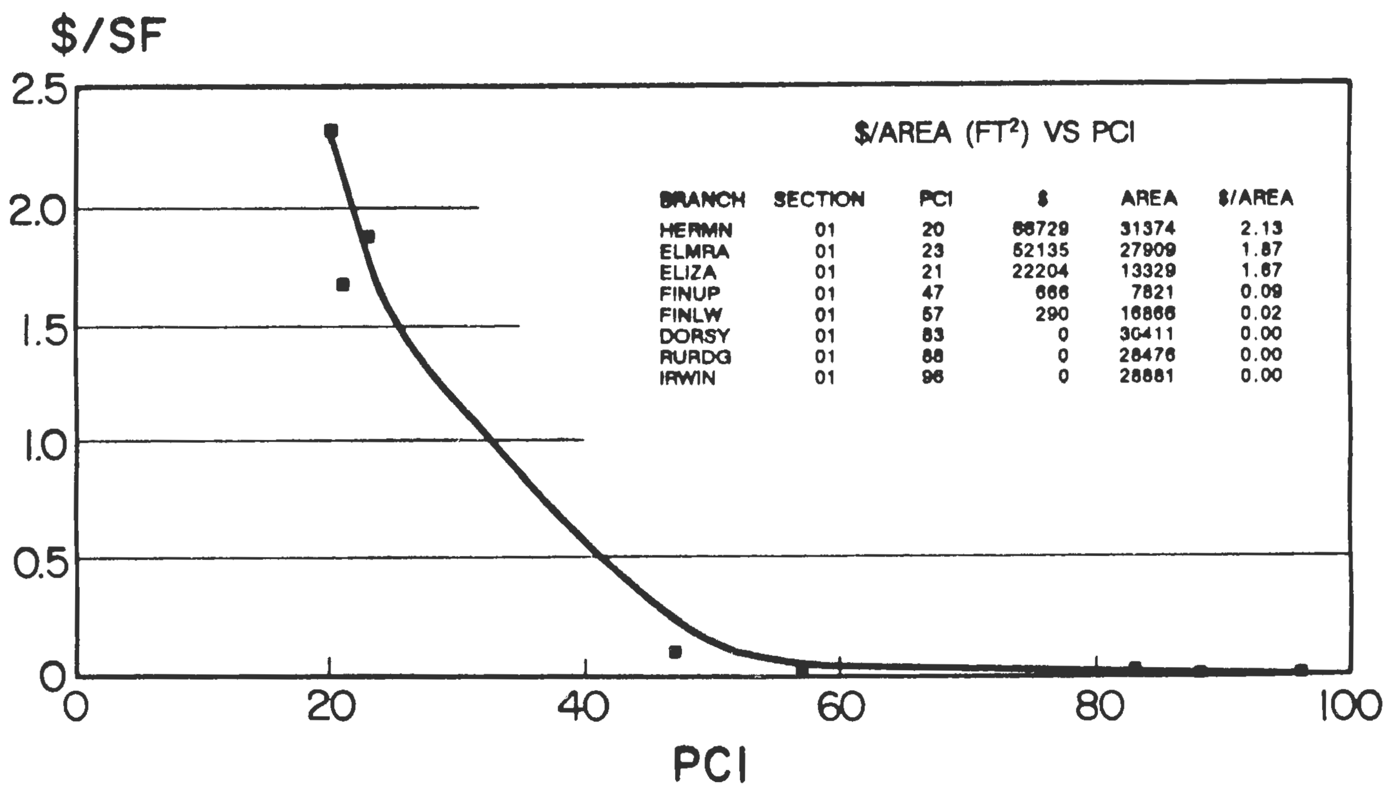

FIGURE 6 Cost per square foot versus PCI.

Localized Preventive

Localized preventive M&R is defined as localized distress maintenance activities that are performed with the primary objective of slowing the rate of pavement deterioration. These activities include crack sealing and various patching techniques. An example of a localized preventive distress maintenance policy is given in Table 1. This policy is applied to pavements above the critical PCI. Note that applying a localized preventive maintenance policy to pavement sections below the critical PCI is not cost-effective.

Global Preventive

Global preventive M&R is defined as those activities that are applied to the entire pavement section with the primary objective of slowing the rate of condition deterioration. These activities include surface treatments for asphalt surfaced pavements and joint sealing for concrete pavements. Global preventive M&R is applied to pavements above the critical PCI. Applying global preventive M&R to pavements below the critical PCI is often not cost-effective.

The current version of MicroPAVER accommodates three types of global preventive M&R for asphalt surfaced pavements. These three types are assigned to the pavement sections on the basis of existing distress types as shown in Figure 8. This is done to optimize the selection of the surface treatment type on the basis of existing distresses. Type 3 is recommended for pavements with skid-causing distresses such as bleeding. Type 2 is recommended for pavements with climate-related distresses such as block cracking. The selection of the M&R type is also a function of the use of the pavement. For example, aggregate seals may not be appropriate for runways due to the possibility of foreign object damage to aircraft engines. A thin overlay should be used instead.

Major M&R

Major M&R is applied to the entire pavement section to correct or improve existing structural or functional requirements. Major M&R is divided into two types: major M&R applied to pavement sections above the critical PCI, and major M&R applied to pavements below the critical PCI.

PRIORITIZE M&R

Factors used to prioritize M&R include M&R type, pavement use, pavement rank, and PCI value. Priorities are

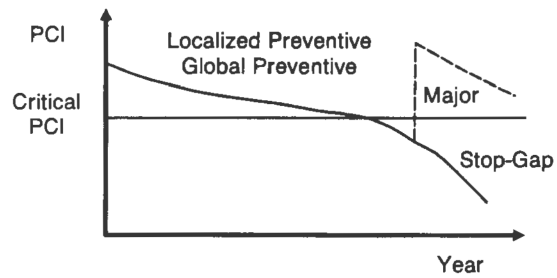

FIGURE 7 M&R types.

first established on the basis of M&R type as listed, with Type 1 being the highest priority:

1. Localized stopgap (safety);
2. Localized preventive;
3. Global preventive, Type 1;
4. Global preventive, Type 2;
5. Global preventive, Type 3;
6. Major, equal to or above the critical PCI; and
7. Major, below the critical PCI.

For M&R Types 1 through 5, priorities are assigned within each type based on the section PCI, with the lower PCI receiving higher priority. For example, within M&R Type 1, a pavement section with a PCI of 20 would receive a higher priority than a pavement section with a PCI of 50.

For M&R Types 6 and 7, priorities are assigned within each type based on user-defined criteria as presented in Table 2. Pavement sections within each major M&R type are ranked by PCI, the lower PCI receiving the higher priority.

CALCULATE M&R COST

The calculation procedure is slightly different for pavement sections above and below the critical PCI.

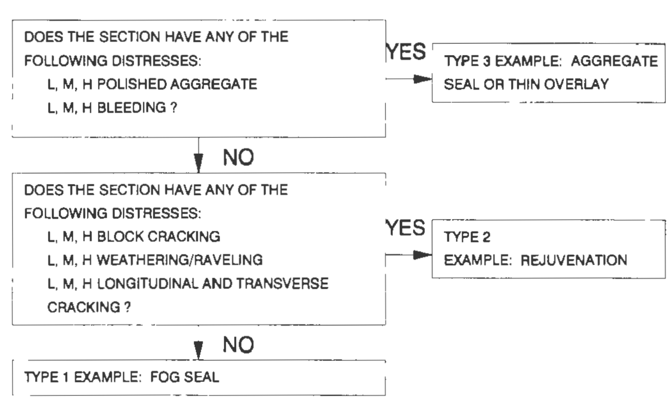

FIGURE 8 Asphalt global preventive maintenance.

TABLE 2 Major M&R Priority Table

Rank / PCI	Roadway P	Roadway S	Roadway T
70 - 100	2	4	10
Critical - 70	1	3	9
40 - Critical	1	3	9
0 - 40	2	4	10

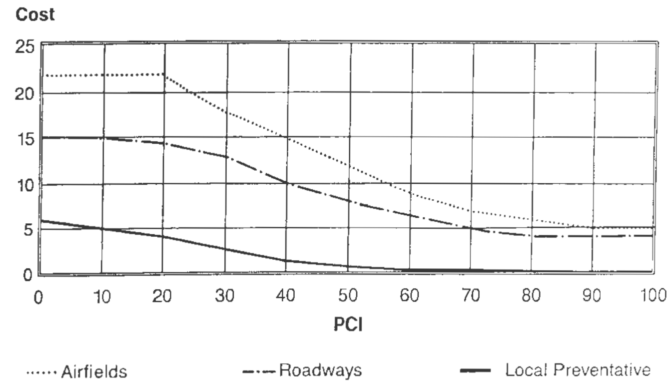

FIGURE 10 M&R cost per square yard.

Pavement Sections Above Critical PCI

The first step is to investigate if the pavement section has a structural distress (Figure 9). Structural distresses include alligator cracking and rutting in asphalt pavements and corner break and divided slabs in concrete pavements.

Pavement Sections With No Structural Distress

1. Apply localized preventive M&R using the preventive distress maintenance policy and the extrapolated distress data from the last condition survey. For subsequent years in which the PCI is predicted but the distress information is not available, the cost of localized preventive maintenance is estimated on the basis of the user-specified PCI–versus–unit cost relationship (Figure 10).

2. Apply global preventive M&R on the basis of the user-specified interval between applications. And the maximum number of applications per pavement section should not be exceeded. The selection of the type of global M&R for asphalt pavements was presented in Figure 8.

3. If a global M&R is selected, section PCI will be increased according to specified value. A preferred method of accounting for the effect of global preventive maintenance on pavement performance is to let the user specify the ultimate increase in pavement life (T) and calculate the effective increase in PCI (Figure 11).

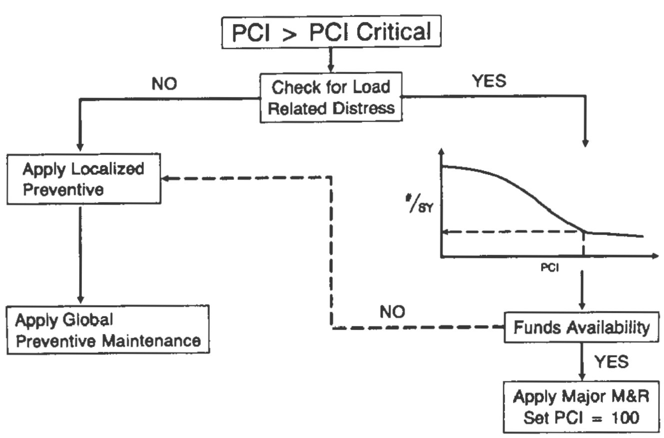

FIGURE 9 Pavement sections above critical PCI.

Pavement Sections With Structural Distress

1. Determine the cost for major M&R based on the PCI–versus–unit cost relationship (Figure 10).
2. Check on the availability of funds on the basis of available budget and M&R priorities.
3. If funds are available, apply major M&R and set the PCI value to 100. If funds are not available, apply the same process as in the previous section. Check on the availability of funding for major M&R in the following years.

Pavement Sections Below Critical PCI (Figure 12)

1. Determine the cost for major M&R on the basis of the user-specified PCI–versus–unit cost relationship (Figure 10).
2. Check on the availability of funds on the basis of budget and priorities.
3. If funds are available, apply major M&R and set the PCI value to 100. If funds are not available, apply localized stopgap (safety) M&R. Check on availability of funding for major M&R in the following years.

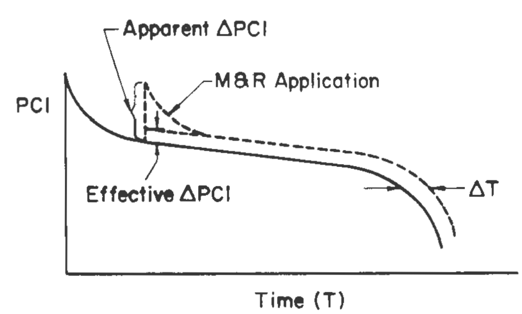

FIGURE 11 Effect of global preventive maintenance on pavement performance.

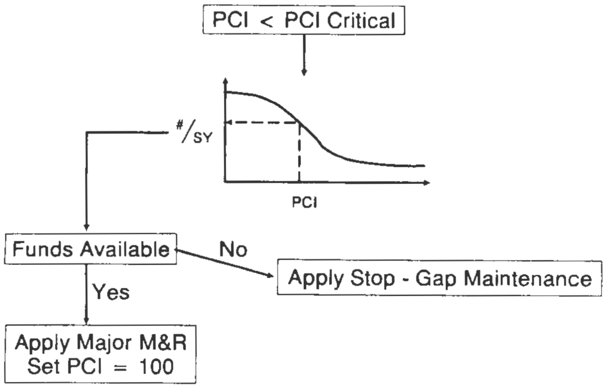

FIGURE 12 Pavement sections below critical PCI.

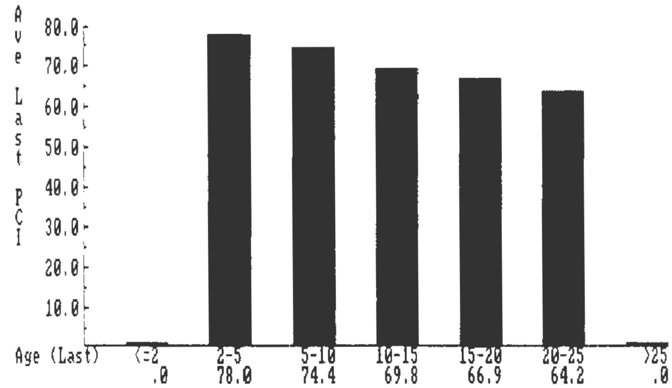

FIGURE 13 Average last PCI by age (last inspection).

To summarize, pavements above the critical PCI receive localized preventive maintenance (such as crack filling or patching) and global preventive maintenance (such as surface treatments). Pavements below the critical PCI receive stopgap maintenance (such as pothole filling) until money becomes available for major rehabilitation. Pavements above the critical PCI with structural distress are scheduled for detailed condition investigation and major rehabilitation. The factors used to assign M&R priorities include pavement use, pavement rank (functional classification), and PCI. The critical PCI technique yields results that agree with engineering judgment and output from dynamic programming techniques, developed as part of the MicroPAVER research effort (*3*).

Budget Scenario Analysis

The ability to analyze the consequences of different budget scenarios and rehabilitation philosophies for a road network has been automated as part of the MicroPAVER system. The example network consisted of 1,427,304 yd^2 divided into more than 200 pavement sections with an age to PCI distribution as shown in Figure 13. The average PCI for the network was 66 in 1992 (when work planning was initiated). Analysis of the family curves determined a critical PCI of 70 for the installation.

Two budgeting plans were considered; a minimal budget of \$100,000 and an affordable budget of \$2 million a year (Tables 3 and 4). The minimal budget represented a pothole repair and stopgap program and resulted in a total unfunded requirement of \$11.2 million by 1999 and an average PCI of 60. In this scenario, many section PCIs would be below 60, indicating that many roads have unacceptable operating conditions. The \$2 million/year represented the affordable budget for pavement M&R and resulted in a zero unfunded requirement by 1996 and an average PCI of 70, where all pavements are acceptable. The total amount of funding required would be \$8.9 million for the \$2 million/year scenario and \$11.9 million for the \$100,000/year scenario, leading to a total cost avoidance (funded plus unfunded) of \$3 million.

Cost Comparison of Three M&R Strategies

Three M&R strategies were compared to illustrate the impact of M&R strategy on long-term pavement perfor-

TABLE 3 Pavement Budgeting Plan, \$100,000 Annual Funding

Year	Dedicated Funding (\$)	Total Funding (\$)	Unfunded Requirement (\$)	Total Requirement (\$)	Avg PCI
1993	100,000	100,000	6,200,000	6,300,000	67
1994	100,000	200,000	6,800,000	7,000,000	65
1995	100,000	300,000	7,600,000	7,900,000	64
1996	100,000	400,000	8,300,000	8,700,000	62
1997	100,000	500,000	9,000,000	9,500,000	61
1998	100,000	600,000	10,000,000	10,600,000	61
1999	100,000	700,000	11,200,000	11,900,000	60

TABLE 4 Pavement Budgeting Plan, $2,00,000 Annual Funding

Year	Dedicated Funding ($)	Total Funding ($)	Unfunded Requirement ($)	Total Requirement ($)	Avg PCI
1993	2,000,000	2,000,000	4,300,000	6,300,000	74
1994	2,000,000	4,000,000	3,000,000	7,000,000	78
1995	2,000,000	6,000,000	1,500,000	7,500,000	81
1996	1,800,000	7,800,000	0	7,800,000	83
1997	220,000	8,000,000	0	8,00,000	79
1998	361,000	8,400,000	0	8,400,000	75
1999	497,000	8,900,000	0	8,900,000	72

mance and M&R costs: thin AC overlays (less than 2 in.), 3- to 4-in. overlay with or without fabric, and structurally designed rehabilitation.

The analysis developed and used typical family curves for overlays 1 to 2 in. thick, overlays 3 to 4 in. thick, and structurally designed rehabilitation (Figure 14). The family curves were selected as typical from available data bases. Each family was assigned to the network, and three 20-year work plans were created (one for each family assignment); Figure 15 shows the results. The economic analysis feature in MicroPAVER converted these numbers to a cost per square yard using an interest rate of 6 percent and an inflation rate of 0 percent. The conservative interest and inflation rates were chosen to yield the minimum cost difference between the M&R types.

The results of the economic analysis show that the annual difference in M&R cost per square yard is $1.50, $1.25, and $1.14 for the 1- to 2-in., 3- to 4-in., and structurally designed overlays, respectively. The M&R cost for the thin (1- to 2-in.) overlay is $0.36/yd^2 higher than the M&R cost for the structurally designed pavement. For a pavement network of 1.5 million yd^2, this leads to a difference in cost of more than $500,000/year:

M&R Strategy	*Annual M&R Cost ($/yd^2)*	*Predicted PCI*
Structural design	1.14	65
3- to 4-in. overlay	1.25	65
1- to 2-in. overlay	1.50	67

The pavement conditions after 20 years are nearly identical, but they have very different costs. These results confirm that the structurally designed M&R is more effective and costs much less than the commonly used AC overlay.

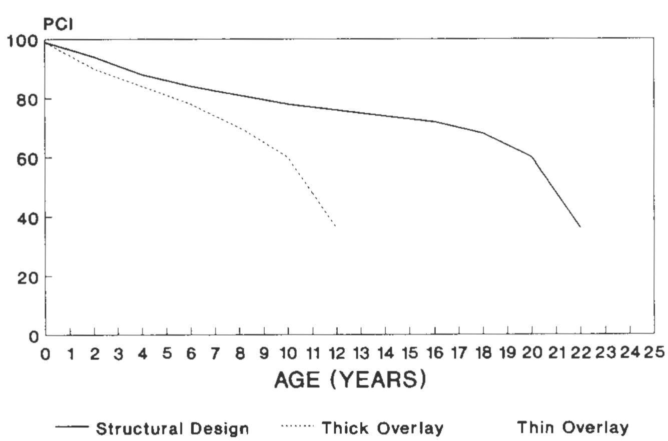

FIGURE 14 Family curves for three types of M&R.

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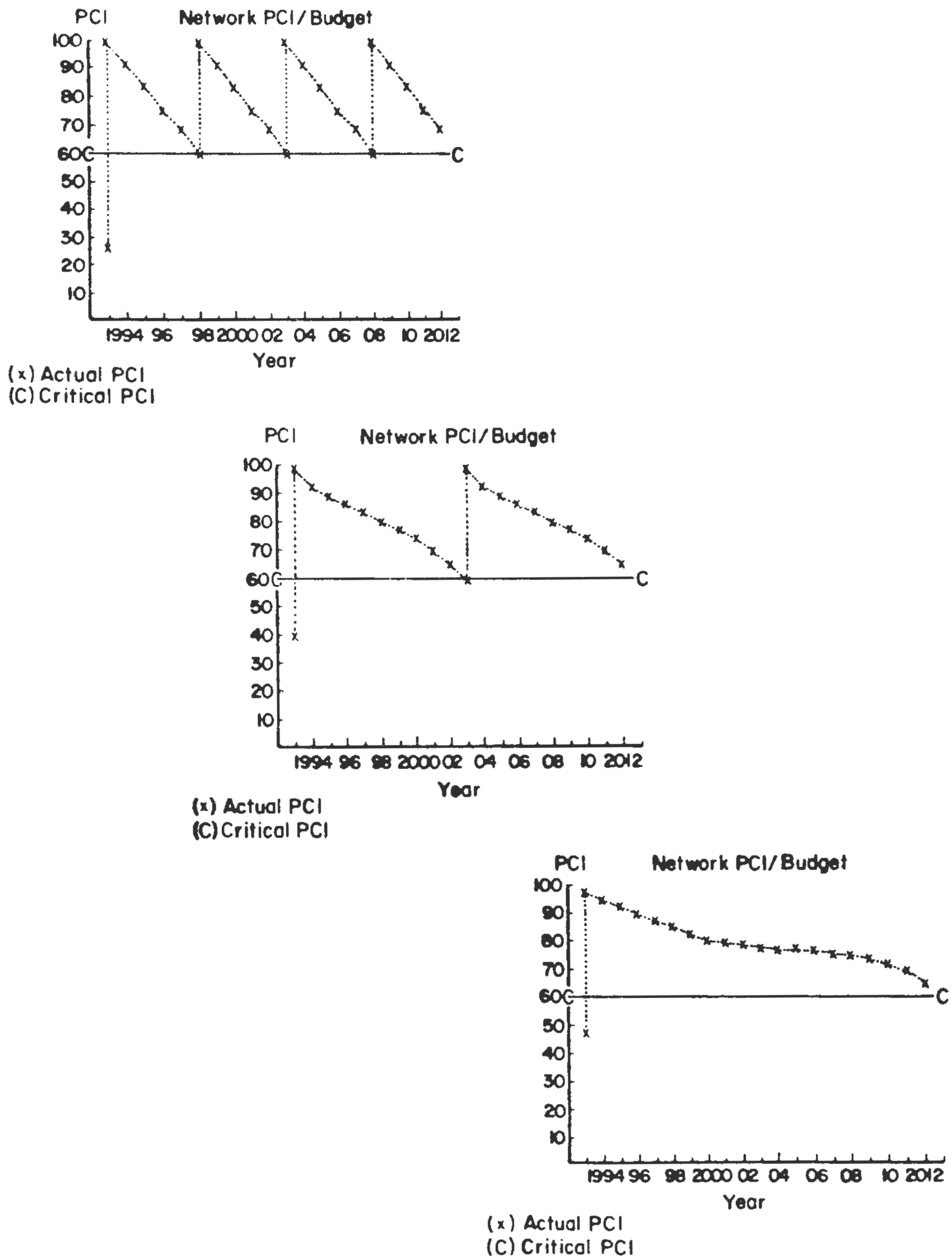

FIGURE 15 Twenty-year work plans for three types of M&R.

HDM-III Model—Appropriate Pavement Maintenance and Rehabilitation Programs Under Conditions Prevailing in Central European Countries

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The study of possibilities for using the Highway Design and Maintenance-III (HDM-III) model to optimize selection of appropriate pavement maintenance and rehabilitation programs under conditions prevailing in Central European countries is presented. The analysis was carried out on a part of the South Bavarian road network, and it is the first attempt to apply the HDM-III model for optimizing road maintenance and rehabilitation in this West European country. The results obtained clearly point to the numerous advantages of using the HDM-III model, if regional specificities are realistically presented. Particular emphasis is placed on the critical analysis of HDM-III model results with respect to the great number of input parameters used as a basis for modeling, including the possibility of error in defining individual values of so many parameters. The influence of various parameters on the performance of the model is analyzed in detail. This task is performed in the context of a sensitivity analysis of the HDM-III model. The analysis justifies the global ranking of input data according to their importance in the HDM system. The research was carried out in Munich, Germany, in 1991.

The model-based pavement management system has not yet been accepted in the Federal Republic of Germany as a basis for selecting appropriate road maintenance strategies. In the circles of building authorities this system is almost unknown, and the many efforts being made to enable its introduction and implementation are still widely considered superfluous. Such an attitude is somewhat unusual or even imprudent since road maintenance costs in Germany are starting to exceed new construction costs and, for that reason, any improvement aimed at rationalizing decision making in the sphere of road maintenance would result in considerable savings. On the other hand, an eminent expert in this field, Alfred Schmuch, claims that the present aloofness related to the application of this system for decision making and optimization in Germany can hardly be understood, as widely recognized institutions such as the World Bank for Reconstruction and Development and some highly developed countries (e.g., the United States) have been developing such systems since 1969 and are continuously working on their improvement. Until recently, such developments were practically ignored in Germany. This is mainly due to the fairly good state of German roads (except those in the former East Germany) and to the fact that German engineers have generally not been showing sufficient interest in economic issues and in the science of economics, being a scientific basis for both creative thinking and decision making.

Only in the late 1970s were the first German attempts made to develop appropriate economic procedures. In the early 1980s, these activities, initially involving investigation of surveying procedures, pavement condition evaluation, and determination of maintenance requirements, were extended to other related areas. This research was greatly supported by the Federal Ministry of Transportation and by the Road Department of the Hessen Province.

In the late 1980s, experts from Croatia and some other former Yugoslav states acquired some knowledge related to the use of the Highway Design and Maintenance-III (HDM-III) model. This knowledge is primarily based on the pilot study of the HDM-III model application that was performed in Croatia in collaboration with World Bank experts.

The present study, based on the experience gained in Croatia, was performed at the University of Bundeswehr, Munich. The author was engaged to investigate possibilities of applying the HDM-III model under the conditions prevailing in Central European regions. The results obtained are presented in the following sections (*1*).

Possibilities of Applying HDM-III Model in Federal Republic of Germany

Aim of Analysis

During the process of road network maintenance and rehabilitation, road authorities strive to select an optimum maintenance strategy from a number of alternatives. This selection may be obtained only through a realistic prognosis of total costs incurred (employer costs plus user costs) during the life of a road. In addition, an economically acceptable maintenance strategy may be selected among a number of maintenance alternatives only if it is possible to rapidly calculate and compare cost variations over a longer period.

The HDM-III model (*2*) is one of a few existing models that generally meet this precondition. This paper focuses on the technical and economic possibilities of using the HDM-III model under conditions prevailing in Central European regions, which are represented here by appropriate road sections in southern Bavaria.

Individual aims of this research consisted in defining

- Economically optimal maintenance strategies
- The most favorable maintenance strategies in case of limited financing,
- Maintenance and rehabilitation costs using such strategies, and
- Individual input parameters for the HDM system.

The final objective of the analysis is to evaluate the applicability of the HDM-III model under the aforementioned conditions.

Analytic Procedure

The analysis is based on the prognosis of road deterioration when different maintenance strategies are applied and on calculating costs while selecting optimum maintenance strategies for individual road categories.

The selected part of the Bavarian road network was classified into individual sections on the basis of pavement structure, pavement condition, and traffic volume. Pavement condition was then predicted for all sections defined in such way, and the corresponding maintenance activities for the period from 1991 to 2010 were defined.

These predictions served as a basis for defining road maintenance costs and user costs, mainly consisting of vehicle operating costs, which have been discounted to the present value. An optimum maintenance strategy was thus defined for each selected section.

The analysis using the HDM-III model was performed in three stages:

1. Data input and data consistency control,
2. Simulation of traffic flows and simulation of the change in pavement condition including maintenance activities required in the period under consideration, and
3. Economic analysis and comparison of maintenance alternatives for the selected road sections based on the net present value for different discount rates.

Procedure for Selecting Roads in Bavaria

The selection of road sections within the Bavarian road network was performed taking into account

- Pavement structure (construction method used),
- Traffic load (traffic volume, vehicle types, traffic growth),
- Pavement condition, estimated according to the actual road surface condition (particularly with respect to unevenness), and
- Soil characteristics (bearing capacity).

The required information was collected by the Road and Bridge Construction Section of the Civil Engineering Department, Ministry of the Interior (Oberste Baubehörde im Bayer, Staatsministerium des Innern).

In this way, the pilot study provided analysis of practically all road categories (highways included) present in Germany:

1. Federal Road B2 (Bundesstrasse B2): three sections between KM 30.960 and KM 40.500.
2. State roads (Staatsstrassen):
   –St 2063 (five sections between KM 34.600 and KM 45.900),
   –St 2067 (for KM 1.750 to KM 3.080),

–St 2068 (three sections between KM 32.465 and KM 33.670),
–St 2069 (three sections between KM 2.550 and KM 6.270),
–St 2070 (four sections between KM 6.330 and KM 20.140),
–St 2073 (nine sections between KM 1.700 and KM 16.900), and
–St 2349 (from KM 22.200 to KM 26.310).
3. District roads (Kreisstrassen):
–STA 3 (four sections between KM 19.880 and KM 37.040), and
–STA 9 (two sections between KM 0.050 and KM 4.200).
4. County-level roads (Gemeindestrasse: Puchheim–Aubing): from KM 13.200 to KM 14.700

The total length of all 36 analyzed sections amounts to 55.145 km.

Analysis of Maintenance Strategies

For the purpose of this study, several maintenance strategies have been defined and analyzed according to different technical-maintenance procedures and specific types of damage. Maintenance measures include all road maintenance activities: from repairing potholes and individual cracks, to strengthening pavement using different asphalt layer thicknesses, to rehabilitating pavement by completely changing its structure.

The so-called zero-alternative, comprising all regular (routine) maintenance activities outside of the pavement structure, was defined to enable comparison of various maintenance alternatives. The regular maintenance was included in all other maintenance strategies. Winter maintenance costs were not considered.

Alternatives to the analyzed maintenance strategies contain different combinations of the following maintenance activities:

- Regular (routine) maintenance includes care for the roadside vegetation, shoulder maintenance, drain cleaning, and traffic sign maintenance and cleaning.
- Patching activities include local repairs on the pavement surfacing and the repair of potholes or individual cracks, calculated as a percentage of the total pavement surface.
- Surface treatment with or without previous profile correction. The extent of individual damage (damaged spots, joints, ruts) must be known before proceeding to this maintenance activity.
- Road strengthening by adding an additional asphalt layer of variable thickness if the pavement surface would be elevated by up to 40 mm by doing so. The frequency of strengthening by a 40-mm layer depends only on the unevenness of the road surface.
- Rehabilitation by gradually reconstructing either the existing pavement or some of its parts if the damage also affects layers beneath the surfacing layer. Rehabilitation activities include strengthening, additional construction, or removal of the corresponding part of the pavement. When that is done, one or several additional asphalt layers of variable thicknesses (80 and 140 mm) are placed. Rehabilitation may also be performed by modifying the placing method and layer thickness to achieve better mechanical resistance of pavement to changes in volume.

All 15 maintenance strategies are presented in Table 1 (all alternatives include regular routine maintenance).

Input Data for HDM-III Model

The following groups of data are required to enable effective functioning of the HDM-III model:

- Up-to-date characteristics of the analyzed road network sections (route elements, structure of and damage to the pavement structure, environmental impact estimate),
- Traffic load (volume, growth),
- Maintenance standards and unit rates, and
- Characteristics of motor vehicles and unit rates

Characteristic Features of Analyzed Road Sections

Route elements (rise plus fall, horizontal curvature, pavement width, shoulder width) are primarily used in the analysis to determine vehicle operating costs.

Structural properties of pavements are defined using the structural number (SN). This number indicates the change in pavement condition and is therefore the most significant parameter for predicting such a condition. The SN coefficient (SNC), being a statistically appropriate indicator of the mechanical resistance of pavements to volume change, is suitable for the analysis and may be described as a linear combination of coefficients of individual materials and thicknesses of pavement layers above the subgrade, including the contribution of the subgrade itself.

As to the information on road condition, the HDM-III model requires quantification of all damage to the pavement surface: all types of cracks, wide cracks, raveling (due to bitumen or mortar cutoff), potholes, rutting, and unevenness. Pavement surface unevenness was visually observed according to indications given elsewhere (3) and classified in the range from "hardly noticeable" to "very pronounced." Visual estimates of unevenness were then converted to the international roughness index (IRI) (meters per kilometer) and the values obtained were applied

TABLE 1 Alternative Maintenance and Rehabilitation Strategies for Selected Bavarian Roads

Maintenance alternative	Patching (%) of the road surface with damage)	SURFACE TREATMENT (ST) with profile correction	SURFACE TREATMENT (ST) without profile correction	Overlay (wearing course WC - 40 mm)	RECONSTRUCTION Strengthening	RECONSTRUCTION New pavement construction
ALT 00	0					
ALT 01	100					
ALT 03	100		at 50% road surface damage			
ALT 04	100		at 50% road surface damage			
ALT 06	100	at 50% road surface damage				at 7.0 IRI
ALT 07	100	at 25% road surface damage				at 7.0 IRI
ALT 08	100			at 5.0 IRI		
ALT 09	100			at 4.2 IRI		
ALT 10	100			at 3.5 IRI		
ALT 11	100				immediately 80mm + ALT 08	
ALT 12	100				immediately 80mm + ALT 09	
ALT 13	100				immediately 80mm + ALT 10	
ALT 14	100				immediately 140mm+ ALT 08	
ALT 15	100				immediately 140mm+ ALT 10	
ALT 18	100					immediately + ALT 10

in the model. Other pavement condition properties were registered either visually or through appropriate measurements. These properties were then used to define homogeneous road sections, as given in Table 2.

Environmental Impacts on Pavement Condition

Damage to the pavement surfacing (cracks, raveling, and potholes) develops in two stages:

2.1. Initiation stage: the period in which the damage to the pavement surfacing is not yet visible, and

2.2. Progression stage: the period in which the extent of damage increases.

The model considers only the progression stage in case of structural damage such as rutting and unevenness.

As the model was initially designed for conditions prevailing in Brazil, variable environmental conditions (temperature, precipitation, type of soil, and drainage) are taken into account by modifying the HDM-III model using the so-called damage factors. These factors are in fact linear multipliers enabling prediction of individual types of damage. For example, the damage factor 1 is used for conditions prevailing in Brazil.

A detailed study of the pavement damage process in the investigated area would be required to properly adapt the model to different environmental conditions. As such a study is normally not feasible, it is necessary to define average representative values of the pavement performance factors.

These damage factors were determined for each type of pavement damage by taking into account actual average climatic conditions prevailing in the southern Bavarian regions where the investigated road sections are situated:

Damage Factor	*Abbreviation*	*Value*
Crack initiation	K_{cl}	0.9
Crack progression	K_{cp}	1.2
Raveling at initiation stage	K_{ri}	0.9
Relationship between unevenness and pavement age	K_{age}	1.5
Pothole progression	K_{pp}	1.3
Rutting depth increase	K_{rdp}	1.0
Unevenness increase	K_{rqp}	1.0

These damage factors are used to linearly correct the influence of environment on the initiation and progression of pavement damage with respect to the Brazilian results.

The average precipitation in the area under investigation amounts to approximately 0.10 m/month (from 0.075 to 0.13 m/month), and the average altitude of this area is 637 m (from 520 to 705 m).

Traffic Volume

The following traffic-related information was used in the analysis: (*a*) traffic density and types of vehicle, and (*b*) annual traffic increase rate. These data were obtained from the Bavarian Road Authority. The most recent traffic count results (1985), corrected for an annual traffic

TABLE 2 Characteristic Features of Selected Road Sections in Southern Bavaria

Road section	Pavement wearing course age (years)	Modified structural number (SNC)	Unevenness IRI (m/km)	Cracks all/wide (% of road surface)	Rut depth (mm)	Thickness wearing c./ supporting c. (mm)
B 2/1	30/13	6.5	2.8	2.5/0	1.0	30/100
B 2/2	30/5	9.8	2.0	1.0/0	3.0	40/190
B 2/3	30/13	6.7	2.0	5.0/0	4.0	35/100
St 2063/4	30/23	3.4	2.8	7.0/0.2	9.0	30/0
St 2063/5	30/23	3.4	8.7	3.0/0.2	10.0	30/0
St 2063/6	30/3	3.9	4.6	7.0/0.3	9.0	50/0
St 2063/7	30/9	8.5	1.2	9.0/0	2.0	40/150
St 2063/8	30/10	8.4	1.2	1.5/0	2.0	35/155
St 2067/9	30/3	3.4	2.8	2.5/0	1.0	30/0
St 2068/10	30/7	8.5	1.2	1.0/0	4.0	40/150
St 2068/11	30/13	8.3	2.8	1.0/0	10.0	35/150
St 2068/12	30/13	8.3	2.8	1.0/0	10.0	35/150
St 2069/13	30/12	8.3	2.0	1.0/0	2.0	35/150
St 2069/14	30/3	3.4	7.6	7.5/0.4	6.0	30/0
St 2069/15	30/3	3.4	4.6	3.5/0.5	10.0	30/0
St 2070/16	30/20	9.8	2.0	1.5/0	6.0	70/150
St 2070/17	30/3	4.0	4.6	2.5/0.1	2.0	70/0
St 2070/18	30/21	6.4	7.6	1.5/0.2	1.0	30/95
St 2070/19	30/3	4.0	7.6	7.0/0.5	2.0	50/0
St 2349/20	30/3	4.6	4.6	1.5/0.4	6.0	70/0
St 2073/21	30/30	2.5	7.6	22.0/2.3	7.0	25/0
St 2073/22	30/30	2.5	7.6	12.7/1.9	10.0	25/0
St 2073/23	30/30	2.5	7.6	7.9/1.5	9.0	25/0
St 2073/24	30/26	2.4	4.6	12.8/1.1	8.0	20/0
St 2073/25	30/5	8.3	4.6	7.5/0.1	9.0	120/120
St 2073/26	30/24	2.5	4.6	2.2/0.1	2.0	25/0
St 2073/27	30/24	2.4	4.6	16.4/0	3.0	20/0
St 2073/28	30/4	6.7	2.8	1.9/0	1.0	40/80
St 2073/29	30/3	3.3	4.6	8.6/0	6.0	50/0
STA 3/30	30/30	5.8	2.0	1.5/0	3.0	35/70
STA 3/31	30/30	5.8	1.2	1.0/0	1.0	35/70
STA 3/32	30/30	5.8	2.0	1.0/0	8.0	35/70
STA 3/33	30/30	5.8	2.0	2.5/0	6.0	35/70
STA 9/34	30/12	6.0	2.8	1.5/0	3.0	35/70
STA 9/35	30/12	6.0	3.5	2.5/0	3.0	35/70
Gem. 36	30/18	2.5	10.0	4.1/0.6	2.0	20/0

growth of 3 percent, were used to define traffic volume for the first year of the 20-year period (i.e., for 1991). This annual traffic growth rate was also applied for the period 1991 to 2010.

In 1991 the average daily traffic (ADT) volume in vehicles per 24 hr, presented by vehicle type for all analyzed road sections, was as follows:

Vehicle Type	*ADT*
Passenger car	540 to 9,239
Bus	0 to 80
Light delivery truck	3 to 312
Medium-weight truck	1 to 66
Heavy truck	1 to 86
Heavy truck with trailer	0 to 157

Maintenance Strategies and Unit Rates

Appropriate maintenance strategies were defined for the investigated roads or their sections, as presented in Table 1.

The unit rates for individual maintenance tasks to be performed in the scope of defined maintenance strategies were provided by the Bavarian Road Authority and by a major Bavarian civil works contractor. The rates adopted in this analysis are given in Table 3.

Elements of the Vehicle Operating Costs (Vehicle Characteristics and Unit Rates)

The following elements were defined and used for calculating vehicle operating costs:

1. Vehicle type: passenger cars, buses, light delivery trucks, medium-weight trucks, heavy trucks, and heavy trucks with trailers.
2. For each vehicle type: the number of equivalent standard-axle loads, total weight, number of axles, annual load rate (in percentages of allowable load), and average fuel consumption.
3. For each vehicle, unit rates for: fuel, motor oil, tires, servicing and maintenance (spare parts, maintenance time).

In this analysis, the vehicle operating costs were calculated on computer using the HDM-III model as applied under Brazilian conditions.

TABLE 3 Unit Rates for Individual Maintenance Tasks

Task	Unit Rate (DM)[a] Financial Price	Economic Price
Regular (routine) maintenance	620.00/km/year	539.00/km/year
Patching	20.00/m²/year	17.40/m²/year
Surface treatment, without previous profile correction	4.00/m²	3.50/m²
Surface treatment, with previous profile correction using 30-mm AC[b] leveling course	10.56/m²	9.20/m²
Strengthening using 40-mm AC wearing course	10.30/m²	9.00/m²
Pavement rehabilitation by strengthening with layer 80-mm thick	13.44/m²	11.70/m²
Pavement rehabilitation by strengthening with layer 140-mm thick	23.46/m²	20.40/m²
Rehabilitation by reconstruction[c]	44.73/m²	38.90/m²

[a]DM = Deutsche marks
[b]AC = asphalt concrete
[c]Includes placement of gravel layer 400 mm thick as frost protection, road base course 100 mm thick, and AC wearing course 40 mm thick.

Optimum Maintenance Strategies and Related Costs

One of the individual aims of the HDM analysis was to determine economically optimum maintenance tasks for each road or road section analyzed. In addition to road user costs, the analysis also focuses on maintenance costs in the 20-year interval (1991 through 2010).

The value discounted from the cost difference between the so-called zero strategy (regular routine maintenance) and individual maintenance strategies is used as the criterion for evaluating alternative maintenance strategies (this is a net present value, which shows possible savings in the total costs when selecting a particular maintenance alternative).

Table 4 contains an overview of optimum maintenance tasks, including years in which such tasks are performed. All costs are related to the period of 20 years and are discounted using a 4 percent interest rate.

Table 4 indicates that the model selected the following optimum maintenance and rehabilitation strategies out of all possible alternatives for the total of 36 sections covered:

1. ALT 15 + ALT 14: in 19 cases, or 53 percent,
2. ALT 13 + ALT 12: in 6 cases, or 17 percent,
3. ALT 18: in 5 cases, or 14 percent,
4. ALT 07: in 4 cases, or 11 percent, and
5. ALT 10: in 2 cases, or 5 percent.

In general, it may be stated that the HDM-III model proposes, in 70 percent of all cases, an optimum maintenance strategy consisting of strengthening the road section to a total thickness of 140 mm (53 percent) or 80 mm (17 percent) in 1991, and a subsequent additional strengthening of some road sections using an asphalt layer 40 mm thick in the period beginning in 2000.

For the remaining 30 percent of road sections, an optimum maintenance strategy proposed by the HDM model consists in rehabilitation by reconstruction (14 percent), surface treatment (11 percent), and strengthening using an asphalt layer 40 mm thick (5 percent). Regular maintenance tasks and possible local patching activities are not presented as separate items in Table 4.

The following funding is required in the first 5-year period (1991 through 1995) to implement the optimum maintenance strategies for 55.145 km of analyzed roads:

Year	*Funding (DM)*
1991	5,441,260
1992	140,085
1993	113,197
1994	133,678
1995	30,101

These figures do not cover costs for the partial improvement of the route (grade, radius, cross section), special costs (e.g., for drainage and slope improvement), and winter maintenance costs.

If funding cannot be secured for implementing optimum maintenance strategies in their entirety, then the HDM-III model enables selection of other appropriate maintenance strategies. Thus the financial loss is reduced to a minimum in case of insufficient funding.

Critical Review of HDM-III Results

The HDM model has not previously been applied in Central European countries. The practical experience on the

TABLE 4 Optimum Maintenance and Rehabilitation Strategies for Bavarian Road Network

Road section	Chainage from km to km	Road length (m)	Maintenance alternative	Maintenance activity and year of implementation (time period: 1991-2000)
B 2/1	30.960 - 31.120	160	ALT 15	140 mm strengthening in the year of 1991
B 2/2	34.120 - 34.450	330	ALT 15	
B 2/3	38.000 - 40.500	2.500	ALT 15	
St 2063/4	34.600 - 31.120	700	ALT 15	140 mm strengthening; 1991
St 2063/5	35.850 - 36.580	730	ALT 18	new pavement construction;1991
St 2063/6	37.300 - 37.640	340	ALT 15	140 mm strengthening; 1991
St 2063/7	37.700 - 37.800	100	ALT 07	surface treatment(ST);1992 & 1999
St 2063/8	44.900 - 45.900	1.000	ALT 07	ST; 1994 and 1999
St 2067/9	1.750 - 3.080	1.330	ALT 14	140 mm strengthening; 1991
St 2068/10	32.465 - 33.470	1.005	ALT 07	ST; 1994
St 2068/11	33.470 - 33.570	100	ALT 15	140 mm strengthening; 1991
St 2068/12	33.570 - 33.670	100	ALT 15	140 mm strengthening; 1991
St 2069/13	2.550 - 3.310	760	ALT 15	140 mm strengthening; 1991
St 2069/14	3.930 - 5.395	1.465	ALT 18	new pavement construction; 1991
St 2069/15	5.395 - 6.270	875	ALT 15	140 mm strengthening; 1991
St 2070/16	6.330 - 6.560	230	ALT 10	40 mm WC overlay (2002)
St 2070/17	11.260 - 13.045	1.785	ALT 13	80mm strengthening;1991(and2002)
St 2070/18	16.810 - 18.240	1.430	ALT 18	new pavement construction; 1991
St 2070/19	18.240 - 20.140	1.900	ALT 18	new pavement constructions; 1991
St 2349/20	22.220 - 26.310	4.090	ALT 15	140 mm strengthening; 1991
St 2073/21	1.700 - 3000	1.300	ALT 13	80 mm strengthening; 1991 + 40 mm WC overlay; 1993
St 2073/22	3.000 - 4.750	1.750	ALT 12	80 mm strengthening; 1991 + 40 mm WC overlay; 1993
St 2073/23	4.750 - 5.800	1.050	ALT 13	80 mm strengthening; 1991 + 40 mm WC overlay; 1993
St 2073/24	6.000 - 8.000	2.000	ALT 13	80 mm strengthening; 1991 + 40 mm WC overlay; 2001
St 2073/25	8.000 - 9.500	1.500	ALT 13	80 mm strengthening; 1991
St 2073/26	10.000 - 12.500	2.500	ALT 15	140 mm strengthening; 1991
St 2073/27	13.500 - 14.500	1.000	ALT 15	140 mm strengthening; 1991
St 2073/28	14.500 - 15.850	1.350	ALT 14	140 mm strengthening; 1991
St 2073/29	15.850 - 16.900	1.050	ALT 15	140 mm strengthening; 1991
STA 3/30	19.880 - 23.810	3.930	ALT 10	40 mm WC overlay; 1999
STA 3/31	23.810 - 26.920	3.110	ALT 07	ST; 1994 and 2000
STA 3/32	27.600 - 28.960	1.360	ALT 14	140 mm strengthening; 1991
STA 3/33	29.500 - 37.040	7.540	ALT 15	140 mm strengthening; 1991
STA 9/34	0.050 - 1.260	1.210	ALT 14	140 mm strengthening; 1991
STA 9/35	2.125 - 4.200	2.075	ALT 14	140 mm strengthening; 1991
Gem. 36	13.200 - 14.700	1.500	ALT 18	New pavement construction

model use has mainly been gained in the developing countries (countries where the traffic volume is much smaller). The aim of this study was to investigate possibilities of HDM application under conditions prevailing in Bavaria and to determine possible conditions and limitations related to such application.

Besides the useful information and realistic results obtained during HDM model application under Central European conditions, the study has shown that some questions still remain open.

Calculation Procedure

The calculation (simulation) procedure using the HDM model requires numerous input data. On one hand, the collection of such a huge amount of information may cause considerable practical difficulties; on the other hand, unrealistic results may be the outcome if sufficiently accurate data are not available. Optimization results based on such a great number of parameters are generally burdened with at least some inaccuracies.

In addition, each individual parameter is to some extent unreliable. For instance, it is not known whether the traffic load in an individual case amounts to 8,000 or 9,000 vehicles per day, although this information significantly influences the final result.

All input data used in the calculation procedure revolve more or less around a single average value, which means that the accuracy of the registered parameter values relies on a single statistical probability. In cases when the influence of individual parameters is multiplied, the accuracy of input parameters decreases with the number of parameters used.

This point can thus be summarized as follows:

- Too many input data are required,
- Each individual parameter is to some extent unreliable, and

• The accuracy of input parameters is significantly reduced in case of parameter multiplication

Influence of Individual Parameters

To what extent do individual parameters influence the final result? After answering this question, the decision can be made to (*a*) omit irrelevant parameters, and (*b*) define highly significant parameters, that is, those that must be determined with the highest level of accuracy (sensitive visual determination or determination through measurement).

It would therefore be sensible to examine in more detail parameters such as the precipitation and thickness of layers forming the pavement structure. It can also be assumed that the heavy traffic load considerably influences the pavement condition. Consequently, the traffic load must be determined with great precision, which, although not a great problem in countries having low traffic density, is difficult to achieve in Central European countries characterized by a high level of motor vehicle traffic.

Calculation Results

Some calculation results cannot logically be explained, thus, in some cases the results can hardly be considered plausible. The following conclusions can be made by comparing optimum maintenance strategies and pavement construction methods defined using the HDM model to the German guidelines for road pavement standardization [*Richtlinien für Standardisierung des Oberbaues von Verkehrsflächen* (RStO 86)]:

• In one-third of calculations made according to HDM model, the strengthening level is greater when compared to RStO 86 guidelines.

• In the middle third of calculations made according to HDM model, the strengthening level is lower when compared with RStO 86 guidelines.

• In the final third of model calculations, the strengthening level according to HDM model coincides with RStO requirements.

The reason for this discrepancy may, among other things, be sought in the fact that RStO 86 guidelines do not account for road condition data. On the other hand, the HDM model is based on the modeling procedure requiring numerous input data of variable significance and accuracy.

It would therefore not be reasonable to accept HDM calculation results without previously performing an appropriate plausibility control. This plausibility control may consist in a comparison with relevant calculations (i.e., with the corresponding guidelines for pavements). The plausibility control could also be performed on the basis of subjective evaluation of the technical and economic feasibility of the solution obtained using HDM system. Such a control should be performed by an experienced pavement engineer.

Immediate Maintenance Activities

Some maintenance strategies defined as optimal by the model would require immediate realization of some maintenance activities (this particularly concerns pavement strengthening). However, this could hardly be considered realistic in practical situations, since such hopeless road conditions as those defined by the model can hardly be expected under the circumstances now prevailing in Central Europe. If this were the case, the sections analyzed would be in a state of complete collapse in the spring, which is not true for the well-maintained Bavarian roads.

Two aspects should be considered when attempting to provide a rational explanation for such HDM-model results.

1. The reason for requiring immediate pavement strengthening as an optimum maintenance strategy may be sought in the philosophy of the HDM system, which examines the road maintenance issue by assessing costs incurred by the national economy (i.e., primarily the road user's costs and then the employer's costs).
2. The need to perform such immediate maintenance activities generally arises in case of pavements characterized by a small asphalt layer thickness. However, such layers may prove satisfactory if an effective drainage system is provided. In other words, effects that are the same or similar to pavement strengthening may be obtained by appropriate drainage system improvements. In this sense, it is appropriate to mention that, for several sections situated on national road St 2073 and characterized by a relatively small traffic volume, the HDM model proposes strengthening using asphalt layers 140 mm in thickness. In addition, geometrical features of the route should be considered to reduce the total transportation costs on these sections.

As for costs related to the implementation of optimum maintenance strategies, it should be noted that the HDM model takes into account only the pavement construction costs. Other costs required to provide for routine maintenance activities (drainage, slope improvement) are not included in the cost calculation when the HDM model is used.

The model also does not consider the route improvement costs (for some of the sections analyzed, improvements are required not only because of the poor pavement conditions, but also to improve locally deficient route elements).

It would therefore be interesting to consider some alternative maintenance strategies to be implemented by the HDM model instead of the present expensive maintenance activities such as multiple-asphalt-course strengthening and pavement rehabilitation. Such alternative solutions for the maintenance and rehabilitation of roads might prove acceptable not only for Central European roads, but also for road networks existing in other regions of the world.

The analysis of influence exerted by individual parameters on the HDM-III model results (the sensitivity analysis) was performed to gain a better insight into some of the issues studied in this paper. This analysis consisted in selecting maintenance strategies (optimum strategy determination) depending on changes in the values of individual parameters. In other words, the influence of individual parameters on calculation results was examined in the scope of that analysis. The analysis provides more accurate answers to such questions as Which parameters may be left out due to their insignificance for the calculation? and Which parameters are particularly significant for the calculation (i.e., for which parameters must a high level of accuracy be ensured)?

Sensitivity Analysis of HDM-III Model

Analysis of the HDM-III model sensitivity to the influence of individual parameters (and of their input data) was performed for two road sections: Section 5 (St 2063, from KM 35.850 to KM 36.580) and Section 10 (St 2068, from KM 32.465 to KM 33.470). These sections are characterized by the features described in Table 5.

Section 5 is in a relatively poor condition with cracks on approximately 3 percent of the pavement surface, an average rut depth of 10 mm, and an IRI of 8.7. The precipitation rate for this region is 0.09 m/month.

TABLE 5 Characteristics of Sections 5 and 10

Characteristic	Section 5	Section 10
Pavement structure		
AC thickness (cm)	3	4
Gravel subbase thickness (cm)	20	15[a]
Frost-resistant layer thickness (cm)	0	50
ADT (1991)		
Passenger cars	9,205	8,790
Trucks	136	247

[a]Bitumen-stabilized gravel.

The HDM model results based on these input parameters show that an optimum maintenance strategy for this section would be that specified for ALT 18, that is, complete replacement of the existing pavement (rehabilitation by reconstruction) in 1991 and strengthening, several years after reconstruction, using a wearing course of asphalt concrete 40 mm in thickness, as soon as the unevenness attains the value of 3.5 IRI.

Conversely, Section 10 is in very good condition: cracks appear on 1 percent of the pavement surface, the average rut depth is only 4 mm, and the unevenness amounts to 1.2 IRI. The precipitation rate is also 0.09 m/month. In this case, an optimum maintenance strategy proposed by the HDM model is the alternative ALT 07, that is, surface treatment for 25 percent of the damaged surface and pavement rehabilitation by full reconstruction at a later time when unevenness attains the value of 7.0 IRI.

The sensitivity analysis was made for the following six parameters:

1. Structural number (SN),
2. Bearing capacity [California bearing ratio (CBR) value for the subgrade or subbase],
3. Unevenness (IRI),
4. Traffic volume (average daily light and heavy traffic),
5. Precipitation rate, and
6. Unit rates for maintenance activities.

The calculation was performed as a simple sensitivity analysis whereby a specified parameter is modified while all others remain unchanged.

The values of individual parameters were modified within the following ranges:

- SN for Section 5 gradually changed from −30 to +100 percent, while this number for Section 10 gradually came down to −70 percent.
- The CBR value for Section 5 gradually changed from −80 to +100 percent, while this value for Section 10 decreased from +25 to −70 percent.
- The unevenness value for Section 5 gradually decreased (in increments of 1.0) from 8.7 to 2.0 IRI, while this value increased by several times for Section 10 (from 1.2 to 10.0 IRI).
- The traffic volume for Section 10 remained unchanged as this section is not suitable for analyzing sensitivity of this parameter due to its strong pavement structure. In case of Section 5, the traffic volume decreased by −30, −50, and −80 percent.
- The precipitation rate for both sections gradually changed in −50 percent increments up to +100 percent.

• Unit rates for both sections gradually changed in −50 percent increments up to +100 percent.

The sensitivity analysis shows that of the six parameters examined, only the change in unevenness and in traffic volume resulted directly in the change of an optimum maintenance strategy. Thus the improvement of unevenness for approximately 200 percent (reduction of the roughness index from 8.7 to 5.0 IRI) resulted in selecting ALT 14 as an optimum strategy, instead of ALT 18. This means that by changing the roughness index for 1.7 times, that is, by improving evenness by 1.7 times, the strengthening by asphalt layers of 140 mm in total thickness appears as an optimum maintenance activity, instead of rehabilitation by full pavement reconstruction. On the other hand, the alternative ALT 14 replaces the previous ALT 07 as an optimum maintenance strategy for Section 10 due to the fall in evenness value manifested in the roughness index increase from 1.2 to 5.0 IRI. Practically, this means that in this case strengthening by 140-mm asphalt layers is more favorable than surface treatment. Consequently, these results show that *unevenness is an extremely significant parameter of the HDM system.* The sensitivity of the HDM system to the change in IRI (manifested through the preceding changes in optimum maintenance strategies) may also be manifested through the changes in total road-use costs or net present values.

The 80 percent traffic volume reduction results in the change of an optimum maintenance strategy, in the modification of time schedule for performing maintenance activities, and in the change in both maintenance costs and net present value. The 10 percent change in heavy-vehicle structure influences the total road use costs as well as the net present value. Similarly, the sensitivity analysis has shown that the 1 percent change in the number of vehicles results in a change in both maintenance strategy and net present value. These results show that *the traffic volume is a significant parameter of the HDM system.*

The change of other parameters (SN, CBR, monthly precipitation rate, and unit rates for maintenance activities) within limits set for this analysis did not result in the change of an optimum maintenance strategy (i.e., only slight differences in total road-use costs were observed). The changes in roughness index influence to a certain extent the time schedule for performing maintenance activities and hence the total maintenance and road-use costs.

Relatively small sensitivity in the HDM model to the change in unit rates for maintenance activities may be explained by the fact that vehicle operating costs account for up to 94 percent of the total transportation costs. Therefore, the percentage of maintenance in the total costs is insignificant.

The results of the analyses performed indicate that the SN, roadbed bearing capacity, precipitation rate, and unit prices for maintenance activities may be considered less significant parameters of the HDM system.

Conclusion

Particular emphasis has been placed on the sensitivity analysis performed to differentiate very significant from less significant and negligible parameters. The sensitivity analysis results constitute the basis for classifying input parameters according to their significance for the HDM system. This results in a double benefit: (*a*) the total number of parameters is reduced since some of them may be neglected because of their insignificant influence on the final results, and (*b*) greater emphasis is placed on parameters that must be precisely quantified as they determine the accuracy of the results. It was established that only two of the six analyzed parameters may be considered really significant: pavement surface unevenness and traffic volume. The detailed analysis showed that pavement surface unevenness is a particularly important parameter and that traffic volume is one of the significant parameters for the HDM system. It is interesting to note that the influence of maintenance cost on the HDM model is practically negligible, which is due to the considerably greater proportion of vehicle operating costs in relation to total transportation costs (>94 percent). Such a great proportion of vehicle operating costs has also been noted in several road studies performed in developing countries (75 to 95 percent) (*4*).

The final part of the paper stresses that some of the details of the HDM-III model should be modified and also simplified in part so that it may properly be used under conditions prevailing in Central Europe. These simplifications primarily concern the differentiation of significant from negligible parameters. The HDM-III model should be used as a valuable tool in selecting appropriate road maintenance strategies, although it should not lessen the role of experienced pavement engineers who decide on the spot whether measures proposed by the model are acceptable. However, the results of this investigation clearly point to the many benefits that might be gained through use of the HDM-III model within the pavement management system, provided that regional specificities have been evaluated realistically.

With respect to future model-related investigations, which certainly must be performed, the primary task is to determine criteria for deciding at what point pavement maintenance or rehabilitation activities should begin. It seems that the most favorable maintenance strategy for roads where traffic density exceeds 1,000 vehicles per day should be based on the percentage of wide cracks in the pavement surfacing, not on the pavement surface unevenness (which is currently the case). This conclusion is based on the experience gained by Riley (M. Riley, personal communications, 1991–1992) on road maintenance projects in Thailand and Indonesia, where he analyzed the possibility of applying the model for optimizing road maintenance costs. It is obvious that these initial findings need to be further confirmed from the standpoint of practical experience.

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Maintenance and Rehabilitation Effectiveness Evaluation (MAREE) System

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Every year, hundreds of millions of dollars are invested in cities, provinces, and states to preserve the pavement system. The challenge is to spend these funds wisely. To do this, one must plan, then observe, evaluate, and analyze the results of various alternative actions in order to learn which are suitable for which conditions. The concepts of two rational and systematic procedures to analyze maintenance and rehabilitation options or treatments are introduced. The first procedure refers to the rationality testing and formulation of past maintenance and rehabilitation (M&R) selection policies. More precisely, it tests the rationality of the past decision-making process in selecting M&R options within an administration, measures its degree of rationality, identifies the prerehabilitation conditions that led in the past to the selection of each specific option, and mathematically formulates a systematic decision rule that describes past M&R option selection. The second procedure evaluates the performance and the optimum application conditions of each M&R option treatment. It verifies whether and to what extent the performance of a specific treatment depends on the prerehabilitation characteristics of the treated sections. In essence, the intent is to formulate a systematic decision rule that mathematically expresses the optimal conditions within which a specific M&R option performs well.

Public authorities face many demands in making spending decisions. Paved roads have difficulty competing for funds in such an environment. This is why it is important to quantify the effectiveness of an intervention (*1*). The initial decision to spend money on paving roads may be considered an investment. Equally important, however, are the continuing decisions to spend money on maintenance and rehabilitation (M&R). These continuing decisions can have significant long term effects in terms of costs to the road users and costs to the road owners. If the proper sections of the roads receive funds and the right type of work is done at the right time, these long-term costs can be minimized and good value obtained.

Spending decisions on paved roads should consider what type of M&R is best for the traffic and the pavement characteristics. The challenge for wise spending decisions is to observe, evaluate, and analyze the results of alternative actions to identify which are suitable for which conditions.

In this paper, the concepts of two rational, systematic, and complementary procedures to analyze M&R options are introduced. The two procedures, shown in Figure 1 and applied on a subnetwork level basis, refer to (*a*) the rationality testing and formulation of the past M&R option selection policy, and (*b*) the performance evaluation and the formulation of the optimum application conditions of each option (2).

The tasks of the first procedure, as illustrated in Figure 2, are to

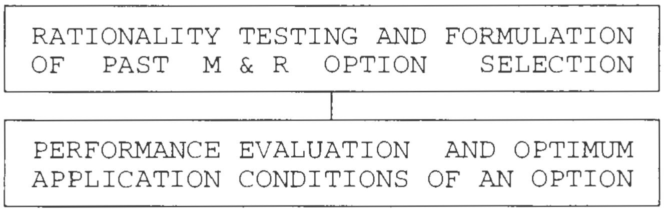

FIGURE 1 Rehabilitation performance evaluation.

1. Test, within an administration, the rationality of the past M&R decision-making process as to the extent it depended on the prerehabilitation variables,
2. Measure the degree of rationality or consistency of that process,
3. Identify, if the selection process is found to be rational, the prerehabilitation conditions that led in the past to the selection of each specific type of M&R, and
4. Formulate a systematic decision rule that mathematically describes the past M&R selection policies.

In the event that the process is found in Step 1 to be rational (i.e., based on the prerehabilitation variables), the end product in Step 4 is clearly a decision-making system that takes the same decisions as local administrators have taken in the past. If the selection of a M&R option is found in Step 1 to have been performed regardless of the prerehabilitation conditions, the decision process is strongly subjective. In this case, selections are independent of the prerehabilitation variables (i.e., regardless of the pavement condition, its traffic, and characteristics).

The primary aim of the second procedure is to analyze the performance of each option. It verifies whether, and to what extent, the performance of a specific M&R option depends on the prerehabilitation characteristics of the treated sections, such as the pavement structure and capacity, soil, traffic, climate, surface condition, and roughness.

The tasks of the second procedure, as illustrated in Figure 3, are to

1. Test whether the performance of a specific intervention or option depends on the prerehabilitation variables and to what extent,
2. Measure the degree of influence of each prerehabilitation variable on the postapplication performance or success of an intervention,
3. Identify the prerehabilitation conditions leading to the good or the bad performance of a M&R intervention, and
4. Formulate a systematic and automatic decision rule that mathematically expresses the optimal conditions within which a specific M&R treatment performs well.

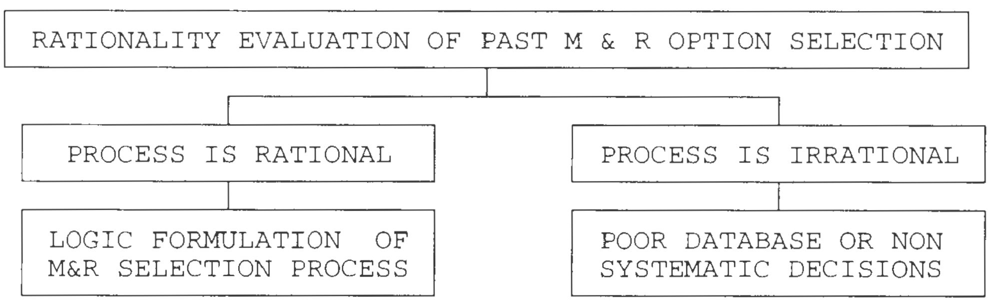

FIGURE 2 Rationality analysis and formulation of past M&R selection.

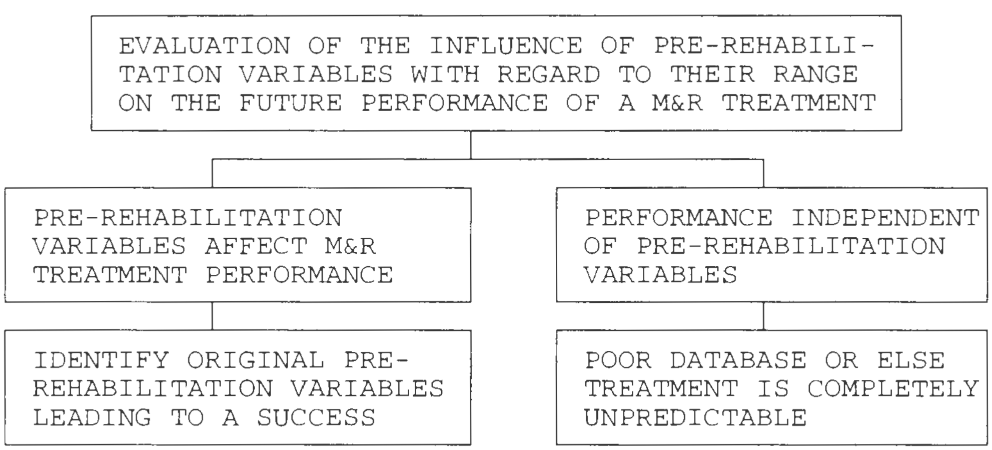

FIGURE 3 Performance evaluation and optimal application conditions of option.

If none of the prerehabilitation variables affects the performance of a treatment, then the treatment is totally independent of these variables and the performance cannot be forecast.

The treatment selection is therefore irrational, and, unless often successful, such M&R options should be avoided because of unknown postapplication performance.

In the expected situation in which the prerehabilitation variables affect the performance of a M&R treatment, the procedure isolates the following:

- The most influential prerehabilitation variables that affect future performance.
- The extent of their contribution, and
- The combined intervals within which they are influential and within which a specific M&R treatment performs well or badly.

M&R Decision Policy Rationality Testing and Formulation

Method

The problem addressed in this section is to assess, in the light of the recorded preapplication conditions, which treatments have been used and in which conditions. The prerehabilitation conditions clearly refer to the condition, characteristics, and properties of the pavement before the application of the treatment. The task in the next section is to assess which option should be used and for which conditions by evaluating the postapplication performance of each M&R option within the administration's network.

The global problem of formulating optimal decision rules involves first the formalization of the actual M&R selection practice rules (Step 1). It then involves the detection of successful M&R options (Step 2) for various intervals of preapplication conditions. The formulation of the past M&R decision-making process (Step 1) is needed to compare with the optimal M&R decision policies (Step 2).

The developed procedure is explicative. It relates a qualitative variable—the choice of an intervention—to a set of parameters that identify a section before rehabilitation. These variables integrate traffic, climate, soil, structural, distress, and roughness data. It is descriptive in the sense that it reduces to a minimum the number of prerehabilitation quantitative variables that explain the qualitative variable that is the choice of the M&R option. It is finally predicative since it defines a decision making or an assignment tool that allows one to estimate the qualitative variable (past M&R choice) for any set of prerehabilitation quantitative variables.

In this context, each treated section is identified by a set of prerehabilitation variables and a qualitative variable varying from 1 to r, designating the M&R option. The process is to deduce, from past practice, a rule that stochastically associates for any set of preintervention values, a specific M&R option, formalizing the past decision policy that will be compared with the optimum policy presented in Step 2.

Model

Let us suppose $\Omega = \{w_1, w_2, \ldots, w_n\}$, the set of past rehabilitated sections w_i having received one of r M&R options. Ω consists of r classes $C_1, \ldots, C_r$ whereas each C_j regroups the sections w_i that received option j; j equal to one of r possible options.

Let Φ be a function from Ω to Γ that associates with each section w_i a vector of p prerehabilitation variables related to the pavement structure, soil, traffic, climate, capacity, surface condition and roughness. The values of the prerehabilitation variables are identified for section w_i as the components of the vector $\Phi(\mathbf{w}_i)$:

$$\Phi(\mathbf{w}_i) = [x_1(w_i), x_2(w_i), \ldots, x_n(w_i)] \qquad \text{for instance, } \Phi(\mathbf{w}_i) = [100, 200, 80]$$

where

$x_1(w_i)$ = traffic intensity before rehabilitation (i.e., DTN = 100),
$x_2(w_i)$ = deflection before rehabilitation (i.e., 200 μm), and
$x_3(w_i)$ = amount of cracking before rehabilitation (i.e., 80 discipline).

The function Φ associates with any section w_i a vector of p variables:

$$\Phi : \Omega \longrightarrow \Gamma$$
$$w_i \longrightarrow \Phi(\mathbf{w}_i) = [x_1(w_i), x_2(w_i), \ldots, x_n(w_i)]$$

A decision rule is a function Θ applied from Γ to $\{1, \ldots, r\}$ that associates with each vector $\Phi(\mathbf{w}_i) \in \Gamma$ of prerehabilitation variables, a rehabilitation option $j \in \{1, 2, \ldots, r\}$

$$\Omega \xrightarrow{\Phi} \Gamma \xrightarrow{\Theta} \{1,2, \ldots, r\}$$
$$w_i \longrightarrow \Phi(\mathbf{w}_i) \longrightarrow j \qquad j \in \{1,2, \ldots, r\}$$

where

w_i = pavement section i;
$\Phi(\mathbf{w}_i)$ = prerehabilitation vector of pavement section w_i;
j = type of M&R treatment applied $= 1, 2, \ldots, r$;
Ω = set of rehabilitated sections under analysis; and
Γ = space of all vectors of prerehabilitation variables.

Conversely, if a section w_i is such as $\Theta[\Phi(\mathbf{w}_i)] = j$ then $w_i \in$ to C_j. This leads to a classification of all sections having received a specific treatment j in the class C_j.

The past M&R selection policy can be formulated with the following partition of Γ in j classes ($T_1, T_2, \ldots, T_r$):

$$T_j = \{\Phi(\mathbf{w}_i)/\Theta[\Phi(w_i)] = j\} \qquad j = 1, 2, \ldots, r$$

This expresses the partition of the multidimensional vectorial space generated by the prerehabilitation variables in j subspaces, such that each subspace T_j regroups those values of prerehabilitation variables or vectors that led in the past to the selection of the alternative treatment j.

For any other section of the network in need of a treatment, the function θ can stochastically assign the most frequently used treatment applied in the past for comparable sections in terms of the prerehabilitation vector. The decision-making selection, based on the maximum likelihood formula in discriminant analysis (2) that minimizes the error of misclassification, states that a pavement section is assigned to a rehabilitation treatment j if w_i has the highest probability P to belong to the associated partition T_j:

$$\Theta[\Phi(\mathbf{w}_i)] = j$$

$$\text{if } P(w_i \in C_j) = \operatorname{Sup} P[\Phi(\mathbf{w}_i) \in T_k]$$
$$j = 1, 2, \ldots, r \text{ and } k = 1, 2, \ldots, r$$

Figure 4 illustrates the rationality analysis of past M&R selection policies. It shows the prerehabilitation variables that most significantly affected the choice of Treatment A instead of Treatment B along with the combined boundaries or intervals of these variables that led to the selection of Treatments A or B. It may further be observed that sections received Treatment A when traffic intensity was less than 100, cracking was less than 20 percent, and bitumen penetration was larger than 5.

Performance Analysis and Optimum Application of Option

Method

This procedure relates to the performance evaluation of any M&R option and the rational formulation of its optimal application conditions.

Any M&R option should be evaluated in order to assess the conditions for which it performs well. The performance of an option is evaluated a number of years after it is applied and codified as either good or bad. The number of years after which a M&R option is classified as successful or not depends to some extent on data availability, although a minimum of 4 years is necessary before one can make any judgment.

The prerehabilitation condition and characteristics of the treated sections are further needed to carry out the analysis. This set of variables is the same as the one required in the previous procedure. The qualitative variable, however, instead of relating to the nature of the rehabilitation option, concerns its postperformance evaluation with respect to a good versus a bad rating.

The first step in the procedure is to verify whether the postapplication performance of an option depends on the prerehabilitation conditions and characteristics related to the pavement structure, soil, traffic, climate, structural capacity, surface condition, and roughness of the treated sections. When the prerehabilitation conditions and characteristics are found to affect the performance of a specific option, the procedure computes the degree of influence or the weight of each of those variables on the performance of that option. The procedure partitions, for that option, all possible combinations of preapplication characteristics in one of two outcomes: namely, good or bad future performance. It detects the values of the boundary limits or the combined intervals associated with these influential variables, beyond which a specific treatment performs

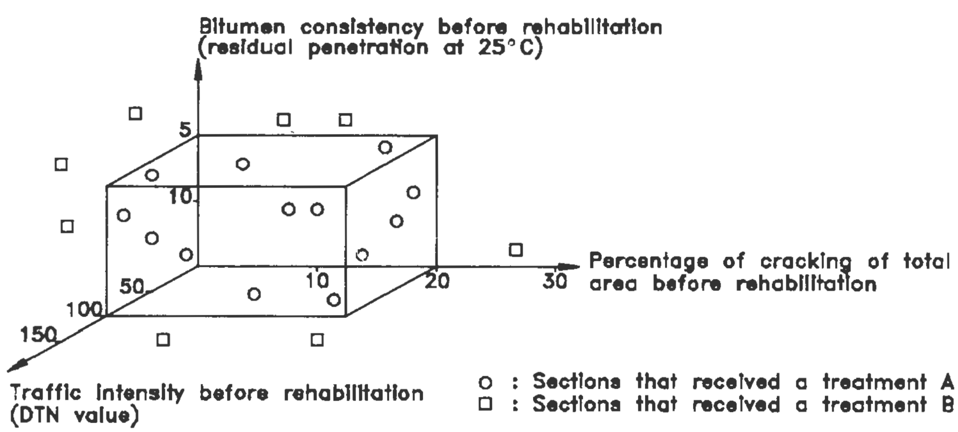

FIGURE 4 Rationality analysis and formulation of past M&R selection process.

well or badly. As a result, the procedure formulates a decision rule that expresses the probability that an option will perform well or poorly for any combination of prerehabilitation characteristics. The objective of this procedure is clearly to deduce a rehabilitation assignation tool that associates the best rehabilitation strategy for any deteriorated pavement characterized by its prerehabilitation parameters.

In this regard, this procedure formalizes the optimum M&R selection process that identifies the specific conditions for which a particular option is expected to perform well. This process is based on the tracking of the prerehabilitation conditions that did lead to good performance for each of the past applied M&R options. It should however be separately applied to each option. In the very particular case in which none of the prerehabilitation variables affects the performance of a specific M&R option, the latter is apparently totally independent of the collected prerehabilitation conditions and characteristics and its performance can never be forecast.

Such an alternative should be avoided, unless the treatment is cheap and often successful, because its postapplication performance (good or bad) is unpredictable. Another reason may be that the prerehabilitation characteristics are missing a major parameter that dictates the success or the failure of the option. In fact, the failure of a treatment, for instance, may indicate an independence with the prerehabilitation variables. This does not necessarily prove that the treatment is inappropriate. The explanation may be that the treatment was badly applied and quality-control data should in this case be integrated with prerehabilitation variables.

As an example, a very successful European patented chip seal treatment applied in Montreal failed and the treatment was rejected; later it was discovered that a binder component had been stored for more than a year in a warehouse.

The necessity of this M&R postapplication evaluation has been demonstrated, but its sufficiency will always be a function of common sense and engineering judgment.

Model

To fix ideas, let $\Omega = \{w_1, w_2, \ldots, w_n\}$ be the set of sections w_i having received one specific treatment, and r the number of postrehabilitation performance grades for instance good, fair, or bad. The set Ω consists of r classes $C_1, \ldots, C_r$. Each class C_j regroups the sections w_i that relate to specific postrehabilitation index j; j equals one of r possible performance indexes, $(j = 1, \ldots, r)$.

Let Φ be a function from Ω to Γ associating to each section w_i a vector of p prerehabilitation variables related to its surface, structure, and so on, and identified as

$$\Phi : \Omega \longrightarrow \Gamma$$

$$w_i \longrightarrow \Phi(\mathbf{w}_i) = [x_1(w_i), x_2(w_i), \ldots, x_n(w_i)]$$

A decision rule is a function Θ applied from Γ to $\{1, \ldots, r\}$ that associates with each vector $\Phi(\mathbf{w}_i) \in \Gamma$ of prerehabilitation variables, a postrehabilitation performance index $j \in \{1, \ldots, r\}$.

$$\begin{array}{c} \Phi \qquad \Theta \\ \Omega \longrightarrow \Gamma \longrightarrow \{1, \ldots, r\} \\ w_i \longrightarrow \Phi(\mathbf{w}_i) \longrightarrow j \qquad j \in \{1, \ldots, r\} \end{array}$$

Hence, if a pavement section w_i with a prerehabilitation vector $\Phi(\mathbf{w}_i)$ is such as $\Theta[\Phi(\mathbf{w}_i)] = j$ then w_i belongs to C_j. This leads to a classification of all pavement sections having a postrehabilitation performance index j in the class C_j. The identification of which sections lead to a specific postrehabilitation performance index can be deduced with the following partition of Γ in j classes $(T_1, T_2, \ldots, T_r)$ such as

$$T_j = \{\Phi(\mathbf{w}_i)/\Theta[\Phi(\mathbf{w}_i)] = j\} \qquad j = 1,2, \ldots, r$$

Figure 5 illustrates the partition of the space generated by the preapplication variables in two subspaces, such as each T_j $(j = 1, 2)$ represents the combined intervals that lead to the performance index j. Figure 5 shows that the evaluation of the performance and the optimal application conditions of a treatment is based on the prerehabilitation variables that most significantly affect its future performance. The function Θ assigns the most probable future performance index for any section with a particular set of prerehabilitation variables. The selection, based on maximum likelihood, in discriminant analysis (2) that minimizes the error of misclassification, assigns a performance index j if w_i has the highest probability P to belong to the associated partition T_j:

$$\Theta[\Phi(\mathbf{w}_i)] = j$$

$$\text{if } P[w_i \in C_j] = \operatorname{Sup} P[\Phi(\mathbf{w}_i) \in T_k]$$
$$j = 1, 2, \ldots, r \text{ and } k = 1, 2, \ldots, r$$

Application of MAREE Procedure: Data Analyzed

The pavement network of the city of Montreal accounts for more than 1500 km, of which about 150 km are rehabilitated each year for a budget of more than $15 million. The city network is divided into more than 5,000 sections. The network is evaluated with a visual surface

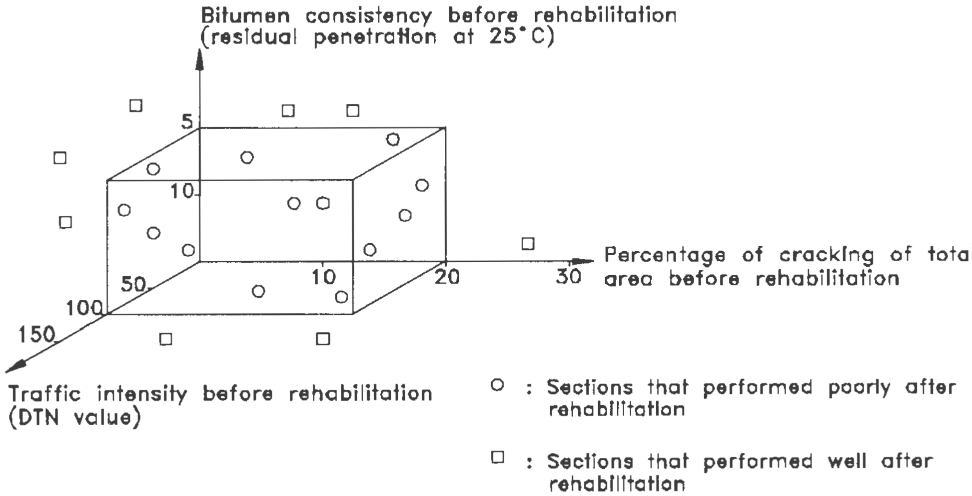

FIGURE 5 Performance evaluation and optimal application representation.

quality index (SQI) that reflects the global surface distress condition on a 0-to-5 scale in 1980 and in 1985. The higher the visual SQI (maximum of 5), the more the section is distressed; conversely, the lesser the visual SQI (minimum of 0), the better the section. By city standards, a value of 3.25 indicates a need in the sense that some M&R treatment may eventually be due. The visual SQI introduced by Joseph Hode Keyser has been gathered by the city for more than 20 years and depends on the average visual evaluation of the distresses by three evaluators (2).

The data analyzed include the following variables:

- Visual SQI in 1980 and 1985 (SQI_{1980}, SQI_{1985}) for 128 sections overlaid in 1980 with a 40 mm of asphalt concrete (AC) versus 180 nonoverlaid sections;
- Traffic intensity indicated in vehicles per day (traffic); and
- Pavement construction year (construction). It does not include either a roughness or a structural capacity index.

The data from the city of Montreal were used to test the system by

- Formulating mathematically on what basis past decisions as to the application of a given treatment were triggered and how consistent or rational was this decision making, and
- Identifying the conditions in which the application of a given treatment led to good postintervention performance (success), the condition in which case it did not (failure), and the predictability of the performance of that treatment.

FORMULATION OF TRADITIONAL DECISION RULE

This first procedure is performed on the data of the city of Montreal. The analysis is carried out in order to assess the particular prerehabilitation conditions of traffic and SQI (SQI_{1980}) that led to the application of a 40-mm AC resurfacing in 1980.

The data included the SQI_{1980} (1980) and the traffic (1980) for 180 unsurfaced sections and 128 surfaced sections. Figure 6 illustrates the sections overlaid in 1980, and Figure 7 illustrates the sections that were not overlaid in 1980.

The data are analyzed with the past decision rule rationality testing and formulation procedure. The similarity test performed between the overlaid and nonoverlaid populations, with regard to the prerehabilitation variables, indicates a probability of 2.29 percent. (If the two populations are assumed to be similar, the probability of obtaining the collected data is 2.29 percent.) In other words, there was a substantial difference in SQI and traffic just before the treatments in 1980, between the overlaid and the non overlaid sections.

The two prerehabilitation variables (SQI_{1980} and traffic) did affect the decision making process as to the choice of a 40-mm AC resurfacing. The impact or the weighting factor associated with the traffic in the decision making was 63 percent, as compared to 37 percent for the SQI in 1980. Traffic was more important in the mind of the decision maker than the pavement surface condition.

The equation of the optimal straight line that optimally separates the sections that received the treatment from those that did not is calculated as shown earlier in the paper:

$$10^{-3} * \text{traffic} + 8 * SQI_{1980} = 34$$

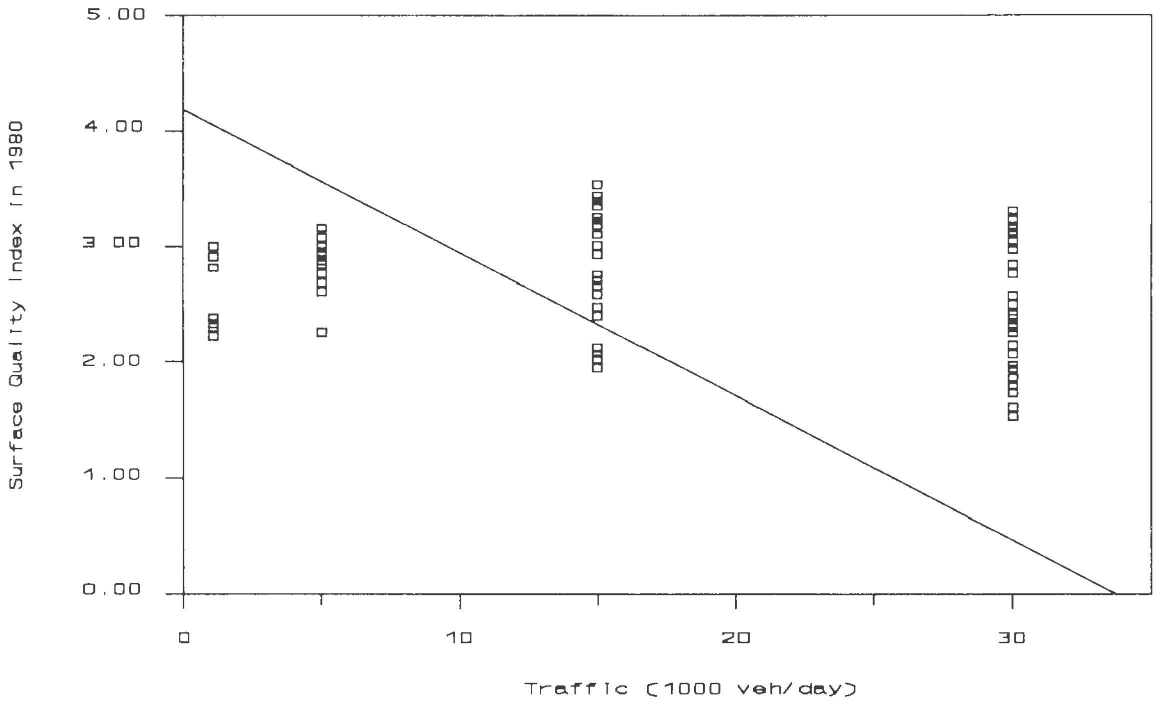

FIGURE 6 Illustration of sections overlaid in 1980 with 40 mm AC, clearly showing strong concentration above optimal separation line.

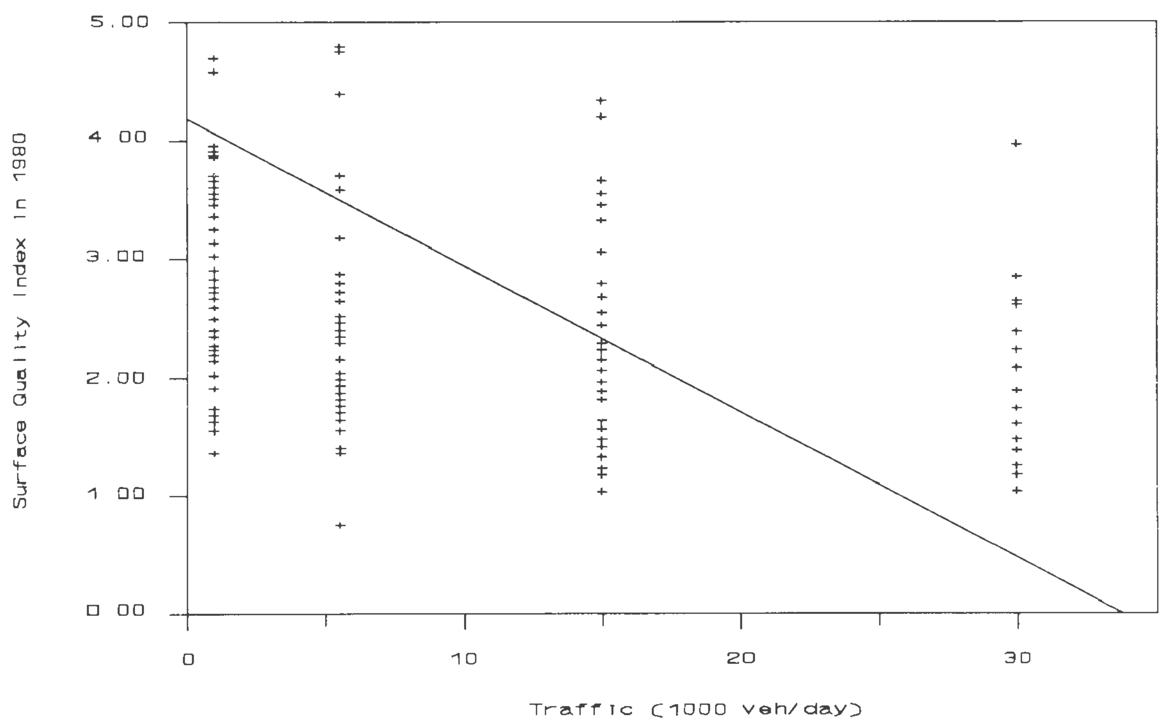

FIGURE 7 Illustration of sections not overlaid in 1980 and clearly showing strong concentration below optimal separation line.

The diagonal straight line cutting each of the two Figures 6 and 7 by half indicates the optimal cutting point that separates the sections that did and did not receive treatment. It is the optimal straight line that, in simple terms, minimizes the error of misclassification. It may be observed that over this optimal line is a concentration of overlaid sections, as illustrated in Figure 6; conversely, below this line is a concentration of nonoverlaid sections, as illustrated in Figure 7.

The construction year had such negligible effects that it was eliminated from the analysis.

Evaluation of Performance of Treatment

This second procedure was also performed on the data from the city of Montreal. The analysis was carried out to assess the prerehabilitation conditions of traffic and SQI (SQI_{1980}) that led in 1985 to a good or a bad performance of a 40-mm asphalt resurfacing that was done in 1980.

The data included the traffic and the SQI_{1980} for 128 overlaid sections in 1980. Of these, 84 sections remained in good condition in 1985 with an SQI_{1985} below 2.0 and 29 sections deteriorated significantly with an SQI_{1985} above 3.25. Figure 8 illustrates the 29 sections in bad condition in 1985, and Figure 9 plots the 84 sections in good condition in 1985.

The data were analyzed with the performance analysis and optimum application of a treatment procedure. The similarity test performed between the sections in bad condition and the sections in good condition indicates a probability of only 0.2 percent for the prerehabilitation variables of these two groups to be similar. (If the two populations are assumed to be similar, the probability of obtaining the collected data is 0.20 percent.) The similarity assumption between the sections in good and bad condition was rejected since the probability is small. In other words, there is a substantial difference in SQI_{1980} and traffic in 1980 between the sections with good and the sections with bad performance in 1985. Therefore, the two prerehabilitation variables (SQI_{1980} and traffic) do affect the performance of the resurfacing. The weighting factor associated with the traffic in influencing the results is 68 percent as compared with 32 percent for the SQI_{1980}. Traffic affects the performance of a 40-mm AC resurfacing more than does the prerehabilitation surface condition. It is furthermore observed that with higher traffic, the performance of the resurfacing is equal to or better than that for lower traffic. This can be due to a number of reasons, including compaction from traffic and stronger initial designs for the high traffic sections.

The formulation of the equation of the optimal decision process that, in simple terms, optimally separates in the SQI_{1980}-traffic graph, the sections that performed well from those that did not, is calculated as shown earlier:

$$10^{-3} * \text{traffic} + SQI_{1980} = 16$$

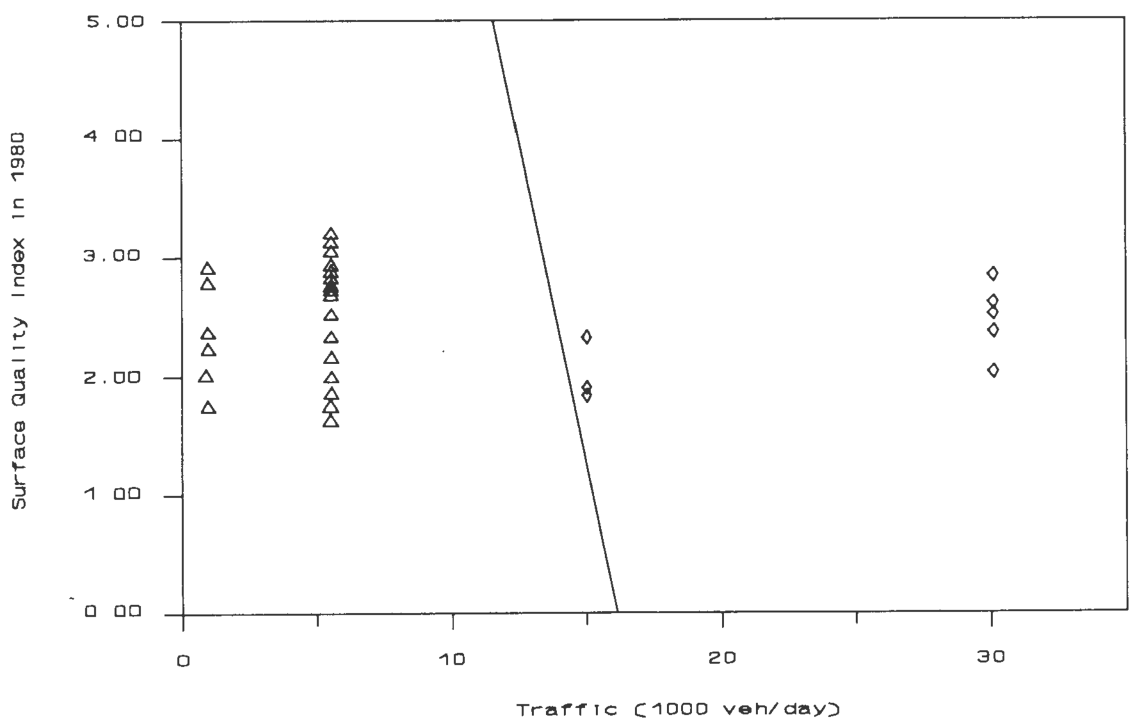

FIGURE 8 Sections overlaid in 1980 and in bad condition (index > 3.25) are present mostly to left of optimal separation line.

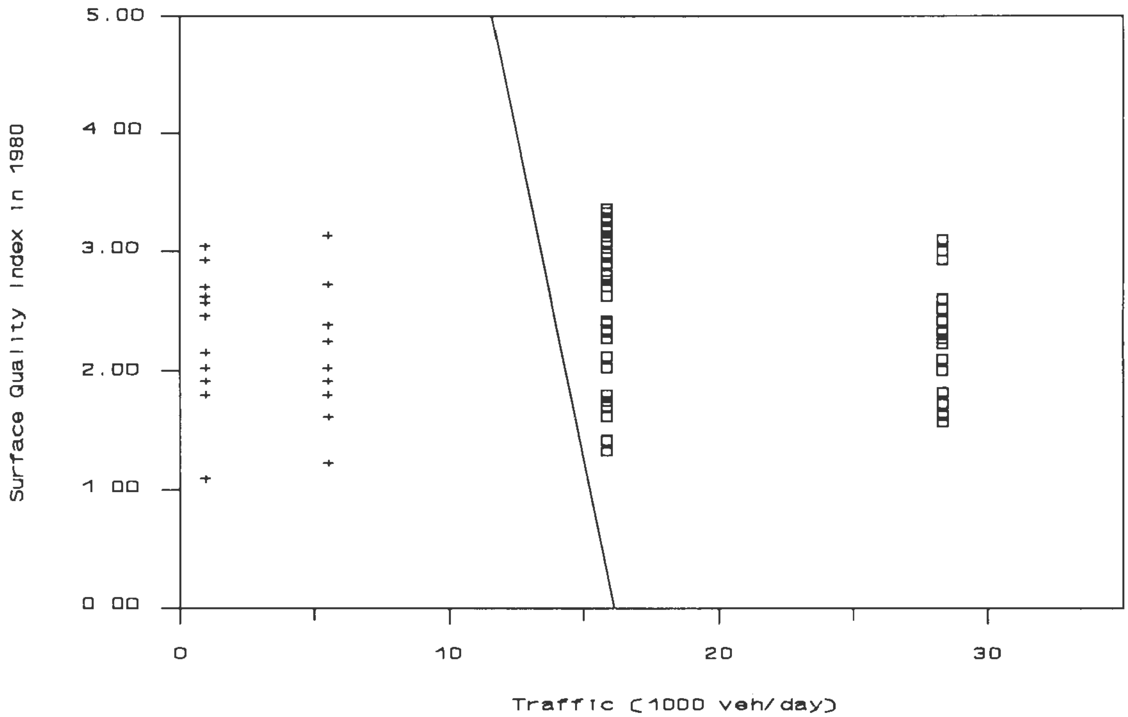

FIGURE 9 Sections overlaid in 1980 and in good condition (index < 3.25) are present mostly to right of optimal separation line.

This optimal straight line, shown in Figures 8 and 9, minimizes misclassification errors. It may be observed that there is a concentration of failed sections on the left of this optimal line, as illustrated in Figure 8, and that there is a concentration of successes on the right of the line, as shown in Figure 9. In this case, too, the construction year had negligible effects and was eliminated.

CONCLUSIONS

The essence of the twofold MAREE methodology is its usefulness in establishing an understanding of pavement performance under various M&R treatments. The system provides the basis of a practical, working package. The framework for integrating the MAREE system into pavement performance modeling and decision-making processes should have a general or universal applicability in pavement management systems. MAREE, of course, does not provide the final decisions, but it certainly is a set of complementary tools that can aid management in selecting M&R options.

The major conclusions arising from the application of the MAREE methodology to the data base of the city of Montreal include the following:

1. MAREE identifies the criteria on which past M&R options were selected, the criteria that were eliminated from the selection process, and the importance attributed to each criterion. The comparison of resurfaced and unresurfaced sections shows a probability of independence between their preapplication conditions of only 2 percent. The weighting factor associated with the preapplication traffic in the decision making is 63 percent, as compared with 37 percent for the preapplication surface condition.

2. MAREE formulates the past M&R selection process in terms of the two or three most influential criteria. This is achieved by formulating the equation of the separation line or plan, within the space generated by the criteria retained, between the different M&R options. This results in a decision-making system that takes the same decisions as in the past, allowing the analyst to project the future condition of the network for various budgets in case the M&R options were to be selected as in the past. Analysis of the choice of a 40-mm resurfacing provides, in Figures 6 and 7, a separation line that optimally segregates the sections that received a resurfacing from those which did not.

3. MAREE verifies, for each M&R option, whether its performance depends on the preapplication conditions. In case one or more of the prerehabilitation conditions affects the M&R performance, then the extent of the influence of each is determined. Analysis of the performance of the 40-mm resurfacing, 5 years after it was applied, shows a probability of independence between the performance of the treatment and the pretreatment variables of about 0.2 percent. The weighting factor associated with the

prerehabilitation traffic is 68 percent, as compared with 32 percent for the prerehabilitation surface condition.

4. MAREE formulates the specific combination of preapplication conditions that lead to good or bad performance of a particular M&R treatment. The resulting equation that separates the well from the poorly performing 40-mm treatments is shown in Figures 8 and 9 on a prerehabilitation traffic-versus-condition plan.

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Introduction of Investment Analysis into Pavement Management Practices in the Philippines

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The successful implementation in the Republic of the Philippines of a powerful and sophisticated pavement management system is discussed. This system is suitable for road network applications ranging from national strategic road networks to regional or district arterial and collector/distributor networks. The system consists of an accurate and up-to-date locational reference system for the road network; automated pavement condition data collection techniques; data management, data access, and data presentation techniques based on an easy-to-use geographic information system, which also provides menu control of data analysis processes; and a pavement investment analysis system. Particular features of the investment analysis system, based on the World Bank Highway Design and Maintenance Standards (HDM-III) package, include the abilities to (*a*) analyze networks of any size, by classifying network elements into pavement categories; (*b*) determine economic impacts of alternative maintenance strategies over the pavement life cycle, by predicting pavement deterioration under the action of maintenance strategies over the life cycle, and predicting the life-cycle cost streams that arise under each strategy; (*c*) include both agency costs and road user costs (i.e., vehicle operating costs and user time costs) in the economic analysis; (*d*) determine the optimum maintenance strategy for each pavement category under budget constraints, or average network condition standard constraints; and (*e*) determine an optimum distribution of budget allocation across a 3-year budget program. The HDM package has proven to be adaptable to technological environments beyond its original domain of relevance. In this project, successful performance and economic modeling of concrete pavements has been achieved, based on historical performance data. Successful implementation of a pavement management system in any road authority requires that three principal issues covering institutional impact be adequately addressed: technology impact, management commitment, and follow-through from planning to delivery.

In 1991 the Government of the Republic of the Philippines embarked on an initiative to introduce formal pavement management practices into the management of maintenance of the Philippines national road network. The initial phase of the initiative was a pilot project designed to introduce appropriate technology and procedures into the planning and administration of pavement upkeep strategies applied to the national network of Luzon Island, with a view to national implementation of a comprehensive computer-based pavement management system (PMS) later. The initial project was also to establish a rolling periodic and preventive maintenance program for national roads in Luzon, on the basis of outputs of the pilot PMS.

Development and implementation of the pilot PMS was executed by a consortium of Australian public sector–owned organizations for the Philippines Department of Public Works and Highways (DPWH), and was funded by a technical assistance grant from the Asian Development Bank.

This paper describes the salient features of a principal component of the pilot PMS—a pavement investment analysis system. This analysis system provides a major decision support tool for formal planning and programming of maintenance and rehabilitation works, based on objective assessment of priority needs, and economic justification in terms of maximized future community benefits.

Scope of Pilot PMS Project

The requirements of the PMS were characterized by

1. Pavement rating methodologies encompassing roughness, visual condition, structural capacity, and associated data base management facilities,
2. An investment modeling system capable of determining
   –Prioritized programs of periodic and preventive maintenance on road sections under given budgetary constraints,
   –Economically justified intervention levels and timing,
   –The economic effects on society of various maintenance and rehabilitation strategies at different levels of intervention, and
   –Optimized application of budget resources to appropriate maintenance and rehabilitation strategies;
3. Economic analysis of community costs and benefits based on vehicle operating costs and agency costs for maintenance and rehabilitation. Other externalities were not required in the pilot;
4. Appropriate overlay design methodology; and
5. Comprehensive training of local personnel in the data collection, analysis, and design methodologies.

Features of Pavement Characterization Methodologies

The approach to pavement investment modeling described in this paper requires that the pavement physical and operating environment be characterized in terms of

- A road reference framework (road identification, location reference system, road section lengths),
- Physical inventory (pavement widths, lengths, type of pavement structure, surface type),
- Pavement functional and structural condition,
- Traffic characteristics (volumes, composition, growth rates, axle load equivalents),
- A range of effective maintenance and rehabilitation treatment strategies for each major pavement group in the network,
- Unit rates of cost for maintenance and rehabilitation treatments, and
- Operating cost characteristics for representative vehicles in the national vehicle fleet.

Methodologies and technologies employed in the collection of these data are briefly noted here. More detailed exposition of the application of particular technologies is, however, beyond the scope of this paper.

The road reference system was established primarily by a vehicle-based resurvey of the road system, which established a system of road identification, accurate road lengths, and location of physical points of reference (intersections, bridges, and so on). In general, collection of new reference information was necessary to overcome the gaps in completeness, inconsistencies, and inaccuracies which inevitably accumulate in old paper-based physical records.

The road reference system was subsequently incorporated into a geographic information system (GIS) (MapInfo for Windows), which then provided the environment for management of all pavement data used in the analysis phase of the pilot PMS project.

Inventory, traffic, and maintenance cost information generally has made use of DPWH records, which, historically, have been consistently maintained and were considered sufficiently reliable. Adopted maintenance and rehabilitation strategies generally followed current practices, but with the introduction of some well-tested and cost-effective strategies (e.g., chip seal surface treatments) used in other countries but not yet in routine usage in the Philippines.

Assessment of pavement condition has required the introduction of several new technologies into normal local practice. Roughness was measured using the Australian standard response meter technology, with automated data recording for later data base loading. Visual condition rating employed windshield surveys, with voice-actuated computer logging of condition ratings. Pavement structural condition was assessed by use of falling weight deflectometer (FWD) technology, together with some limited confirmatory subgrade testing using dynamic cone penetrometers. Specific research was undertaken to provide a correlation between FWD results and structural number (SN) and subgrade California bearing ratio (CBR) measures required by the adopted pavement model.

Development of up-to-date vehicle fleet characteristics and vehicle operating cost characteristics was undertaken in specific focused studies as part of the pilot project.

Scope of Investment Analysis System

The purpose of the pavement investment analysis system is to provide a means for managers of the upkeep of the Luzon national road network to investigate appropriate strategies for maintenance, rehabilitation, or reconstruction, which may be applied across the network, under given levels of agency budget.

The goal of the investment analysis system is to determine an optimum set of maintenance strategies to be applied to those parts of the network in need of upkeep. The optimum set of strategies is determined to provide maximum net benefit to the road user community, when constrained by upper limits on capital budget or recurrent expenditure or constrained by a desired standard for maximum average roughness across the network.

The system is designed to analyze investment possibilities on a network of any size. Thus, it may be applied at the district network level, at the regional network level, to all regions forming Luzon Island, or (as a future expansion of scope) to a nationwide analysis of the national road network. Analysis at any level requires the appropriate setting of budgets available to the selected geographic area.

This flexibility in network analysis has been achieved through the definition of a wide range of pavement categories. Each pavement category is defined in terms of four attributes:

1. Pavement type,
2. Pavement condition,
3. Traffic characteristics, and
4. Quality of pavement structure.

By assembling the appropriate data on pavements in a network, any "project" length of pavement (i.e., a length considered to be a potential candidate for future work) can be classified as belonging to a particular pavement category. Thus, the lengths of all pavement categories in a network may be determined.

The investment analysis for a network is undertaken to determine appropriate treatment strategies to be applied to the pavement categories. Any project length within a category is a potential candidate for that treatment strategy.

The total number of categories defined for the Philippines network is summarized in Table 1. A detailed description of category definitions is given in Figure 1.

In a complete analysis of a network, the system is capable of recommending an optimum treatment strategy for each of 488 pavement categories. The recommended

TABLE 1 Number of Pavement Categories

Pavement Type	No. of Condition Ranges	No. of Traffic Ranges	No. of Quality Ranges	Total
Gravel	4	5	2	40
Asphalt / Bit. Macadam	10	8	2	160
Concrete	11	9	2	198
Overlaid Concrete	10	9	1	90
		Total all Categories		488

treatment strategy will depend on the total available capital budget allocated for the network. Under more restricted budget scenarios, less expensive (and less effective) treatment strategies are recommended. Under normal budget levels, many categories are recommended to receive no capital expenditure and are allocated a "minimum maintenance" strategy (that is, routine maintenance and patching).

The investment analysis system is further designed to determine a 3-year budgetary program. This enables budgets to be set for each of 3 consecutive years. The system determines the best distribution of treatments across the 3-year program, which maximizes the future net benefit to the community. In determining future costs and benefits, the system uses an analysis period of 20 years. In the initial application of this system, the budget and treatment years are 1993, 1994, and 1995, and the analysis period is 1993 through 2012.

To provide a consistent basis for comparison between alternative treatments, the "rules" for a treatment strategy are as follows:

1. The "primary" treatment forming the strategy is applied in the chosen year (Year 1, 2, or 3 of the budget period).
2. If the primary treatment is not applied in the first year, the minimum acceptable maintenance treatment (sometimes referred to as the do-nothing or patch-only treatment) is applied in the preceding year(s) of the budget period.
3. Minimum acceptable maintenance treatment is applied each year after the primary treatment is applied for the remainder of the 20-year analysis period.
4. In the final (20th) year, an appropriate rehabilitation treatment is applied to return the pavement to good condition.

No other major works are assumed applied to the pavement after the budget period, as it is assumed in the Philippines that there is no present control of future allocation of funds to that pavement after the budget period. The final year treatment provides a means to include in the yearly stream of costs a notional future cost of returning all pavements to a comparable level of good condition (but not necessarily returned to a new pavement condition).

The allowable treatment strategies for each pavement type are shown in Table 2. The treatment strategies are defined by the primary treatment applied in the strategy, and by the budget year in which applied. Available numbers of treatment strategies for each pavement type are shown in Table 3.

The investment analysis system is based on application of two World Bank pavement investment analysis tools: the Highway Design and Maintenance Standards Model

p	r	t	q

p = Pavement Type r = Condition identifier t = Traffic identifier q = Quality identifier

GRAVEL

G r

Gravel Cost	Roughness (IRI) <10	>10
Low	A	C
High	B	D

t

% Heavy Vehicles	AADT (vpd) <100	100 - 200	200 - 300	300 - 500	>500
Normal	1	2	3	4	5

q

Quality Normal	Poor
N	P

ASPHALT

A r

% Wide Cracking	Roughness (IRI) <4	4 - 5.5	5.5 - 7	7 - 9	>9
Low or Uncracked	A	B ravelled C	E ravelled F	H	
High		D	G	I	J

t

% Heavy Vehicles	AADT (vpd) <500	500 - 1000	1000 - 3000	3000 - 10000	>10000
Normal	1	2			
Low			3	5	7
High			4	6	8

q

Quality Normal	Poor
N	P

CONCRETE

C r

% Failed Slabs	Roughness (IRI) <4	4 - 5.5	5.5 - 7	7 - 9	>9
Low	A	C	E		
Medium	B	D	F	H	J
High			G	I	K

t

% Heavy Vehicles	AADT (vpd) <500	500 - 1000	1000 - 3000	3000 - 10000	10000 - 20000	>20000
Normal	1	2				
Low			3	5	7	9
High			4	6	8	

q

Quality Normal	Poor
N	P

OVERLAID CONCRETE / CTB

O r

% Wide Cracking	Roughness (IRI) <4	4 - 5.5	5.5 - 7	7 - 9	>9
Low or Uncracked	A	B ravelled C	E ravelled F	H	
High		D	G	I	J

t

% Heavy Vehicles	AADT (vpd) <500	500 - 1000	1000 - 3000	3000 - 10000	10000 - 20000	>20000
Normal	1	2				
Low			3	5	7	9
High			4	6	8	

N

Example : **Category AH3N** : Asphalt surfaced, roughness 7 - 9 IRI, low % wide cracking, traffic 1000 - 3000 vpd, low % HV, normal quality pavement

FIGURE 1 Structure of pavement categories.

(HDM-III), and the Expenditure Budgeting Model(EBM). Detailed descriptions of the nature and application of these tools are available elsewhere (*1,2*).

Other purpose-built software developed within the project provides a range of user-friendly data manipulation functions and the control of program flow required to perform many repeated analysis cycles.

Microcomputer (MS-DOS) versions of all software were employed in the pilot system, as this was judged to be the most appropriate level of computing technology to introduce into local management practices. With the system running on a relatively fast 486 computer, a full analysis cycle would complete overnight, which was judged to be acceptable.

System Overview

The main system elements and information flows are shown in Figure 2. (Numbers in brackets refer to parts of Figure 2.) The MapInfo-integrated (GIS) data base and map base [2] forms a powerful yet easy-to-use central repository for information used by, and generated by the system, and also provides the means for mapbased and statistical interrogation and reporting. All data base processes and investment analysis processes are controlled from a customized front-end menu system built into the MapInfo package. Network elements are classified into pavement categories [3] and category length data [4] are assembled by the GIS.

Life-cycle performance and cost analysis, for all treatment alternatives applied to each category is executed in the category analysis phase [5,6]. The resulting cost streams, which apply to a unit length of each category, are adjusted for actual category lengths [7] and fed to the budget optimization tool EBM [8], which determines an optimum category workplan [11] for a particular trial budget [9] and other constraints [10].

The network data base transforms the category workplan into a network workplan [12] for the trial budget, consisting of a program of candidate projects in each budget year. Summary reports and projections [13] of the physical and economic impact of each budget strategy can be prepared. Finally, when a budget or intervention strat-

TABLE 2 Adopted Maintenance and Construction Treatment Strategies

Pavement Type	Treatment	Notes	Traffic Dep *
GRAVEL	Minimum grading frequency, spot regravelling	Base case ("do nothing") strategy	
	Desirable grading frequency, resheeting		
	New granular pavement, with surface treatment		Y
	New granular pavement, with AC surfacing		Y
	New concrete pavement		
ASPHALT	Patch potholes	Base case ("do nothing") strategy	
	AC overlay 50 mm		
	AC overlay 100 mm		
	Surface treatment reseal		
	AC pavement reconstruction	includes AC removal & scarify	Y
	Granular pavement overlay, with surface treatment		Y
	New concrete pavement	includes drainage works	
CONCRETE	Patch damaged area	Base case ("do nothing") strategy	
	AC overlay 50 mm	force rapid cracking	
	AC overlay 100 mm	force rapid cracking	
	Slab replacement - Low %		
	Slab replacement - High %		
	New granular pavement, with AC surfacing	includes concrete slab disposal	Y
	New concrete pavement	includes concrete slab disposal and drainage	
OVERLAID CONCRETE & CTB	Patch damaged area	Base case ("do nothing") strategy	
	AC overlay 50 mm		
	AC overlay 100 mm		
	Surface treatment reseal		
	New granular pavement, with AC surfacing	includes concrete slab disposal	Y
	New concrete pavement	includes concrete slab disposal and drainage	

* - Treatment design and effect is dependent on Pavement Category traffic level

egy is adopted, budget allocations to districts [14] may be made to allow the work to proceed.

Analysis phases forming the core of the network investment analysis system (i.e., covering system elements [5] to [12]) are further detailed in Figure 3 and are described briefly below.

Network Category Definition Phase

This phase consists of the assembly of all data items required to characterize each pavement category, in terms of the input data requirements for the HDM-III package. In some

TABLE 3 Number of Maintenance and Construction Treatment Strategies

Pavement Type	Base Case Treatment	No. of Treatment Strategies	No. of Budget Years	Total
Gravel	1	4	3	13
Asphalt / Bit. Macadam	1	6	3	19
Concrete	1	6	3	19
Overlaid Concrete	1	5	3	16

cases, interrogation of the PMS data base is required to establish representative data items for categories. The data are assembled into a number of data files that feed the HDM-III input file generation phase.

HDM-III Input File Generation Phase

The HDM-III package requires a set of input files (the Series A to Series K files) to perform a single analysis run. The analysis system sequentially performs analysis runs for every pavement category, one run per category.

To assist in the automation of multiple analysis runs, this input file generation phase makes use of project-developed software to generate HDM series files appropriate for each category.

Pavement Category HDM-III Analysis

This phase consists of the complete execution of a single analysis run for one category, in which the performance and economic consequences arising from each treatment alternative applied to the category are determined and reported. The run includes report directives to produce a standard HDM output report, which feeds the analysis results to the next phase, the EBM interface.

EBM Interface Phase

The EBM interface phase consists of two parts. Each part makes use of special project-developed software. The first part (data extraction) consists of extraction of required data from the HDM output report for a particular category, and occurs within the processing cycle for each category. The data extracted consists of yearly streams of predicted financial and condition data for each category alternative (that is, a treatment alternative applied to the category under analysis). Additional present worth economic summary information, including discounted total costs and benefits over the analysis period and other measures, is also calculated for each category alternative.

The phases of input file generation, category analysis, and EBM data extraction are repeated sequentially for all pavement categories forming a single pavement type. The cyclic process is then repeated for all four pavement types.

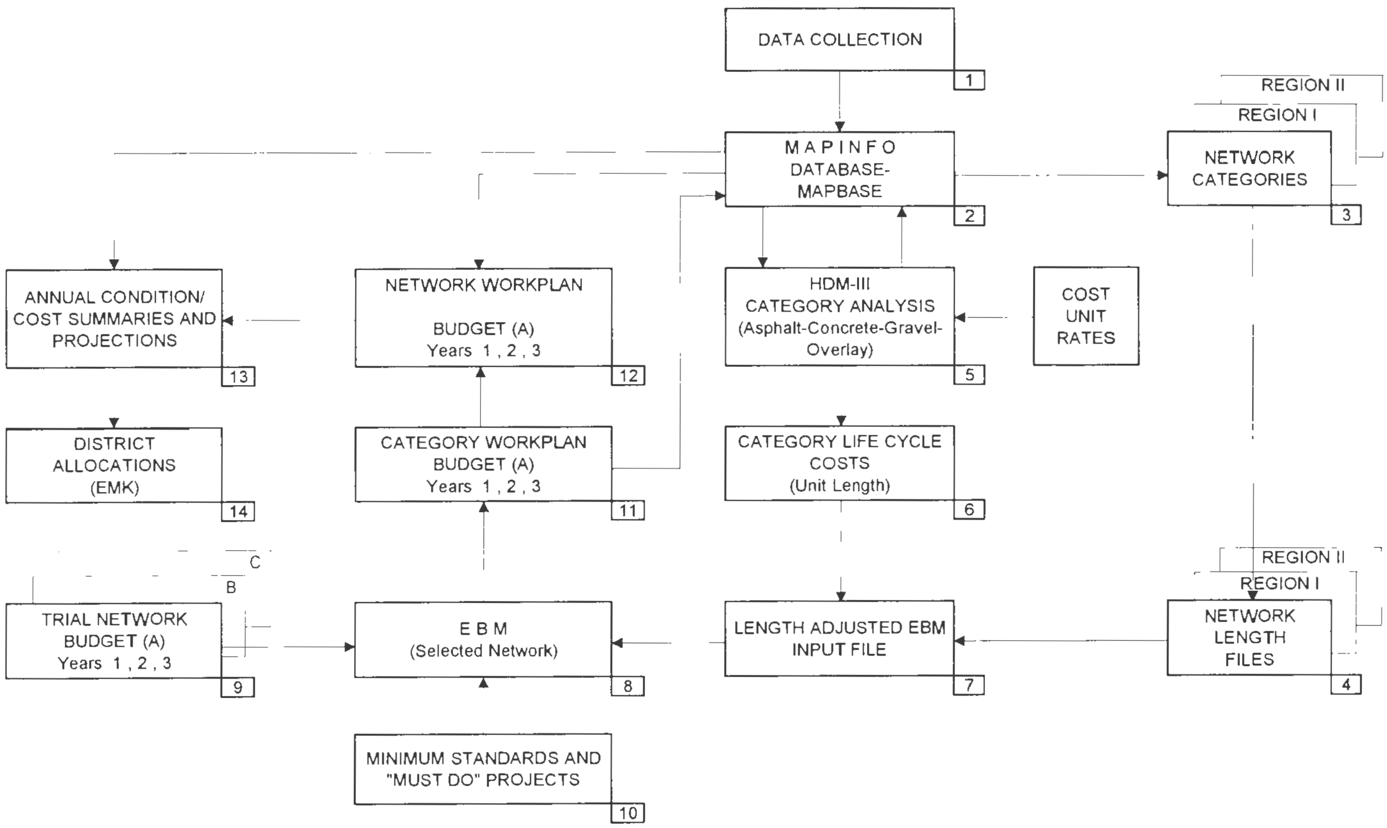

FIGURE 2 Network pavement upkeep investment analysis system overview.

The analysis cycle for all categories of a pavement type (e.g., for 160 asphalt pavement categories) runs continuously, is time-consuming, and generates very large output files. Use of extended memory, however, permits significant reduction in analysis time. Depending on the speed and configuration of the computer used, analysis of all asphalt categories may take between 4 and 20 hr.

The second part of the EBM interface phase (data assembly) occurs after all category analysis runs for all pavement types have been completed. The previous data extractions are assembled into a single file to feed the EBM analysis phase, and the EBM input file is further processed to reflect the impact of actual total lengths of road belonging to each category.

EBM Analysis of Optimal Network Maintenance Strategies

This phase is composed of execution of a special customized version of the World Bank EBM program, called EBM500. Customization has increased the maximum allowable size of the optimization problem, to accommodate 500 projects (categories), 20 alternatives for each, and 3 budget years; it runs within the Microsoft Windows 3 environment. EBM500 accepts the project input file (a large file), which provides yearly data streams for each alternative treatment strategy applied to each of the 488 pavement categories. The program then provides an interactive mode of operation, to allow the analyst to vary budget and network average roughness constraints and the discount rate and to generate sets of optimum category workplans (i.e., the best treatment strategy for each category) applying to different budget scenarios.

The configuration of this phase provides two powerful alternative approaches to determination of optimal investment strategies:

- Budget-constrained investment strategies, and
- Serviceability-constrained investment strategies.

In the former case, optimal treatment strategies are determined for each pavement category under constraints of capital and recurrent expenditure limits for the whole network in each year of the rolling program. Under tighter budget limits, simpler and less cost-effective treatments may be recommended for categories, or fewer categories may receive treatment other than minimal maintenance.

In the latter case, optimal treatment strategies are determined for each pavement category to achieve a minimum average network roughness standard for the network. Normally, imposition of such a standard should be ac-

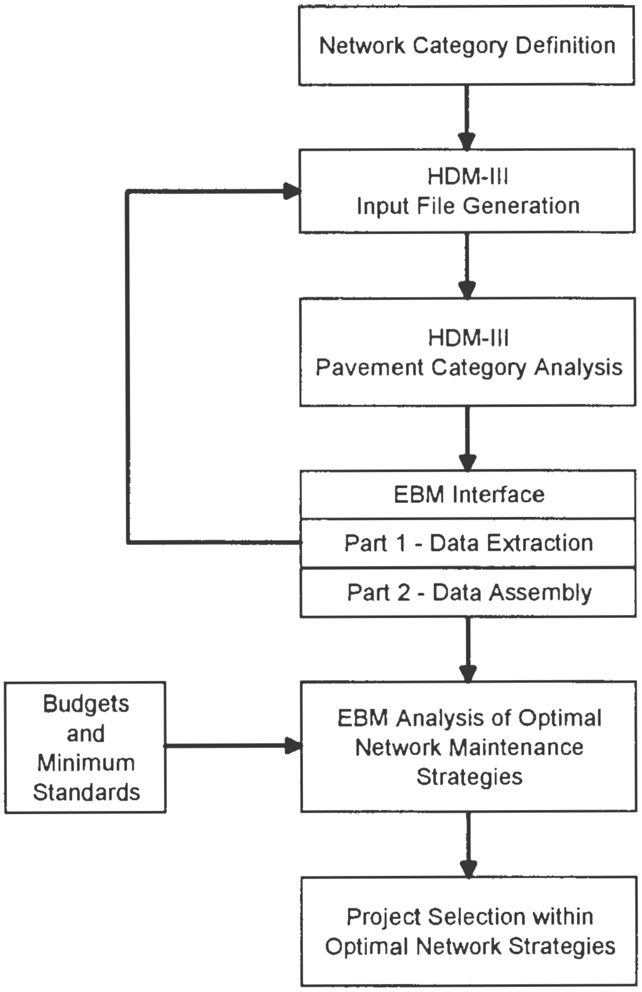

FIGURE 3 Investment analysis process flow.

companied by a relatively unconstrained budget, to achieve a feasible solution. The solution in this case represents the type and quantum of investment required to maintain a network at a prescribed serviceability level (expressed in terms of roughness).

Although this latter approach may not normally prove to be useful in practical application (network investment decisions are normally always budget constrained), the approach can be beneficial in, for example, demonstrating and justifying potential additional community benefits available under alternative network management policies.

Project Selection Within Optimal Network Strategies

This final phase is applied to those budget scenarios considered worthy of further detailing to identify actual project lengths that qualify as candidates for particular treatment strategies. Interrogation of the PMS data base will provide a list of project lengths for each category, for the network under analysis. Each project length is then a potential candidate for the recommended optimal treatment strategy for that category. In all cases, these potential candidate project lengths must then be investigated in detail to ensure that the recommended treatment strategy is, in fact, appropriate. It may also be possible for adjacent project lengths on the same road to be combined with larger projects, for treatment under the same strategy at one time. The final assembly of rationalized project lengths represents the network workplan.

Control of Data Flow and Analysis Processes

A complete investment analysis of a network starts with extraction of specific data concerning the selected network, then transformation and transfer of the data to the HDM III and EBM analysis modules, and finally transfer of the analysis results back to the GIS data base and transformation into forms relevant for specific network elements. All data flows and initiation of analysis processes are controlled from a customized menu incorporated into the GIS package. This greatly facilitates the training, use, and supportability of the investment analysis package.

Future Extension of Scope

A limitation to the design of the pavement categories was imposed by the size of the optimization problem that could be handled by the enhanced EBM program EBM500. Consequently, the category definitions were limited, for example, in the number of cracked ranges within the condition classifier, the number of traffic ranges within the traffic classifier, and the number of quality ranges, which reflect a broad characterization of structural property. Some category ranges in the current definition may be considered coarse and therefore unlikely to be good differentiators in prioritizing maintenance needs in different parts of a network.

An increased number of pavement categories can be accommodated by either or both of the following enhancements now in place or proposed:

1. In the EBM analysis, not every category will be populated by a length of pavement in the network under study. "Unpopulated" category alternatives in the EBM input file are removed to reduce the problem size.
2. A newer enhancement to EBM, raising the problem size to 1,000 projects, is under development.

Model Calibrations

Among the great strengths of the HDM model are the inbuilt capabilities for calibrating model outputs to local experience. Calibration is possible in two main areas: calibration of pavement performance prediction and calibration of life-cycle cost prediction.

Effective calibration of performance prediction requires reliable and representative historical data that relate a known past pavement environment (the combination of structure, climatic setting, traffic loading, and maintenance activity) to objective observations of pavement deterioration over a substantial period. In this pilot project, it was possible to assemble a number of reasonably reliably known as-constructed pavement environments, but in general an adequate history of progression of roughness or initiation and progression of cracking was not available. The best that could be obtained was, for example, an estimate (based on knowledge of the construction process) of as-constructed roughness, a measure of roughness and cracking in 1985 (the time of a major pavement study), and a measure of current roughness and cracking. This type of problem (gaps in critical data) will commonly be experienced in any PMS implementation project.

Consequently, a highly controlled calibration study was not possible in this project, apart from the concrete pavement study described later. Calibration of performance prediction, even though based where possible on the backcalculation of observed performance, relied on a judgment of the reasonableness of predicted outcomes in the light of local experience. Calibration focused mainly on roughness and cracking performance of asphalt-surfaced roads. Rutting was generally observed to be a relatively minor phenomenon on Luzon national roads.

Calibration of cost predictions is addressed by attention to appropriate unit rates of cost and should be accompanied by comparison of predicted and actual historical expenditure for known amounts and types of maintenance work. Again in this project, some inadequacies of available data required that judgment, based on experience, of the reasonableness of predicted cost outcomes was necessary.

Particular attention was paid in the project to up-to-date characterization of vehicle operating cost parameters, to support the credibility of the very large predicted user cost savings produced by the model for recommended treatment strategies, which commonly tended toward overlay strategies for roughness control.

The standard HDM-III vehicle operating cost (VOC) model was employed, but the extensive range of input data that this model requires, to characterize the operating and cost characteristics of the typical vehicle classes in the Philippines vehicle population, were completely revised from normal (Brazilian) data defaults. The revision, undertaken by a senior transportation economist within the project team, brought together recent Australian research into VOC characteristics with specific Philippines data collation and current VOC parameters used for planning purposes by the DPWH.

Analysis and Calibration of Concrete Pavement Performance

Approximately a third of the national road network of Luzon Island consists of concrete pavements. Consequently, the investment analysis system was required to successfully model the physical and economic performance of concrete pavements over their life cycles. Development of the HDM-III model did not encompass concrete pavements within its various performance models, although cement-bound pavements were included.

To maintain a consistent economic modeling approach for all pavements in the network, it was necessary to conclusively demonstrate the feasibility of concrete pavement modeling using the HDM approach. Two aspects of the feasibility needed to be proven:

1. The feasibility of predicting the deterioration of concrete under the action of traffic: this requires prediction of roughness progression and the initiation and progression of cracking and potholes (resulting from severe spalling and punchouts). In this case, the issue is performance model calibration, recognizing that the model would be applied to a problem outside its original domain of relevance.
2. The feasibility of incorporating typical concrete pavement treatments—such as reconstruction in concrete, slab replacements, and asphalt overlay on cracked concrete—that are not available in the range of standard treatments offered in the HDM model: the issue in this case is correctly reflecting the effect of a treatment on pavement condition after treatment, and correctly reflecting any change in performance after treatment.

Feasibility of Deterioration Modeling for Concrete

The first aspect of feasibility was proved successfully by undertaking a detailed calibration study, using the calibration capability (i.e., deterioration factors) provided in the HDM model. The project was very fortunate to have available the results of a detailed Pavement and Axle Load Study undertaken under World Bank funding in 1983 through 1985 (*3*). This study included derived relationships (from field studies) between roughness, the extent of wide cracking, and traffic loading (measured as cumulative equivalent single-axle loads). This provided an historical base reflecting the progression of roughness and cracking with cumulative traffic loads suitable for model calibration.

Critical assumptions made in the model calibration included the following:

- The rigid pavement was modeled as a cement-treated base pavement with moderate to high resilient modulus (20 GPa).

- A subgrade CBR of 8 would reflect the composite effect of a relatively low-quality sub base and normal subgrade;
- The pavement SN was 5, compared with calculated SN from FWD testing typically in the range 5 to 7;
- Unlike asphalt surfacings, historical evidence indicated that there was no pronounced crack initiation period (*3*). To suit the model, this required that new concrete started with 5 percent all (i.e., fine) cracking;
- Raveling and rutting were considered not possible for a rigid pavement;
- Potholing occurred (and therefore required prediction) in severely deteriorated concrete pavements as a result of severe spalling and block punching; and
- Maintenance was performed at the low (nominal) rate of 1 percent of the severely damaged pavement area (wide cracking or potholes) per year, adjustable to reflect actual average maintenance expenditure.

Appropriate deterioration factors were determined by trial and error for a range of cases representing low to very high traffic loading (equivalent single axles per year) and normal and poor-quality concrete base (defined by either historical performance or concrete and subgrade moduli). Deterioration factors were determined for these cases as follows:

Deterioration Factor	*Value*
Crack initiation	0.1
Crack progression	0.01 to 0.6 (varies as function of initial yearly traffic and quality)
Roughness age	0.2
Roughness progression	3.6
Pothole progression	0.13
Rut depth progression	0.0 (to suppress occurrence of these conditions)
Raveling initiation	10.0 (to suppress occurrence of these conditions).

Definitions of these factors are specific to the HDM-III model design and may be obtained from Watanatada et al. (*1*). They provide the mechanism by which performance prediction may be altered from that observed in the original Brazilian pavement studies, from which HDM-III was developed.

A typical comparison of HDM predicted cracking and roughness with the 1985 study observations is shown in Figure 4. In this case (medium traffic, normal construction) the HDM-predicted roughness was allowed to overestimate the 1985 model roughness for high pavement ages, as the latter was reported in that study to underesti-

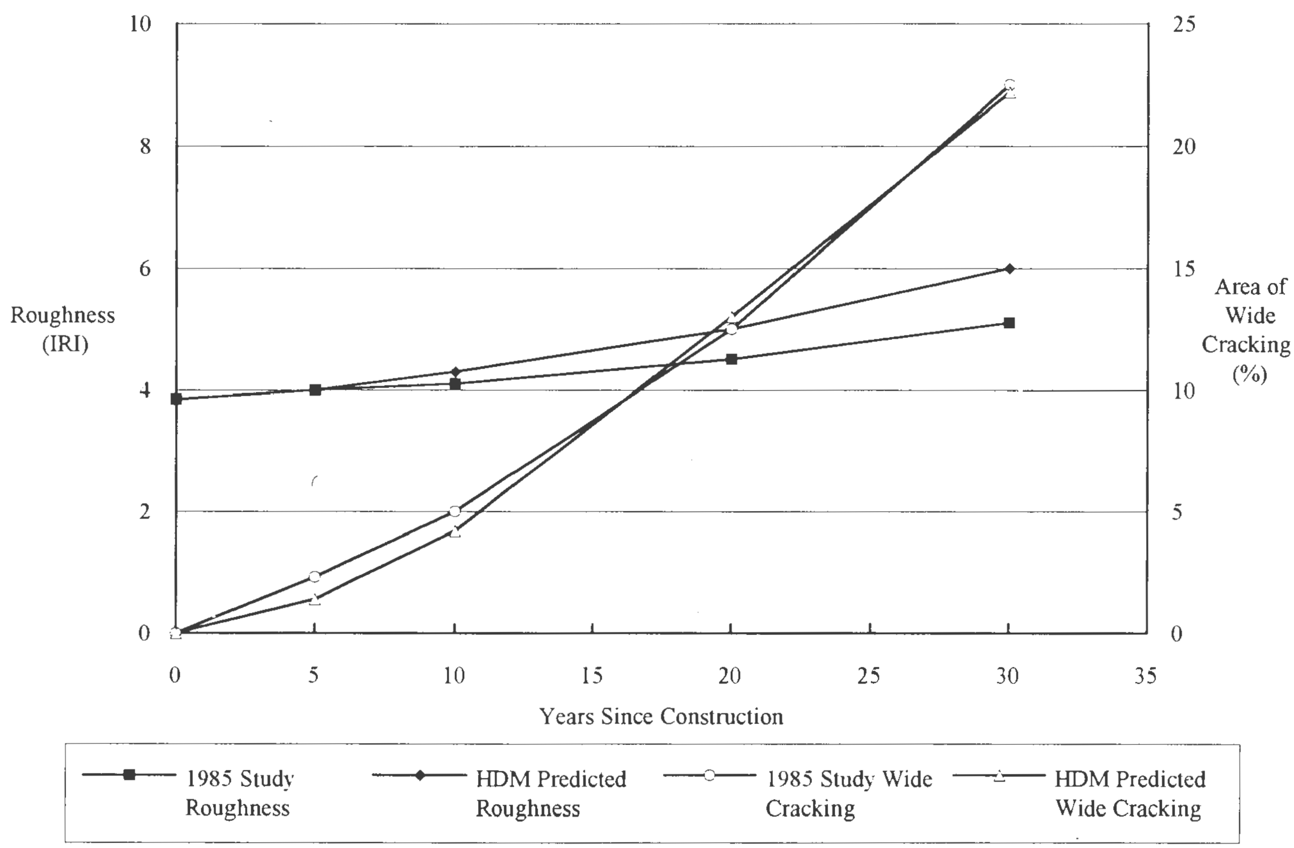

FIGURE 4 Typical result for HDM calibration for concrete.

mate the effects of significant spalling (corresponding to extensive wide cracking).

Feasibility of Concrete Treatment Modeling

Successful modeling of the effects of concrete maintenance treatments required some innovative manipulation of HDM analysis cases and outputs. Concrete treatments generally required that cracking after treatment be reduced but not eliminated, and for this reason standard HDM treatments could not be used. For example, new concrete (as reconstruction in concrete) must be modeled as cracked when constructed, and slab replacements must be modeled as reducing the extent of wide cracking and modifying roughness. Asphalt overlay placed an old concrete required resetting of deterioration calibration factors after treatment.

All of these requirements were beyond the capabilities of normal HDM maintenance or construction treatments. However, all were successfully accomplished by separately modeling the before and after cases as separate pavement sections and then programmatically combining the relevant parts of the before and after predicted condition streams and predicted cost streams, as part of the HDM analysis postprocessing before EBM optimization analysis. All data manipulations occur external to the HDM III program, which was not altered in any way.

PMS Implementation Issues

The primary objectives of the pilot PMS project were to develop and introduce into practice systems for collecting and managing critical pavement-related data, an investment analysis system for identifying and prioritizing beneficial maintenance strategies and for identifying candidates for work, and initial application of these developments for establishing a rolling maintenance program. Implementation of these developments entails introduction of a range of testing, computing, data management, and data access technologies that are not widely used in the normal infrastructure planning operations of the Philippines DPWH.

Consequently, a secondary objective of the project was to identify the issues and barriers that would impede effective implementation of the system into wider practice throughout the nation. Solutions to these issues would then be needed in subsequent technology transfer activities. Principal issues identified included the following.

Technology Impact

Microcomputers and their application software, and pavement testing equipment with associated vehicle-based computer data logging, had not been used before in some operational units, particularly in the line organization. Skills, knowledge, and experience of these technologies were at a very low level. Effective solutions to training and ongoing support are needed, as is a means for ensuring that the technology will continue to be maintained and, where appropriate, kept in calibration.

Management Commitment

Improved formal pavement management practices, which require substantial organizational and technological change, are rarely successful without solid management commitment. The commitment is required during the development and implementation phases, and then as a continuing commitment to apply, improve, and capitalize on the benefits that only slowly accumulate in the early years of application. If the management support and commitment, and the belief by management that such systematic change will be good for the organization, does not arise naturally from the prevailing organizational culture, then there is substantial risk of eventual system breakdown after the early enthusiasm has dissipated.

Follow-Through from Planning to Delivery

The planning phases of pavement management—involving identification of need, analysis, strategy setting, investigation of budget and treatment alternatives, development of a works program, and allocation of budgets to regions and districts—are conducted by units of central management. However, this exemplary activity is of no value unless there is assurance that budget will be expended and works performed by the district units that supervise and carry out the works, in accordance with the works program. This is likely to require political commitment at the local level, to proceed in accordance with the program, and resistance to pressures for reprioritizing expenditures to suit political agendas.

Conclusion

A powerful and sophisticated PMS, suitable for road network applications ranging from national strategic road networks to regional or district arterial and collector/distributor networks, can be designed and implemented at a relatively low cost using the techniques discussed in the paper. The system described consists of

- An accurate and up-to-date locational reference system for the road network;
- Automated pavement condition data collection techniques;

- Data management, data access, and data presentation techniques based on an easy-to-use GIS, which also provides menu control of data analysis processes; and
- A pavement investment analysis system, which is the major subject of this paper.

Use of automated survey and condition rating systems—for roughness, visual condition, and FWD strength—has proved successful and is believed to offer greater prospects for sustainability than alternative manually based systems.

The MapInfo GIS, providing an integrated combination of relational data base, mapping, graphing, programming, and customizing capabilities, is an integral and most important part of the system.

The pavement investment analysis system, based on the World Bank HDM-III package, offers sophisticated and powerful capabilities:

- The ability to analyze networks of any size, by classifying network elements into pavement categories;
- The ability to determine economic impacts of alternative maintenance strategies over the pavement life cycle, by predicting pavement deterioration under the action of maintenance strategies over the life cycle and predicting the life-cycle cost streams that arise under each strategy;
- The ability to include both agency costs and road user costs (i.e., vehicle operating costs and user time costs) in the economic analysis;
- The ability to determine the optimum maintenance strategy for each pavement category under budget constraints or average network condition standard constraints; and
- The ability to determine an optimum distribution of budget allocation across a 3-year budget program.

As institutional capabilities and requirements develop, a detailed project-level analysis capability can be added to the system.

The investment analysis system has proved to be flexible in adapting to application to the analysis of pavement technologies that were not within its original domain of relevance. The calibration capabilities are critical in this regard, and calibration of the HDM models in different environmental and technological contexts will be a fruitful area for future research.

This project has demonstrated that the condition and economic performance of concrete pavements can be analyzed by suitable calibration and manipulation of HDM analysis runs. Further investigation is required, particularly into the performance of concrete pavements and the effects of concrete rehabilitation treatments; this will be pursued in ongoing projects in the Philippines.

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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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