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Management Tools for Bus Maintenance

Current Practices and New Methods

May 1983

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Final Report
May 1983

Prepared by
James Foerster, Floyd G. Miller,
Maria Kosinski and Amelita Rueda
University of Illinois at Chicago
P.O. Box 4348
Chicago, Illinois 60680

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16. Abstract

Management of bus fleet maintenance requires systematic recordkeeping, management reporting, and work scheduling procedures. Tools for controlling and monitoring routine maintenance activities are in common use. These include defect and fluid consumption reports, work order systems, historical maintenance records and performance and cost summaries. While those tools are necessary, they are not sufficient for effective maintenance management. Current management methods should be supplemented by strategic planning tools to improve maintenance performance and to control costs. The techniques having the greatest potential for improving the cost-effectiveness of maintenance are work methods analysis and standard job time and cost analysis. Failure history analysis and workload and budget forecasting procedures are also expected to improve strategic planning capabilities. These methods logically lead to the development of maintenance policy testing applications. Most of the data required to implement these methods are captured in current reporting processes, but special attention to maintaining accurate and accessible historical records is essential for use of these methods.

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I. INTRODUCTION

A. Purpose of the Report

This report summarizes current and potential uses of analytical methods in transit maintenance management. It provides an overview of current record keeping practice, identifies a number of newly emerging quantitative techniques, and outlines their potential role in improving the reliability and cost-effectiveness of transit operations. The objectives of this report are to:

1. Summarize current maintenance management procedures.
2. Identify gaps between management needs and current decision-making aids,
3. Survey potentially beneficial analytical tools,
4. Assess the data requirements and potential benefits of new approaches to maintenance management.

B. Major Findings

1. Maintenance management tools for controlling and monitoring routine daily activities are fairly well developed and have been widely adopted.

Most properties are using systems for preventive maintenance monitoring, work order processing, driver defect reporting, fluid monitoring, and cost analysis. These systems differ in complexity and degree of automation, but they generally meet the information needs of management and supervisors. The availability of low cost computer hardware is facilitating the adoption of progressive systems at medium and smaller properties.

2. Several techniques for improving the performance of mechanics have been developed and implemented, but they have yet to receive widespread acceptance.

Both the Chicago Transit Authority and the Detroit SEMTA system have had positive experiences with work methods analysis and job performance aids. These systems have been adopted by both properties. Several other operators are interested in these techniques, but most systems are not now using such approaches. The time and cost of developing work standards and job performance aids is a major barrier to their adoption.

3. Current maintenance management tools do not address strategic planning issues.

Current techniques are focused on controlling and monitoring daily activities. They do not produce the type of information needed to prepare budget forecasts, to predict the impact of changes in the level and timing of maintenance, or to evaluate alternative maintenance schedules. Methods for vehicle replacement analysis are also not widely used.

The absence of strategic planning methods can be attributed to the relatively recent nature of concern about cost control in maintenance, the data requirements of strategic planning tools, and strong pressures on management to deal with day-to-day issues.

4. A number of analytical methods have potential for improving management's strategic planning capability.

The most promising are survivor curve methods for performance analysis and workload projection. These techniques can be used to project future workload levels and budget needs on the basis of vehicle and component life expectancies. They can also be used to test the impact of alternative maintenance policies and schedules on performance and budgets.

The more advanced maintenance schedule optimization methods also have potential, but they require stronger assumptions about the type of maintenance activities involved. The probability that these methods will be adopted in the near future is lower than that for the survivor curve and forecasting techniques.

It is least likely that the industry will adopt prescriptive vehicle replacement methods. While these methods are being used to control costs of large non-transit fleets, they are based on assumptions which do not correspond well with the budgeting and management environment of U.S. transit operations.

C. Recommendations

The research team believes that current maintenance management tools can be effective in controlling routine, day-to-day activities. However, it has concluded that improvements in cost control and reliability can be expected if management gives increased attention to work procedure improvement methods and adopts a strategic planning approach to budgeting, maintenance schedule setting, and vehicle replacement decisions.

Because the adoption and diffusion of innovations is a slow process, and because transit management has a strong day-to-day orientation in the maintenance area, it is important that UMTA encourage the further development and testing of new techniques in both the work methods and strategic planning areas. But because new methods must be tailored to the practical needs of management, it is imperative that these efforts involve transit management as direct clients for new products.

1. In the work methods area, we recommend that evaluations of existing work methods analyses and job performance aids be conducted and disseminated to the industry.

   Special emphasis should be given to evaluating the transferability of results and the development of guidelines for using task instructions and standard performance times. This could be done through an independent contract or as an element of the National Cooperative Transit Research Program. In order to insure responsiveness to industry needs and concerns, the transferability component should be assessed in the context of trial applications of specific procedures in the operation of several interested properties. A central clearinghouse should be established to provide for sharing of improved job procedure descriptions and time standards.

2. In order to improve organizational planning, we recommend that transit operations enhance their maintenance management by adopting strategic planning tools.

   These should include procedures for comparing the performance of subfleets, garages, and component suppliers, for projecting workload and maintenance cost levels with a one to two year planning horizon, and for analyzing the impacts of changes in preventive maintenance policies. An important element in developing a strategic planning approach is the identification of linkages between maintenance, the budgeting component of the transit operations, and other relevant actors including regional transit authorities, metropolitan planning organizations, and state departments of transportation. The inputs from maintenance to the budgeting cycle should be made clear, along with qualitative assessments of how agency budget shortfalls are reflected in the maintenance budget. Maintenance management should then review relevant techniques. At a minimum, the development of a strategic planning capability in maintenance will require the establishment of a data base organized at the vehicle level and adoption of a simple cost projection methodology. The data base should permit analysis of component life statistics and cost experience. The cost analysis procedure (see Sections IV.C and IV.D) would facilitate budget projections and maintenance policy testing.

3. We further recommend that transit operators maintain and share data on maintenance histories, costs and component life expectancy.

   Such data are needed because a strategic planning approach must be based on an analysis of component and vehicle reliability histories. It is especially critical that cost data be maintained so that they corresponds to the vehicle maintenance record. Some central repository for this data would be desirable, along with agreement on reporting formats. The examples of the trucking industry are illustrative of this approach. The centralized collection of these data would be especially helpful to smaller systems which lack the expertise needed to develop in-house planning capabilities and whose fleets are too small to generate timely and statistically meaningful reliability statistics.

D. Organization of the Report

The remainder of the report provides background for these recommendations and an overview of current and emerging methods. It is organized as follows: Section II discusses the importance of maintenance management, current variations in industry cost and reliability statistics, and the need for systematic management procedures. Section III documents current record-keeping and management reporting methods. Section IV identifies and evaluates new techniques for improving mechanic and management performance. Section V summarizes the more promising of the new methods, identifies their data requirements and relates their functions to an overall planning framework.

The report references a number of research products generated over the past three years. These include the Year I and II final reports entitled, "Implementing Cost-Effective Service Interval Planning Methods for Bus Transit Vehicles: A Case Study" and "Development of Transit Bus Component Failure Statistics from Conventional Bus Card Records" as well as masters' theses and conference papers. Copies of all these documents are available from the University of Illinois Urban Transportation Center. (See Appendix A.) A number of vehicle replacement models are inventoried in Appendix C.

II. BACKGROUND

A. Importance of Maintenance

Historically, maintenance has not been a very visible part of transit operations. There are several reasons for this. The first is that transit vehicles designed before the new generation of advanced design buses were relatively simple to maintain. In addition, the availability of federal operating subsidies, the 80%-20% formula for funding capital acquisition, and a distinctive "hardware" orientation have all contributed to a lack of public awareness of the importance of this function. As long as budgets were flexible, maintenance management could keep vehicles in good condition, and little was heard about this aspect of transit. Indeed, the major questions for debate were those associated with system expansion and equipment procurement.

This situation is now changing: new federal funding priorities and proposed changes in grant programs, as well as lowered local fiscal capabilities, are increasing pressures on local transit (Meyer and Hemily, 1982). Operators are being asked to make do with lower budgets or less generous budget increases than in the past. In some cases, this has led to cuts in service, and in others it has resulted in attrition in several personnel areas — including maintenance.

The importance of preserving a vigorous maintenance function has been underscored by the conduct of two major conferences on the topic in the last year. The multifaceted nature of maintenance was emphasized at a workshop sponsored by UMTA and TRB in April of 1982. The findings of the Bus Maintenance Improvement Workshop indicated that advances in maintenance effectiveness would require action in a number of areas, including relations with general managers and boards of directors, improvement in data bases and management information systems, closer attention to human relations and personnel issues, and facility and vehicle design innovations (TRB, 1983). The importance of maintenance to the overall mission of transit was made clear in discussion at the August 1982 Transit Service Reliability Workshops. That workshop recognized that proper vehicle maintenance is a fundamental precondition for effective service provision, and is equally as important as route design and driver selection and training (Abkowitz, 1983). Clearly, proper maintenance is essential if missed runs, late pullouts, and roadcalls — leading to the deterioration of headway reliability and ultimately to reductions in ridership — are to be avoided.

In recognition of the importance of maintenance, transit operators are developing new systems for tracking maintenance performance and researchers are being encouraged to develop new methods using techniques from industrial engineering, systems analysis, psychology, and educational testing and training to address maintenance concerns. All of these efforts are aimed at the objective of increasing transit service reliability in an environment of increasingly tight budget constraints.

B. Maintenance Performance and Cost

Transit bus maintenance costs constitute approximately 20% of total operating costs. They totaled 310.7 million dollars in 1981. As Exhibit II.1 shows, maintenance expenditures are positively associated with system size, as is the frequency of roadcall events. These expenses can be broken down into three major categories: direct wages, benefits, and materials. Direct wages constitutes 50% of maintenance expenditures industry wide. This cost item varies from 36.5% for the smaller systems (under 25 vehicles) to 50.1% for systems with over 1000 vehicles. Fringe benefits average 20% of total maintenance costs industry wide, (with a range of 9.3% to 22.9%) and are strongly correlated with system size. Material costs vary from 24% to 30% of total costs (Jacobs, 1982).

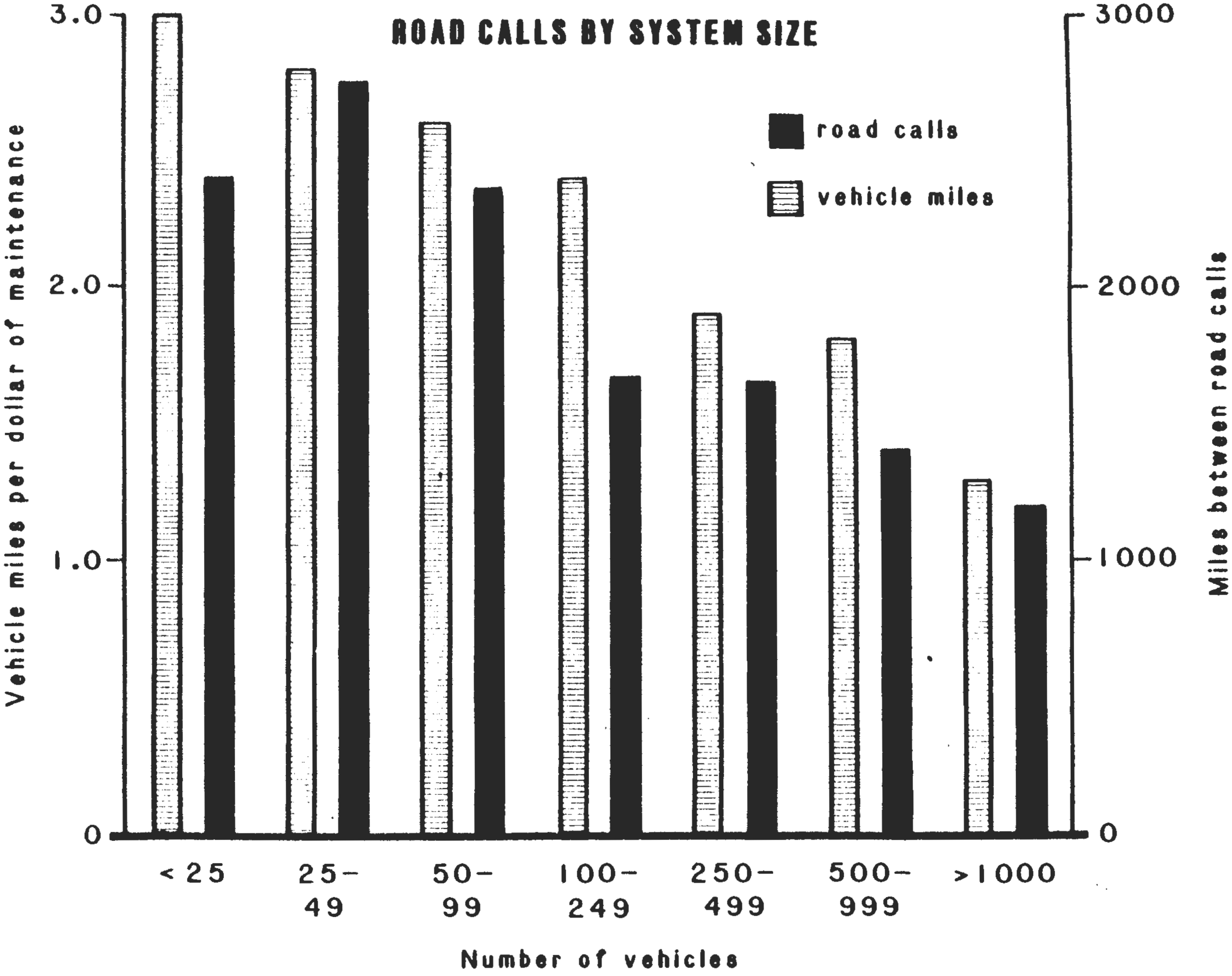
The effectiveness of these expenditures seems to vary greatly. This is apparent from the declining relationship between miles of service per maintenance dollar and system size shown in Exhibit II.1, as well as from the lower number of miles between roadcalls experienced by larger systems. Part of the observed pattern is certainly due to the more intense service profile vehicles are subject to in large urban areas and to higher wage scales. But other factors also are reflected in the data, including fleet age, peak to base requirements and overall management efficiency. Regression and correlation models based on 1980 Section 15 data illustrate the complexity of these factors. The first model, based on 62 observations having complete data in the 1981 report, relates the frequency of chargeable roadcalls to maintenance labor effort, peak period utilization, average vehicle mileage, and federal operating subsidy levels. The results show a positive relationship between peak-heavy service and the frequency of maintenance related roadcalls. Systems with base-heavy service and relatively high operating support tend to have lower frequencies of roadcalls. The statistical relationships shown in Exhibit II.2 are significant, but it should be noted that the model explains only 20% of the variation in the data. Further correlation and regression analysis was not successful in improving the predictive validity of the model. It is especially interesting that age, spare ratios, and reserve fleet size did not show significant relationships with roadcall experience.

Maintenance labor commitment shows few systematic relationships across properties. This is evident from the correlations shown in Exhibit II.3. There are only two significant predictors of maintenance effort -- operating subsidy levels and fleet utilization. The results strongly indicate that more intensively used vehicles receive less maintenance attention and that federal operating subsidies seem to increase the ability of properties to support maintenance staffs.

The lack of fleet size and age effects reflected Exhibit II.3 was also evident in several (unshown) regression analyses. None of these analyses were able to identify strong relationships between the variables listed in Exhibit II.3 and labor effort, except for vehicle use and operating support. This was explained by one mechanic as the result of strong pressures on mechanics and supervisors "to keep busy or at least look busy."

EXHIBIT II.1

MAINTENANCE EFFICIENCY AND MILES BETWEEN ROAD CALLS BY SYSTEM SIZE



(Source: Jacobs, 1982 pp.1-25 through 1-31 and 1-62)

Exhibit II.2
REGRESSION ANALYSIS OF ROADCALL FREQUENCY

Dependent Variable

$R^2 = .19$
$F(4,57) = 3.42$
$P \quad .01$

Mechanical Failures per Vehicle Mile

Independent Variable	Coefficient	Significance Level
constant	.00012	
labor hours per vehicle mile	+.0046	.21
annual per peak mileage per vehicle	$+.922 \times 10^{-10}$	.009
annual total system mileage per vehicle	$-.666 \times 10^{-10}$	.07
$ Section 5 per bus mile	$-.038 \times 10^{2}$	.06

Exhibit II.3

CORRELATIONS BETWEEN MAINTENANCE LABOR HOURS PER VEHICLE AND SYSTEM VARIABLES

Variable	r	Significance	Variable	r	Significance
fleet size	-.04	.74	peak miles/bus	-.20	.11
fleet age	-.13	.29	spare ratio	.15	.21
$ Section 5 per bus	.23	.06	peak to base ratio	-.02	.85
Annual miles/ bus	-.45	.002	roadcalls/mile	.12	.32

Taken together, these results indicate that maintenance management should improve the efficiency of its operation in anticipation of lower operating support levels, that it should take steps to increase the effectiveness of labor, and that these steps are most necessary in larger and more intensively utilized systems. The need for greater internal efficiency is supported by the significant relationship between subsidy levels and both labor commitment and roadcall frequency. More efficient use of existing resources will be needed to keep maintenance performance high in the face of budget pressures. The need to explore ways to improve the effectiveness of labor is highlighted by the regression results showing that labor effort is not significantly related to roadcall reduction. Although it can be argued that chargable roadcalls are but one indication of maintenance performance, this result reinforces informal discussions which pointed out the difficulty of maintaining the accountability of labor. The final generalization --that attention should especially be directed to larger systems -- is based on the lower level of labor commitment and higher incidence of chargeable roadcalls in systems with large and intensively used vehicles.

C. Opportunities for Improving Maintenance

Maintenance managers have developed a number of tools for controlling their operations. These include work order systems, driver defect reports, periodic cost analyses, and preventive maintenance programs. These tools are generally quite useful for managing daily operations. However effective maintenance requires attention to a number of other concerns. These include fine detail items such as how to best perform a specific maintenance task, as well as more global questions involved in setting preventive maintenance schedules and projecting future budget needs. A fuller understanding of these issues can be developed by comparing the organizational structure of the typical transit property with the distribution of functional responsibility. This comparison shows that the relationship between maintenance and the other aspects of a transit operation is much more complex than the organizational chart indicates. The contrast between organizational structure (Exhibit II.4) and departmental interdependence (Exhibit 11.5) provides the maintenance manager with an extremely challenging professional environment. He is accountable for meeting daily schedule requirements, for minimizing preventable roadcalls, and for directing a diverse array of mechanics, servicers, foremen, and clerks. The maintenance manager's job is especially difficult because his equipment is utilized by drivers accountable to other managers.

Transit managers have long been aware of the importance of maintenance, and they have developed a number of tools for improving its effectiveness. These methods include pre-run inspections, roadcall reporting, work order processing, and preventive maintenance scheduling systems. Some properties have implemented these tools using sophisticated computerized management information systems, while others are using manual record-keeping procedures. Regardless of the degree of automation, these types of records and reports are essential for an effective maintenance program. While the head of maintenance is held accountable for vehicle fueling, repair, and preventive maintenance, his performance is strongly influenced by a number of factors which are not

Exhibit II.4

TYPICAL ORGANIZATIONAL STRUCTURE

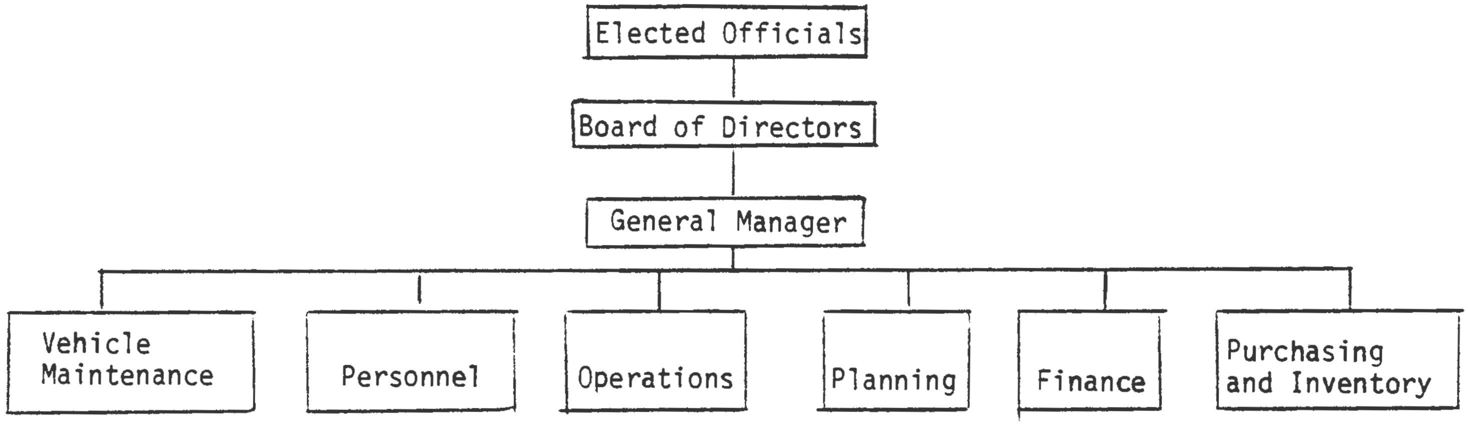
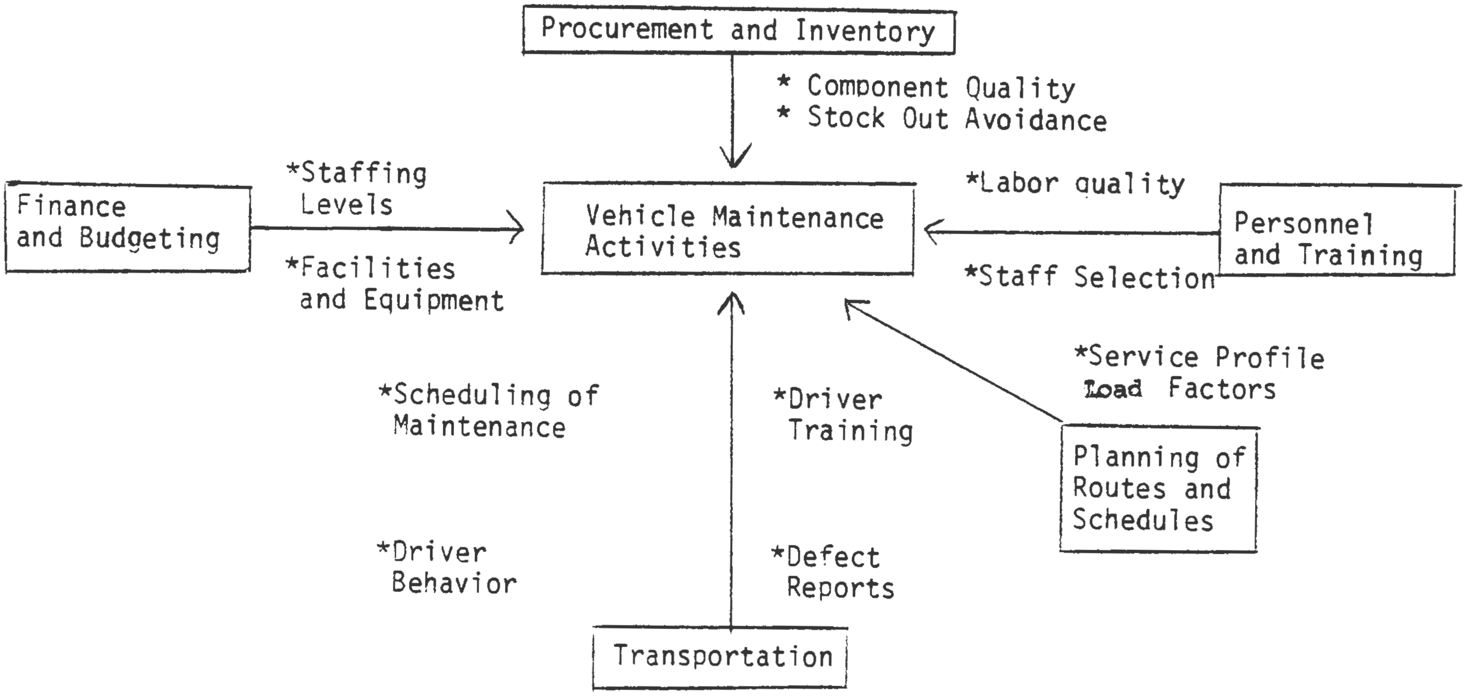


Exhibit II.5

INTERDEPENDENCE OF MAINTENANCE AND OTHER TRANSIT SYSTEM DEPARTMENTS



directly under his control. These include the general structure of the organization, the type and age of equipment operated, the labor agreement, the schedule of service, driver training and performance, street conditions and stop spacing, inventory levels, and funding levels. The complexity of this environment makes the maintenance manager's job quite difficult. His decision-making powers include allocation of mechanics to tasks, scheduling of routine preventive maintenance, and determining appropriate repair actions. Meanwhile, external influences are constantly affecting vehicle condition. The range of responsibilities and the environment in which the maintenance manager operates place him in a position of reacting to problems as they occur by using existing resources. This reactive position is reinforced by the use of general indicators, such as roadcall counts, missed runs, and maintenance-related accidents, to measure maintenance preformance. That current practices do not meet existing needs is clear from the variations in performance discussed above in Section B.

Organizational factors have a major influence on maintenance performance. A significant number of factors affecting vehicle reliability can not be manipulated directly by maintenance department personnel. For example, scheduling and route planning affect the amount of stress imposed on engine, transmission and brake systems, and the intensity of vehicle use places constraints on the availability of vehicles for maintenance. Collective bargaining agreements limit the availability of manpower for third-shift maintenance, and budgets influence both spare ratios and inventory levels.

The sources of maintenance problems can be differentiated by their proximity to the maintenance department. This is shown in Exhibit II.6. Internal problems are under the direct control of maintenance management. These include preventive maintenance policies, management information systems, supervision, and workload levels. It is significant that budget levels for maintenance are becoming recognized as something that can be influenced by maintenance managers -- if they take an aggressive role and develop strong quantitative cases for staff and material needs. Other factors, such as labor agreements, fleet age, routes and schedules, and vehicle procurement are less controllable by the maintenance manager.

This report focuses on the internal decision-making associated with developing a maintenance data base, setting maintenance policies, forecasting workloads, and making budget presentations to general management. Maintenance supervisors need these tools to put their own operations in order and to develop strategies for securing needed resources from management. An important finding of the research is that most innovations in maintenance management have occurred at the level of day-to-day operations. This is understandable in view of pressures to meet peak period demand and keep up the appearance of the transit fleet. The research project has not found this high degree of responsiveness in other areas of maintenance management. Specifically, little attention has been given to development of work methods to improve the accuracy and quality of mechanics' performance and almost no activity has been directed at strategic or long-range planning. We will now survey current methods which are applicable to control of day-to-day operations and then turn to methods which can be applied to meet organizational needs in the work methods and strategic planning areas.

Exhibit II. 6

SOURCES OF MAINTENANCE PROBLEMS CLASSIFIED BY LOCATION WITHIN THE TRANSIT ORGANIZATION

Internal Problems Controllable by Maintenance Manager	Problems Not Under Control of Maintenance
Maintenance Policies	Labor Contract
Maintenance Data base	Organization Structure
Supervision	Fleet Age
Engineering	Quality of Labor
Budget	Service Profile
Workload	Fixed Facilities
	Funding Levels
	Inventory
	Vehicle Quality

III. CURRENT METHODS

All transit systems use some maintenance management tools although systems differ considerably in their degree of sophistocation. This section will doncument some of the more common of these tools. Part A will describe the tools used in the day-to-day operation of the maintenance department. The majority of these tools are simply a procedure for recording the raw data of daily maintenance. Part B will describe the next level of tools which are used for monitoring maintenance and for planning.

A. Data Capture

The first level of management tools includes:

- operator defect reports
- fuel and oil consumption reports
- work order systems
- job cost reports
- periodic inspection and maintenance schedules
- vehicle maintenance records

These reports and control systems are especially important because they contain the information needed to implement emerging forecasting and planning tools. Each is described briefly below:

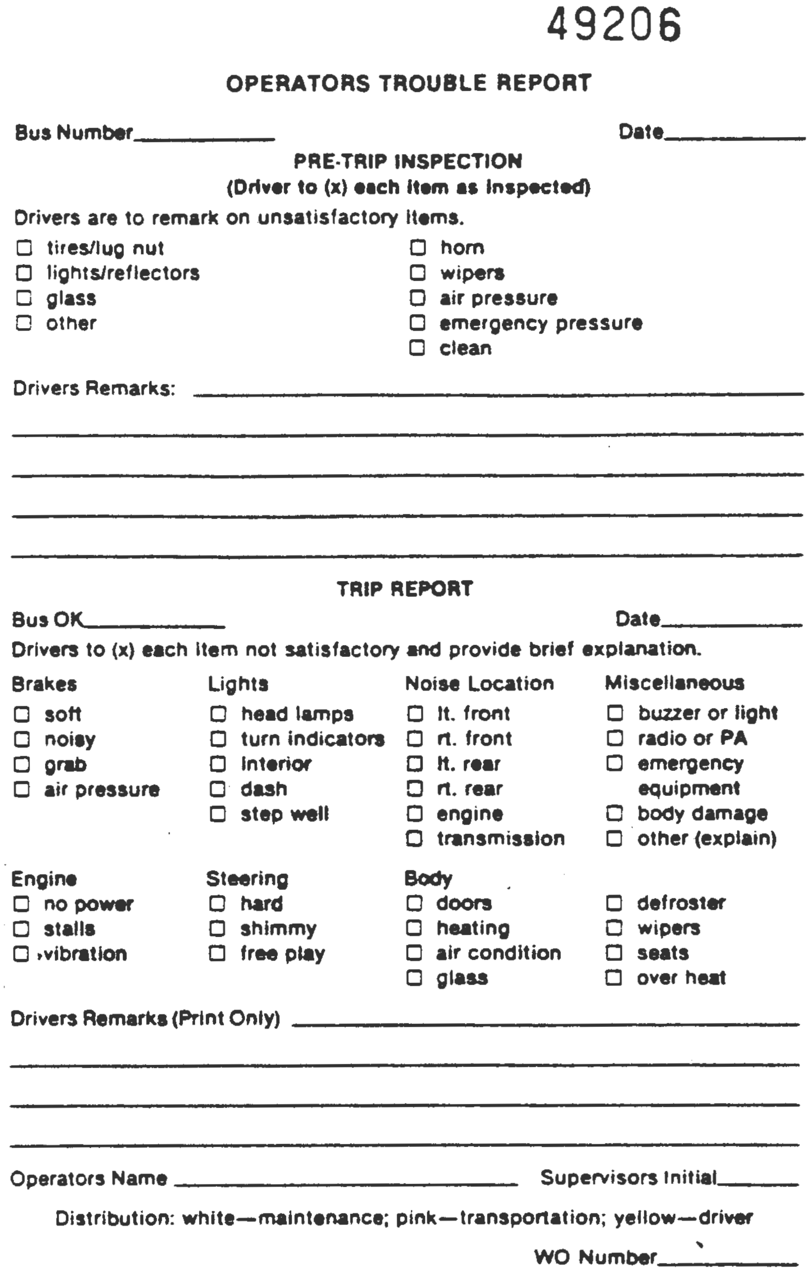
1. Operator Defect Reports

Defect reporting has two components: Pre-trip inspections and in-service trouble reports. The basic purpose of pre-trip inspection is to control the condition of vehicles put into service and to insure proper performance of maintenance. Operation of buses by drivers responsible to the transportation division and maintenance of those buses by mechanics responsible to a different supervisor can lead to endless shifting of blame for vehicle condition. Most properties try to control this by having drivers conduct pre-trip inspections prior to vehicle pull-out. These pre-trip inspections cover safety items such as lights, horns, air pressure and window wipers as well as general cleanliness and body condition. Many operators require mechanics as well as drivers to sign off on vehicles so that responsibility for problems discovered at some later time can be clearly established. This procedure provides a clear record of the completeness and quality of daily maintenance and the degree of care exercised by drivers in operating the equipment.

The second element of defect reporting is the reporting of problems encountered while the vehicle is in operation. This is important for the identification of problems with brake, engine, transmission, heat, and air conditioning systems which are experienced only while the vehicle is in use. Trip or inservice reports also allow the driver to alert the mechanic about noises and other early signs of developing problems. This component of the defect reporting system is essential to the strategy of conducting maintenance by continuous monitoring of vehicle condition.

Exhibit III.1 provides an example of a typical pre-trip inspection and trip report. Note that copies of the report are distributed to

EXHIBIT III.1



49206

OPERATORS TROUBLE REPORT

Bus Number____________ Date____________

PRE-TRIP INSPECTION

(Driver to (x) each item as inspected)

Drivers are to remark on unsatisfactory items.

☐ tires/lug nut
☐ lights/reflectors
☐ glass
☐ other

☐ horn
☐ wipers
☐ air pressure
☐ emergency pressure
☐ clean

Drivers Remarks: ____

____

____

____

____

TRIP REPORT

Bus OK____________ Date____________

Drivers to (x) each item not satisfactory and provide brief explanation.

Brakes
☐ soft
☐ noisy
☐ grab
☐ air pressure

Lights
☐ head lamps
☐ turn indicators
☐ interior
☐ dash
☐ step well

Noise Location
☐ lt. front
☐ rt. front
☐ lt. rear
☐ rt. rear
☐ engine
☐ transmission

Miscellaneous
☐ buzzer or light
☐ radio or PA
☐ emergency equipment
☐ body damage
☐ other (explain)

Engine
☐ no power
☐ stalls
☐ vibration

Steering
☐ hard
☐ shimmy
☐ free play

Body
☐ doors
☐ heating
☐ air condition
☐ glass

☐ defroster
☐ wipers
☐ seats
☐ over heat

Drivers Remarks (Print Only) ____

____

____

____

Operators Name ______________________________ Supervisors Initial________

Distribution: white—maintenance; pink—transportation; yellow—driver

WO Number__________

transportation and maintenance personnel and that the driver retains a copy as well. There is also space to record the number of the work order issued to remedy identified defects.

2. Maintenance Shop Reports

Several types of data are collected through a variety of shop reports. The following paragraphs briefly describe some of the most common. Examples of the report forms are presented in Appendix B.

Consumables Report. This report records the amounts of coolant, fuel oil, transmission fluid, and engine oil added in daily servicing of vehilces. Daily records are generally kept on a vehicle-by-vehicle basis. Some larger systems are currently experimenting with automated methods for recording both vehicle numbers and amounts of fluid added.

Work Order Systems. Work order systems are a vital mechanism for building accountability into the maintenance function. Each maintenance action is initiated by a work order. The system generally involves a write-up of the job after completion, showing what was done, the time for completion, and the identity of the responsible mechanic. Maintenance supervisors generally develop means of monitoring the number of outstanding work orders and tracking those which have been pending for prolonged periods of time.

Maintenance Cost Report. Cost reporting for work orders involves recording the material and labor used for specific tasks. This report will generally carry the work order number initiating the activity. Practices differ on how overhead is charged on labor activities, making inter-company comparisons difficult.

Periodic Maintenance Schedules. All transit systems have some system for periodic inspection, lubrication, and adjustment of vehicle systems. Schedules for PM activities vary (Preston, 1980), but most are initially based on manufacturers' recommendations, with modifications as indicatd "by experience."

Vehicle Maintenance Records. In addition to work order and job cost records, virtually all operators keep a summary record of major repairs. This is generally the "bus card" or "bus file" record which tracks the miles between overhaul or replacement of major components including starters, engines, transmissions, air compressors and brakes. A copy of one record format is shown in Exhibit III.2. This record is of critical importance for applying many maintenance planning methods because it contains the data necessary to analyze performance trends at the vehicle sub-system level.

B. Management Reporting

The items just discussed are part of the daily operation of most properties. It is also common practice to prepare summaries of periodic performance for use in monitoring by management. These types of reports are discussed next. Appendix B contains examples of such reports.

VEHICLE NO. ______________________

Exterior Paint Dates				Interior Paint Dates			

SHOW LINING AND DRUM SIZES

Units / Miles in Thousands	Generator	Voltage Regulator	Starter	Dist.	Air Comp.	App. Valve	Frt. Door Engine	Rear Door Engine	Door Control Valve	Left Front Lining	Right Front Lining	Left Rear Lining	Right Rear Lining	Left Front Drum	Right Front Drum	Left Rear Drum	Right Rear Drum	Rebush Front Axle	Steering Column	
Vehicle Miles Previous O. H.																				
Date of O. H.																				
Unit Miles																				
Vehicle Miles																				
Date of O. H.																				
Unit Miles																				
Vehicle Miles																				
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Vehicle Miles																				

Units / Miles in Thousands	Front Heater Motor	Front Heater Core	Left Heater Motor	Left Heater Core	Right Heater Motor	Right Heater Core	Refgmt Comp.	Refgmt Strainer	Refgmt Heat Exchanger	Refgmt Evaporator	Refgmt. Condenser	Cond. Fan Pump	Cond. Fan Motor	Refgmt Comp. Clutch			Trans. Gov.	Carb.	Fuel Pump	Hyd. Fan Assy.
Vehicle Miles Previous O. H.																				
Date of O. H.																				
Unit Miles																				
Vehicle Miles																				
Date of O. H.																				
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EXHIBIT III.2
VEHICLE HISTORY RECORD

Roadcall Reports. These reports give the frequency of inservice problems. They generally classify the cause of the problem by vehicle sub-system and usually are produced monthly. The format should allow easy comparison of month-to-month variations.

General Performance Summaries. Weekly performance monitoring is conducted by many properties. This involves reports by day of bad order buses, peak schedules met, roadcalls, operator defect reports, inspections performed, etc. These reports "roll up" daily data into summary formats. They can be used to establish performance targets and to monitor goal achievement.

Vehicle Cost Report. Analysis of costs by vehicle complements the reporting of service performed and problems reported. Vehicle cost reports summarize oil and fuel consumption and maintenance costs. Data from these reports help to identify impending engine or transmission problems as well as high-cost vehicles. The cost data is especially important for long-range planning.

Automated Systems. A number of computerized systems have been developed for routine reporting and management. One of the earliest was the Service, Inventory and Maintenance System (SIMS) (MITRE, 1973). This system provided for recording unit changes, initiating scheduled inspections, and preparing cost and consumables reports. It also had capabilities for displaying vehicle status and monitoring inventory activities. The SIMS system was designed as a batch reporting system.

More recently developed systems, which include the Chicago Transit Authority's Vehicle Maintenance Systems (VMS) and the Western Maintenance Consortium's Maintenance and Inventory System, operate interactively. The VMS system was designed with capabilities for bus and work order status reporting, PM scheduling, roadcall monitoring, and employee time accounting. The Western Consortium's System has capabilities for PM scheduling, consumables reporting, inventory management, failure monitoring, work order processing, and management reporting.

IV. NEW TECHNIQUES

A number of methods not currently in use were identified in the course of this research. These include methods for improving maintenance procedures, for analyzing component quality, for forecasting future manpower and inventory needs, for comparing maintenance policies and for evaluating and setting preventive maintenance schedules. These procedures complement current management tools, and support the expansion of management's role into the areas of employee performance monitoring and strategic planning.

A. Methods Analysis

The aim of methods analysis redesign of work to improve the on-the-job performance of mechanics and to give management better control over costs and time allocation. While methods analysis is standard practice in many industries, it has received little attention in transit. However, in a case where it was applied to transit maintenance, costs were reduced by 30 to 50% (Miller and Lane, 1982; Haenisch and Miller, 1976). There are three major components to methods analysis: job time estimation, anlaysis and improvement of procedures, and cost estimation. These components as well as implementation and an example are discussed below.

1. Estimation of Standard Job Times.

Job time estimates are necessary for systematic work planning and cost control. Industrial engineering methods have been developed to generate reasonable, efficient job standards that, when produced uniformly, result in good estimates of standard performance times. The steps necessary for estimating these times include: documentation of existing operations; recording of actual times; reduction of unnecessary transports, delays and out of stock conditions; evaluation of workplace design; improvement in procedures; specification of tools; specification of the number of mechanics, carpenters, and electricians necessary for the job; and an overall assessment of expected performance time.

The first step is to document the way in which the job is currently performed. To document existing procedures, on-site observations are taken of the particular job being studied. Tasks are broken down to small (six-minute) intervals and recorded on an observation sheet. At least three separate observations are recorded although longer or more complex tasks may require more observations. The observations are taken at different maintenance locations, observing the work of several different workers. The initial observation sequence provides an estimate of average work time and quality of task performance. During the observation, actual time is recorded. Each observation is divided into actual performance time and avoidable and unavoidable delay times. The unavoidable and avoidable delays are then subtracted from total time, and the three raw standard times are averaged. No allowances for problem delays are incorporated into the observed average times. If any one of the three observed times is not within 33% of the others, that observation is discarded and a new observation is made.

2. Analysis and improvement of procedure

The determination of the standard time can be made from the average of the three observed times. In most cases, however, more than simple documentation is required. Most often, the procedure must be sequenced and analyzed to determine the length of time that the procedure should take. This analysis begins by combining tasks identified in the initial three observations into one systematic procedure. Each task is analyzed to determine its necessity to the overall procedure, and unneccessary ones are eliminated. The analysis includes allocating work time to securing materials from storage areas, combining tasks to reduce back-tracking and deadheading and listing all equipment needed to eliminate repeat trips. Other steps are added to assure the highest quality finished job. Special tools may be designed to make the job easier. For example, component rebuilding may be divided into tasks for constructing subassemblies, so when replacement is performed, various additional components are already part of the larger subassembly.

3. Synthesis into a Procedural Bulletin

Once work methods are optimized and times are estimated, the improved procedure is presented in the form of a bulletin, which is titled by job and begins with a brief statement of purpose. A repair worker in bus maintenance is able to perform the job completely and accurately by following the bulletin. When necessary, other bulletins are referenced to provide complete information on how to do the job. The intent of the bulletin is not to provide training, but to serve as a guide to help the worker perform the specific task uniformly, and to produce the highest quality product in the safest way. The bulletin provides discrete steps that must be executed. Most importantly, these bulletins provide a path to follow in order to achieve the established standard time for that job. It should be noted that while all buses have the same basic parts, the parts may require different procedures for repair or replacement on different bus models. Accordingly, different bulletins are provided for differing bus models.

During the initial documentation and following analysis a complete material list and a special tool list are developed. These enable the individual assigned to a task to obtain all the materials and tools needed to perform that task before the task is begun, eliminating repetitious returns to the storeroom or tool crib during the job. The lists also eliminate half finished jobs and wasted manpower due to material shortages. In developing the procedural document, every effort is made to reduce unnecessary trips and delays by sequencing the procedure to minimize the amount of time it should take. However, as these factors vary in specific locations or garages, it may be necessary to establish separate standard job time constants for obtaining and returning tools and materials and for moving the vehicle from the storage location to the work location and back for these specific situations.

Work sampling has shown that a 12½% allowance is needed for personal needs. Another 12½% is recommended for deviations from ideal conditions. The allowance factor reflects the following variables:

1. Condition of the garage - some are new with excellent lighting and modern lifts; others are old with service pits and lighting from street car days;

2. The availability of air, electricity, etc.;

3. The size of the working location.

The total of 25% in allowances is added to the observed average time and the performance constants are added to the standard job time in order to establish the estimated standard time for tasks performed in garages. Since the performance and allowance constants can account for a significant part of the total time, especially on short tasks, various types of repair or replacement work should be combined, especially when the same tools and materials are required for the combined tasks. These combined tasks are reflected in one bulletin.

Tasks performed in overhaul shops may not require the same constants as tasks performed in the garages because the vehicle is brought to the designated area by other personnel and because special equipment or subassemblies may be in use. Nevertheless, the shop bulletins are similar to the garage bulletins. Differences may occur if the mechanic does not retrieve the bus, material, or tools. However, the material and tool lists should be supplied so the mechanic can check these items before beginning the job.

4. Implemenation of Methods Analysis

Standard job times and improved work methods can be used for a more efficient daily programming of maintenance tasks and for determining manpower requirements for particular daily work loads. The standard times can be recorded on a computer system to provide summaries of job performance by individual and by particular job, allowing continuous monitoring of productivity by function. This makes it possible to review each individual job or combination of jobs in relation to the overall garage system, providing management with the information they need for increasing efficiency and for providing overall better utilization of manpower.

An example of this approach is Miller's (19) study of 150 functions at ten CTA bus garages. Before implementation of Miller's standards, a thorough review of each bulletin was conducted in a round-table discussion with maintenance management foremen and resident instructors at a working location. Methods personnel also demonstrated the use of the special tools listed in the bulletins. The purpose of the discussion was to increase understanding, assure acceptance, and permit refinement by all parties. The bulletins themselves were displayed in garage locations where the type of work described in the bulletin was performed. The bulletins were placed within a few feet of and completely accessible to the employee performing the task. Copies of the bulletins were also distributed during employee training and kept by the employees.

Each bulletin was coded with a distinct job number. At the CTA this job number is keyed into a computerized data system when an employee begins the job. The employee "jobs off" when the job is completed and the time is automatically computed and stored. Analyses of worker, job, location and system performance can be generated from the collected data to provide better utilization of manpower and job efficiency.

On average, it took approximately 100 person hours to produce each bulletin, although the time varied with job duration and complexity

5. An Example of Methods Analysis

One of the more extensive procedures in the CTA case involved the removal of the Detroit Diesel power plant. Whereas this operation was previously performed on a piecemeal basis, the task is now accomplished by pulling the unit out as an assembly and then partially disassembling the converter and blower. Use of an engine dolly facilitates this method. The revised procedure led to savings of 40%, which amounts to approximately $250 per plant removal in 1982 dollars.

The procedure requires an electrician, a carpenter, and two mechanics. Because of the detail of the bulletin (see Exhibit IV.1), the foreman knows exactly when to call each trade and how long each employee will be needed on this particular job. The extensive detail of the procedure may seem excessive to the observer at first, but such detail is necessary to ensure accurate, uniform, and reproducible results.

A major achievement of the new procedure was the improved scheduling of employees and reduction in delays from one or more not being available. Reduction in waiting time also promoted better worker relations. The initial evaluation of the CTA study showed significant productivity gains averaging in excess of 30% due to improvements in work methods and as well as reductions in time required for the job. For many functions, the gain was in excess of 50%.

6. Analysis of Standard Cost

Once standard methods are established, the estimated times for the jobs can be used to develop standard costs.

Since the standard time is known and a standard labor cost can be determined, only the material cost is needed to determine the total cost of rebuilding a component. Two alternatives to rebuilding components in house should be considered: purchasing a new component from the manufacturer and subcontracting for a rebuilt component. The decision to replace or rebuild depends on several factors: the availability of trained staff in house; the cost of rebuilding versus replacing based on standard time and cost estimates; the availability of the new item and the lead time to obtain it, the ability to and wisdom of stocking in-house rebuilt components versus the ability to and wisdom of stocking new components; the quality and consistency of rebuilt components versus the consistency of replacements.

EXHIBIT IV.1

EXAMPLE OF PROCEDURE BULLETIN

Power Plant Removal 8V-71 Detroit Diesel Eng.	3.0±0.5 h (M) 0.8±0.1 h (C) 0.3±0.1 h (E)	2210
JOB DESCRIPTION	STANDARD TIME	JOB NUMBER
Bus No. 6-9, 21-25, 1000-1524, 7400-7944	Hoist	
VEHICLE SERIES	SUGGESTED LOCATION	

MATERIAL DESCRIPTION	LOT NO.	QUANTITY
Engine Dolly		
Oil and coolant drain drums		

SPECIAL TOOLS	TOOL/LOT NO.	QUANTITY

NOTE: SAFETY IS PART OF THE JOB
Exercise all CTA established safety rules relating to the use of tools, materials, equipment, and personal safety in the performance of these procédures.

PROCEDURE:

Note: Four men are required for this job, two mechanics, one carpenter, and one electrician. The job tasks are grouped by workman type, and are generally sequential within the groupings. The mechanics should begin working immediately upon those tasks which require no previous work by the electrician and carpenter. The electrician and carpenter should work "around" the mechanics, attempting to finish their tasks as soon as possible.

1. Go to Data Entry Unit and job-on.
2. Obtain bus and position in work area.
3. Obtain necessary tools and materials.

Electrician:

1. Disconnect battery cables.
2. Disconnect engine wiring pin connectors (2) at junction panel.
3. Disconnect wire at bottom of junction panel.
4. Disconnect A/C wiring from alternator (5 wires).
5. Disconnect two wires from starter motor, working from inside of coach.
6. Clean up work area—replace tools.
7. Go to Data Entry Unit and job-off.
8. Report to Foreman for next assignment.

continued on next page

EXHIBIT IV.1 continued

Carpenter:

1. Secure engine compartment door:
   a. Raise engine compartment door.
   b. Attach support pin in compartment support brace.
   c. Run a 40-foot length of rope approximately 1/2 inch in diameter under compartment door and through the door's mounting hinges.
   d. Push rear hinged windows out at bottom.
   e. Run rope ends through rear windows.
   f. Tie one end securely to passenger hand rail in bus.
   g. Have mechanic pull support pin out of compartment support brace and push compartment door open to maximum extension.
   h. Pull rope taut and tie loose end securely to passenger hand rail.
2. Remove engine access panels from inside coach.
   a. Lift rear seat. Use prop to support seat.
   b. Remove top panel.
   c. Remove insulation.
   d. Remove bottom panel.
3. Remove back bumper by removing bumper mounting bracket-to-engine cradle mounting bolts (10).
4. Remove radiator closure door bottom mounting bolts.
5. Raise the right side engine compartment closure door and affix closure door support prop.
6. Remove right side bumper extension by removing mounting bolts at bulkhead mounting bracket and extension back mounting bracket.
7. Remove brace member between right end of engine cradle and mounting bracket at lower edge of bulkhead.
8. Return all materials to their proper place.
9. Go to Data Entry Unit and job-off.
10. Report to Foreman for next assignment.

Mechanics (2):

1. Close shut-off valve in heater line.
2. Open access flap for coolant filler.
3. Press and hold vent cock on surge tank to relieve pressure in cooling system.
4. Open filler cap to vent cooling system while draining.
5. Raise radiator closure door and affix support brace.
6. Raise coach.
7. Exhaust air system by opening drain valve on right rear air tank. When system is exhausted, close valve.
8. Position drain coolant drum under lower radiator hose connector drain plug.
9. Remove lower radiator hose connector drain plug. Allow to drain and replace plug.
10. Position drain coolant drum under heat exchanger coolant exhaust line.
11. Loosen hose clamps on rubber connector for heat exchanger coolant exhaust line.
12. Break connector seal and slide back toward heat exchanger. Allow coolant to drain.
13. After exchanger is drained, slide connector forward and tighten hose clamps.
14. Remove drain coolant drum from work area.
15. Position drain oil drum under engine oil pan drain plug.
16. Remove engine oil pan drain plug. Allow to drain and replace drain plug.
17. Position drain oil drum under transmission oil pan drain plug.
18. Remove transmission oil pan drain plug. Allow to drain and replace plug.
19. Disconnect air lines to transmission shift slave cylinder.
20. Remove shift cylinder clevis pin at transmission shift lever.
21. Loosen propeller shaft retaining collar and slide forward on propeller shaft.
22. Disconnect transmission ground strap.
23. Remove A/C dust shield.
24. Remove A/C propeller shaft flange mounting bolts at fan drive.
25. Pull propeller shaft off end of A/C splined shaft and remove from vehicle.
26. Remove engine cradle to bulkhead mounting bracket bolt nuts, flat washers, 1/4-inch aluminum circular plates and rubber bushings. *Do not remove bolts.*

continued on next page

EXHIBIT IV.1 continued

27. Loosen exhaust pipe to muffler clamps (2) and slide towards muffler.
28. Disconnect engine oil by-pass filter input and output lines at filter.
29. Disconnect heat exchanger input and output oil lines at exchanger.
30. Disconnect air compressor discharge line by removing bolts at discharge line flange.
31. Disconnect air compressor intake hose at compressor.
32. Disconnect air compressor governor reservoir port line at compressor.
33. Disconnect compressor governor unloader port line at compressor.
34. Disconnect fuel lines at fuel filters.
35. Disconnect power steering fluid line at compressor. Allow to drain using a can to catch drainage.
36. Cap power steering fluid line receiver at compressor.
37. Disconnect oil manifold line at fitting on generator.
38. Disconnect air line at engine stop solenoid valve.
39. Disconnect air line at fast idle solenoid valve.
40. Remove throttle clevis pin.
41. Remove throttle cable mounting clip on engine compartment door side of engine.
42. Remove engine coolant temperature sending unit.
43. Remove throttle cable mounting clip on bulkhead side of engine.
44. Pull throttle cable toward bulkhead to clear engine.
45. Disconnect speedometer cable from speedometer drive unit on transmission.
46. Loosen exhaust pipe clamp at engine exhaust pipe support bracket.
47. Loosen bottom exhaust pipe clamp at cradle hanger exhaust pipe support bracket.
48. Remove middle exhaust pipe.
49. Loosen top exhaust pipe clamp at cradle hanger exhaust pipe support bracket.
50. Remove exhaust pipe bracket mounting bolts at cradle hanger.
51. Remove exhaust pipe bracket.
52. Loosen hose clamp on surge tank overflow line. Disconnect line.
53. Disconnect surge tank vent line at engine.
54. Disconnect surge tank deaeration line at engine.
55. Loosen hose clamp on heater supply line and disconnect line.
56. Loosen hose clamp on heater return line and disconnect line.
57. Loosen hose clamp on engine coolant supply line at surge tank and disconnect line.
58. Loosen clamps on air-intake silencer at both silencer-to-blower intake cover rubber connector and silencer-to-air-intake filter rubber connector.
59. Loosen bolts on air intake silencer barrel mounting straps.
60. Rotate air intake silencer towards bulkhead.
61. Remove bolts from radiator assembly lower support member. Support bracket.
62. Remove bolt and rubber spacers at radiator upper support.
63. Position engine dolly under engine cradle raising or lowering coach to provide 2-3 inch clearance between engine cradle and dolly.
64. Lower coach until engine cradle is approximately 1 inch from dolly.
65. Connect air line to engine dolly.
66. Inflate engine dolly, checking for dolly-to-cradle contact alignment.
67. Lift engine cradle to relieve stress on cradle hangers.
68. Loosen cradle hanger to coach support bracket bottom mounting bolt nut.
69. Remove cradle hanger to coach support bracket top mounting bolt nut and bolt, adjusting engine dolly lift if needed.
70. Pivot cradle hangers toward the sides of the engine compartment.
71. Raise engine cradle to free cradle to bulkhead support brackets.
72. Remove engine cradle-to-bulkhead mounting support bracket bolts (2).
73. Remove air line from engine dolly.
74. Move power plant away from engine compartment slowly, checking to see that all lines, wiring and controls are disconnected.
75. Exhaust air from engine dolly air bags.
76. Clean work area—replace tools.
77. Take bus to storage area.
78. Go to Data Entry Unit and job-off.
79. Report to Foreman for next assignment.

If all other things are equal, including quality, consistency and availability, the component replacement and rebuilding decisions can be made using the lowest cost criterion. The costs would be assessed as:

In house rebuild:	Standard Time X Labor Cost Per Hour + Material Cost + Overhead
Subcontract rebuild:	Quotation from rebuilder
New purchase:	Quotation from manufacturer

B. Failure Analysis

Failure analysis involves three different activities: estimation of component life, diagnosis of variations in performance, and fault mode analysis. The development of component survival curves is a logical extension of the vehicle history recordkeeping procedure discussed in Section III. This procedure is useful for determining the life expectancy of components, and it also provides the data necessary to identify variations in performance, predict future repair requirements, and assess the desirability of fixed interval replacements vs. failure or inspection based maintenance. Fault mode analysis is used to develop corrective actions to extend the useful life of components.

1. Development of Component Life Distributions

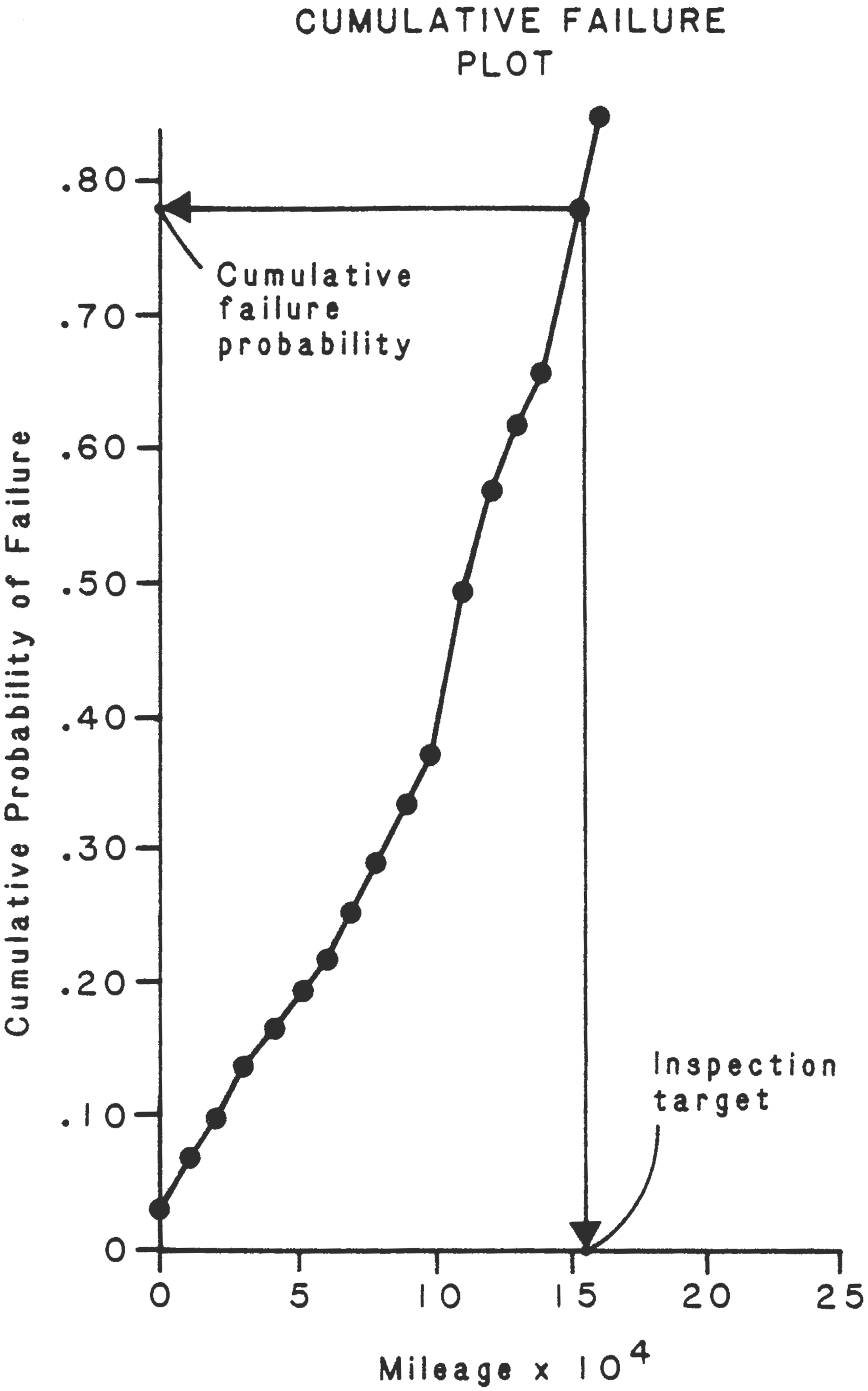
a. Purpose

The distribution of unit failures by miles run is useful information for maintenance management. It is superior to reports of average life expectancy because it provides an indication of the contribution of manufacturing error, random failure, and ageing to component failure. One of the products of recent maintenance research at the University of Illinois (Kosinski et al., 1982) is an operational method for determining failure rate statistics from standard recordkeeping mechanisms used by transit operators, i.e., the bus history card. This procedure is applicable to computer-based repair order and vehicle tracking systems as well. It is flexible enough to be applied in situations where components have variable installation and replacement dates, and does not require that all components be run to failure.

The procedure has five steps: 1) determining the number of miles each observed component accumulated before failure or replacement, or before the point of data collection, 2) grouping the data into intervals of thousands of miles, 3) counting the number of components which aged but did not fail in each interval, 4) calculating conditional failure probabilities for each interval, and 5) calculating cumulative failure probabilities from the conditional failure statistics.

Such information can be used to determine the proportion of bus components which will fail in normal use for a given inspection or replacement schedule and also to set target inspection and replacement mileages on the basis of management policies regarding system reliability (see Exhibit IV.2)

EXHIBIT IV.2


CUMULATIVE FAILURE PLOT
.80
.70
.60
.50
.40
.30
.20
.10
0
Cumulative Probability of Failure
Cumulative failure probability
Inspection target
0
5
10
15
20
25
Mileage x 10^4

b. Example

The practicability of the procedure is demonstrated in a recent study of AC Transit maintenance data (Kosinski et al., 1982). The basic item of interest in this study was the failure rate of each of 17 components (e.g., engines, differentials, clutches) and the functional relationship between the probability of failure for any given unit and the number of miles operated. The focus of the analyis of the data is the mileage that each unit obtained before it was replaced because failure seemed likely or because the unit actually failed. (The terminology here of "failure" is used interchangeably with "replaced in anticipation of failure", the assumption being that if the unit did not fail, the point of replacement was that point just before the unit would fail.)

Mileage between failure for each component is computed in the following manner: for each type of unit in each bus the incidents of failure were sorted in chronological order and the mileages for the first instance of failure were subtracted from the second, and the second from the third, and so on in order to determine the mileage between replacements. This convention was reasonable since AC Transit routinely inspects units both at set mileages and upon the basis of operator reports and then closely monitors their performance. Any replacement is likely to indicate that the unit had reached or was about to reach the end of its useful life. The frequency of the failures in given intervals exhibit the characteristic properties of classic failure curves; that is, there were initial periods of high failure due to manufacturing defects followed by periods of lower failure rates due to random causes.

Determining probabilities of failure requires the use of special procedures for handling "censored" observations (i.e., cases where the unit was removed before failure). This is necessary because most transit operations do not follow block or mileage based replacement policies; rather, components are replaced at failure and at any one time there will be a large variation in the service age of any type of component. The procedure involves the identification of the number of failing and surviving units and the mileage reached to estimate the number of miles to which the unit had survived at the date of data collection. Using frequencies of unit failure and unit survival, conditional failure probability distributions are calculated. The cumulative failure probability distribution function for each unit are determined from the conditional distribution function.

As the data collection proceeded, it became apparent that the quality and consistency of the data obtained from AC Transit was very good. However, there were some indications of scheduling or record-keeping problems, perhaps due to disproportionate workloads between garages and large variations in the mix of maintenance effort. There was also evidence that the mileages specified by AC Transit for inspection of some units may have been set too high because the data indicate that nearly 80% of some units had already failed prior to the first inspection.

c. Implementation

The quality of the data base affects the reliability and utility of conclusions drawn from this method. The data base should cover a timespan sufficiently large to ensure replacement of a significant number of the units under consideration and it should be built upon a reliable maintenance recordkeeping system. The data base should also contain information taken from buses which are representative of the entire fleet, and it should include the cause of unit replacement, i.e., whether they were changed because of driver report, inspection, maintenance policy, or failure.

2. Comparison of Variations in Life History Data

a. Methods.

The procedures described in the previous section can be easily applied due to a recent enhancement to the SPSS (Statistical Package for the Social Sciences) software (Nie and Hull, 1981). The SPSS package, which is commonly available, now has a SURVIVOR procedure which plots hazard rates and survival probabilities. It also has options permitting comparisions of groups of data, such as the performance of components from different suppliers or of different vehicle series. Like the technique described in the previous section, it is also applicable to "censored" data, which is typical of that found on bus card records.

The SURVIVOR procedure is relatively flexible. It can use either raw data files or grouped data as input. Its output includes hazard rate, survival, and cumulative failure plots, and it can produce comparisons of up to eight groups of data. It also calculates an approximate statistical significance test which can be used to compare samples and evaluate the importance of observed differences. The only limitation of the procedure is that it requires preprocessing of the data typically appearing on bus card records. This can be accomplished by using the methods developed by Kosinski et al (1982) and summarized in Section IV.B.1.

b. Example

A good example of this technique is the analysis of AC Transit component history data (Foerster, 1982a). This analysis is based on bus card records assembled according to the procedures previously outlined. The SPSS SURVIVOR procedure was used to compare the life expectancies of 17 bus components over two time periods and across three different garage locations. For each comparison, tabular and graphical data displays were produced. The graphical output, shown in Exhibit IV.3, displays the proportion of components surviving to stated mileages. The graphical symbols in the Exhibit identify the distributions for brakes installed before 1978 (symbol "1") and after 1978 (symbol "2"). This particular graph shows a significant decline in brake life, a problem which is now being addressed by the National Cooperative Transit Research Program. Plots of hazard rates, probability density functions, and logarithmic scaling are all available as options in the program. The program also produces tabular output, shown in Exhibit IV.4, that includes descriptive statistics and optional tests of the significance of inter-group ("treatment") differences.

EXHIBIT IV.3

COMPARISON OF SURVIVAL FUNCTIONS FOR REAR BRAKES FOR TWO TIME PERIODS

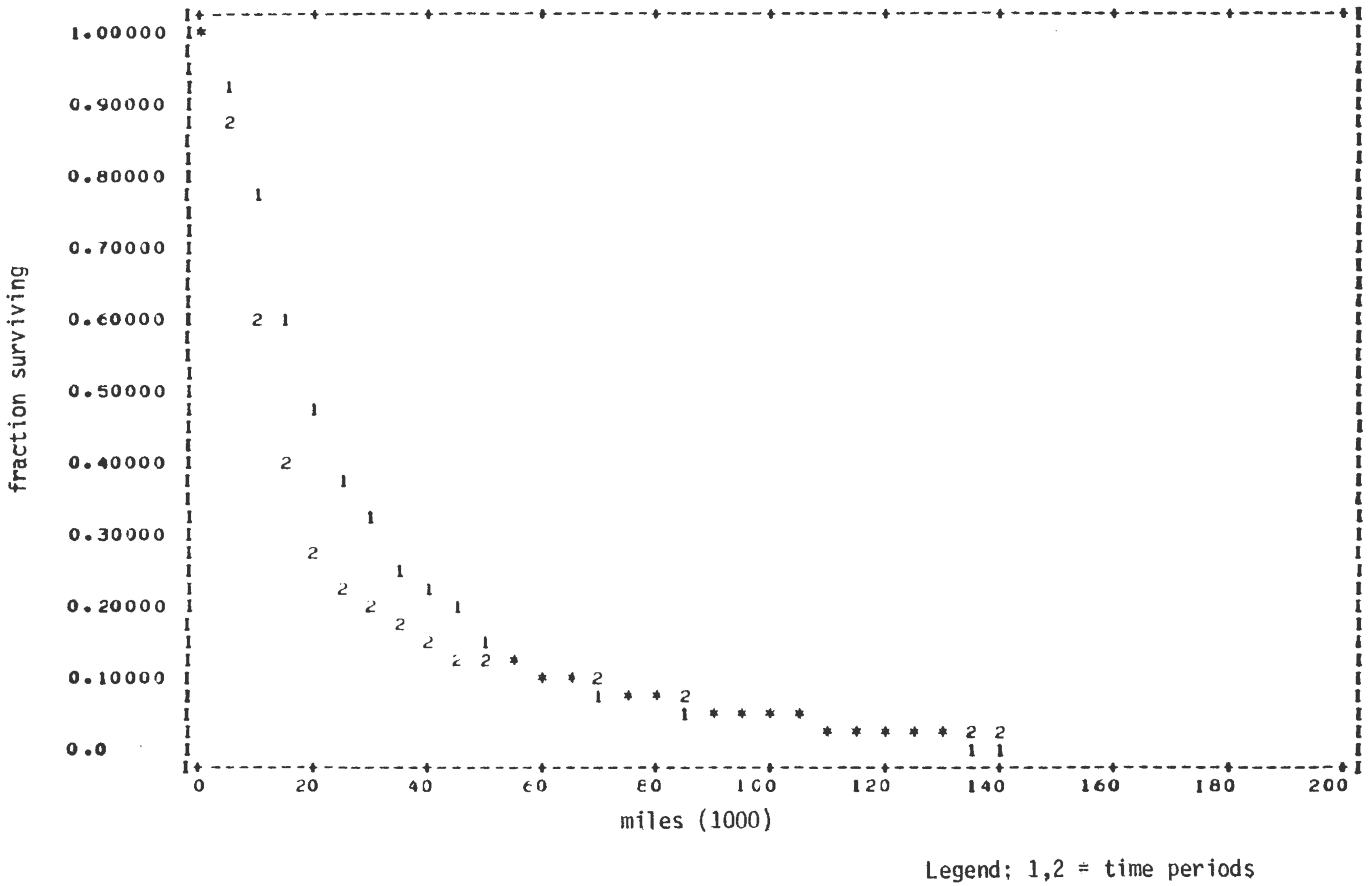


Exhibit IV.4

TABULAR OUTPUT FROM SPSS SURVIVOR PROCEDURE FOR COMPARISON OF BRAKE LIFE

(a) Descriptive Statistics

```
LIFE TABLE
   SURVIVAL VARIABLE  MILES
                 FOR  DIV                                                                  =        2

INTVL   NUMBER   NUMBER   NUMBER   NUMBER                     CUMUL                               SE OF   SE OF
START   ENTRNG   WDRAWN   EXPOSD     OF     PROPN    PROPN    PROPN    PROBA-             CUMUL   PROB-   SE OF
TIME     THIS    DURING     TO     TERMNL   TERMI-   SURVI-   SURV     BILITY   HAZARD    SURV-   ABILTY  HAZRD
         INTVL    INTVL    RISK    EVENTS   NATING   VING     AT END   DENSTY    RATE     IVING   DENS    RATE
------  ------   ------   ------   ------   ------   ------   ------   ------   ------    -----   -----   -----
   0.0   327.0     11.0    321.5     23.0   0.0715   0.9285   0.9285   0.0715   0.0742    0.014   0.014   0.015
   1.0   293.0      8.0    289.0     20.0   0.0692   0.9308   0.8642   0.0643   0.0717    0.019   0.014   0.016
   2.0   265.0      7.0    261.5     15.0   0.0574   0.9426   0.8146   0.0496   0.0591    0.022   0.012   0.015
   3.0   243.0     12.0    237.0     27.0   0.1139   0.8861   0.7218   0.0928   0.1208    0.026   0.017   0.023
   4.0   204.0      1.0    203.5     31.0   0.1523   0.8477   0.6119   0.1100   0.1649    0.028   0.019   0.030
   5.0   172.0      5.0    169.5     36.0   0.2124   0.7876   0.4819   0.1300   0.2376    0.029   0.020   0.039
   6.0   131.0      1.0    130.5     28.0   0.2146   0.7854   0.3785   0.1034   0.2403    0.029   0.018   0.045
   7.0   102.0      4.0    100.0     24.0   0.2400   0.7600   0.2877   0.0908   0.2727    0.027   0.018   0.055
   8.0    74.0      5.0     71.5     22.0   0.3077   0.6923   0.1992   0.0885   0.3636    0.025   0.018   0.076
   9.0    47.0      0.0     47.0      8.0   0.1702   0.8298   0.1653   0.0339   0.1860    0.023   0.012   0.065
  10.0    39.0      0.0     39.0      5.0   0.1282   0.8719   0.1441   0.0212   0.1370    0.022   0.009   0.061
  11.0    34.0      2.0     33.0      6.0   0.1818   0.8182   0.1179   0.0262   0.2000    0.020   0.010   0.081
  12.0    26.0      0.0     26.0      6.0   0.2308   0.7692   0.0907   0.0272   0.2609    0.019   0.011   0.106
  13.0    20.0      0.0     20.0      4.0   0.2000   0.8000   0.0725   0.0181   0.2222    0.017   0.009   0.110
  14.0    16.0      0.0     16.0      2.0   0.1250   0.8750   0.0635   0.0091   0.1333    0.015   0.006   0.094
  15.0    14.0      0.0     14.0      3.0   0.2143   0.7857   0.0499   0.0136   0.2400    0.014   0.008   0.138
  16.0    11.0      0.0     11.0      2.0   0.1818   0.8182   0.0408   0.0091   0.2000    0.013   0.006   0.141
  17.0     9.0      0.0      9.0      1.0   0.1111   0.8889   0.0363   0.0045   0.1176    0.012   0.005   0.117
  18.0     8.0      0.0      8.0      4.0   0.5000   0.5000   0.0181   0.0181   0.6667    0.009   0.009   0.314
  19.0     4.0      0.0      4.0      1.0   0.2500   0.7500   0.0136   0.0045   0.2857    0.009   0.005   0.283
  20.0     3.0      0.0      3.0      2.0   0.6667   0.3333   0.0045   0.0091   1.0000    0.005   0.006   0.612
  21.0     1.0      0.0      1.0      1.0   1.0000   0.0      0.0      0.0045   2.0000    0.0     0.005   0.0

 THE MEDIAN SURVIVAL TIME FOR THESE DATA IS    5.86
```

(b) Test of time-related differences

```
APPROXIMATE COMPARISON OF SURVIVAL EXPERIENCE USING THE LEE-DESU STATISTIC
   SURVIVAL VARIABLE  MILES
            GROUPED BY  DIV

 OVERALL COMPARISON    STATISTIC        20.669  D.F.     2   PROB.  0.0000

 GROUP  LABEL                 TOTAL N   UNCEN      CEN  PCT CEN  MEAN SCORE

     2                            327     271       56    17.13     -29.471
     3                            154      61       93    60.39      87.448
     4                            101      46       55    54.46     -37.921

 PAIRWISE COMPARISON   STATISTIC        19.458  D.F.     1   PROB.  0.0000

 GROUP  LABEL                 TOTAL N   UNCEN      CEN  PCT CEN  MEAN SCORE

     2                            327     271       56    17.13     -32.872
     3                            154      61       93    60.39      69.799

 PAIRWISE COMPARISON   STATISTIC         0.377  D.F.     1   PROB.  0.5391

 GROUP  LABEL                 TOTAL N   UNCEN      CEN  PCT CEN  MEAN SCORE

     2                            327     271       56    17.13      3.4006
     4                            101      46       55    54.46     -11.010

 PAIRWISE COMPARISON   STATISTIC         9.460  D.F.     1   PROB.  0.0021

 GROUP  LABEL                 TOTAL N   UNCEN      CEN  PCT CEN  MEAN SCORE

     3                            154      61       93    60.39      17.649
     4                            101      46       55    54.46     -26.911
```

The tests run by Foerster detected a number of garage-related differences in component service life. These include large differences in front brake life (with median survival mileages of 57,000, 90,000 and 61,000 miles for the three garages studied), and large inter-garage variations in replacement mileages for brake diaphragms and relay valves. The detection of these differences can signal a need to inquire further into the reasons for divergent life expectancies. The front brake differences may be due to topography and load factor variations. The brake diaphragm and relay valve differences are probably due to failure to observe stated replacement policies for these components.

The results also show that some changes over time occurred at only one or two garages. For example, Exhibit IV.5 shows clutch life expectations. The circles indicate survival rates for pre-1978 clutches. These show no difference in life expectancy by garage. There are differences among garages for the post-1978 data. It appears that garage number one is experiencing no differences in clutch life, but that clutches in garage number two are lasting longer while those in garage number three are wearing more quickly. Other differences of this type were also identified in generators and rear brakes. No major time-related differences in the frequency of failure and repair/replacement of air compressors, blowers, generators, starters, clutches, transmissions, front brake, brake relay valves and rear brake diaphragms were noted. No significant time or garage differences were seen for engine work, differentials, transmissions, starters and blowers.

c. Evaluation

The SPSS SURVIVOR procedure is an easy-to-use tool for looking at historical maintenance data. It can be used to identify trends in component life, to diagnose inter-garage variations in performance, and to track the quality of rebuilt or replacement components.

A good data management system would greatly facilitate use of this program. Such a system should provide for recording of failure and replacement data on an ongoing basis (perhaps as the bus card is updated) and should include the reasons that components are replaced (failure, mileage limit, inspection). This is necessary in order to distinguish between component life and replacement policy effects.

3. Fault Mode Analysis

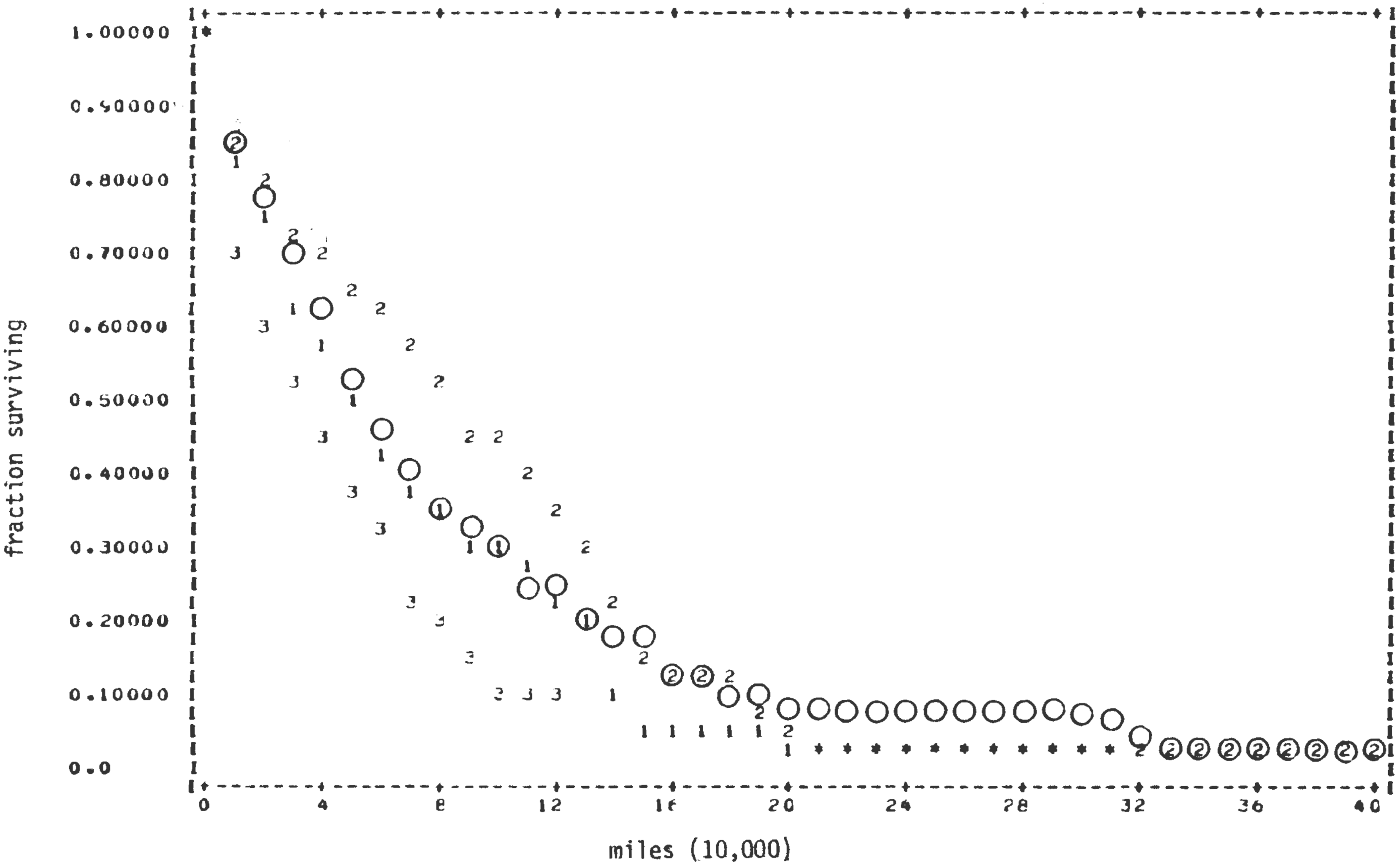
a. Example of Methods

Fault mode analysis is appropriate for components which have a high failure rate. Kelly and Ho (n.d.) advocate the formalization of this practice to control high maintenance costs. This approach uses the the types of data described earlier to identify problem components, but it also involves communication with supervisors and manufacturers to institute operating and manufacturing practices which result in early detacting of failure (See Exhibit IV.6).

A recent application of this procedure resulted from the observation of failures at low mileages for new and reconditioned transmissions. The mean mileage-to-failure for new transmissions was 120,000

EXHIBIT IV.5

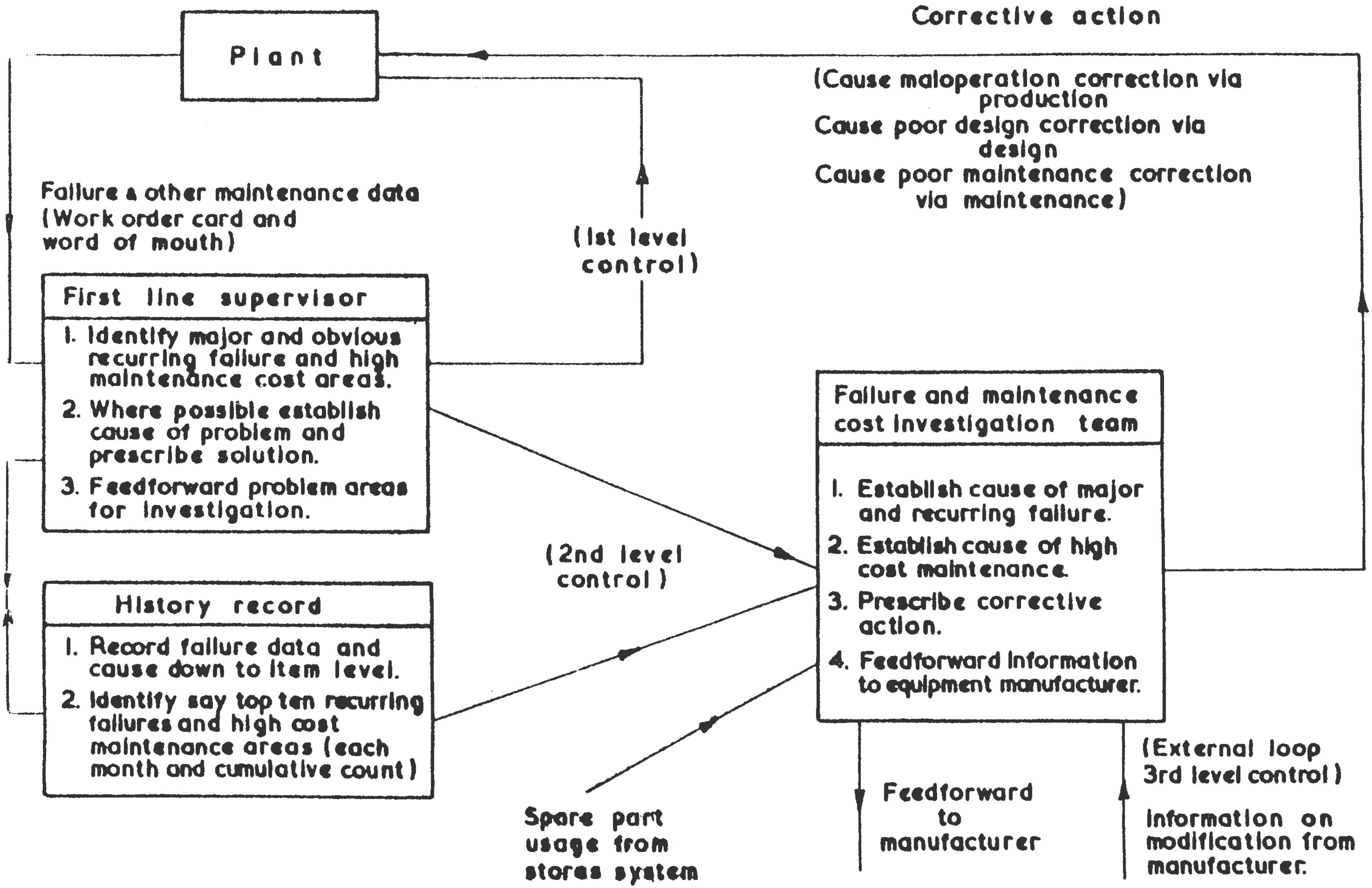
COMPARISON OF SURVIVAL FUNCTIONS FOR CLUTCHES: TWO TIME PERIODS AND THREE GARAGES



Legend: 0 = time period 1, all garages
1,2,3 = time period 2, garages 1,2,& 3

Exhibit IV.6

FAULT ANALYSIS ACTIVITIES



Source: Kelly and Ho, n.d.

miles instead of a target 200,000 miles. Reconditioned transmissions were failing at 58,000 miles.

Detailed engineering analysis indicated that the early failure of the new units was due to use of lubricants poorly suited to the particular application, excessively long lubricant change intervals, inadequate air system inspection, and driver operating habits.

Recommended solutions included more frequent changes of lubricant more frequent adjustment of the transmission, improved air system testing, driver training, and improved component design.

Problems with rebuilt gearboxes were found to result from the use of reconditioned brake bands and gear trains. Recommended remedies included the use of new brake bands in the rebuilding process and instrument testing of gear trains to detect hairline cracks before reuse.

b. Evaluation

Kelly and Ho indicate considerable success with this approach to specific problems. However, they stress the importance of systematic recordkeeping:

> Unless a data collection system has been properly designed it is extremely difficult to extract the type of information necessary for maintenance decision-making. A passenger transport organization using many identical buses should have a data collection system which will gather information on failures down to the item (e.g., gearbox) level. Such information should include the time to failure, the symptoms, and above all, the causes of failure. (Kelly and Ho, p. 8).

C. Workload Projections

The techniques surveyed in the first two parts of this section are concerned with monitoring and improving performance. We now consider methods for planning maintenance activities. Two types of action must be addressed: scheduled and non-scheduled maintenance.

1. Scheduling Regular Maintenance

Scheduled maintenance includes daily servicing as well as periodic inspection and preventive maintenance. Most properties have daily schedules for fueling and cleaning. The more critical need is for preventive maintenance and inspection scheduling. This is addressed in some systems by incorporating inspection targets into the MIS system. The Chicago Transit Authority's Vehicle Maintenance System (VMS) is a case in point. It displays lists of vehicles reaching maintenance mileage targets on a daily basis.

A related need is to plan inspections on a long term basis. This is important when setting staffing levels and phasing in new fleets. Several methods for doing this have been developed (Kelly and Ho, n.d. and Wilson-Hill, 1980) Their common element is the analysis of periods when vehicles are unavailable for maintenance because they are needed to meet peak demand or to maintain spare vehicle ratios. The most advanced tool for this purpose is the Interactive Inspection Scheduling Package (IISP) developed by the Transportation System Center (Wilson-Hill, 1980). It could be profitably adapted for handling not only warranty-related items but also for planning compliance with preventive maintenance schedules.

2. Projecting Emergency Repairs

In addition to estimates of scheduled maintenance workloads, management also needs to have estimates of non-scheduled (failure) maintenance. With cuts in subsidies to passenger bus transportation, more tightly controlled budgets will result. This will require more accurate assessments of future needs in budgeting for maintenance. One way to develop good estimates of future money, manpower and facility needs in the maintenance area is to base budgets on the expected number of maintenance actions. Accurate failure predictions on a monthly, quarterly or yearly basis can be translated easily into corresponding manpower and equipment requirements if an accurate data base is already in place. These estimates, in turn, can be used to plan labor schedules and part orders. The resulting reductions in overtime and of excess inventory can yield cost savings.

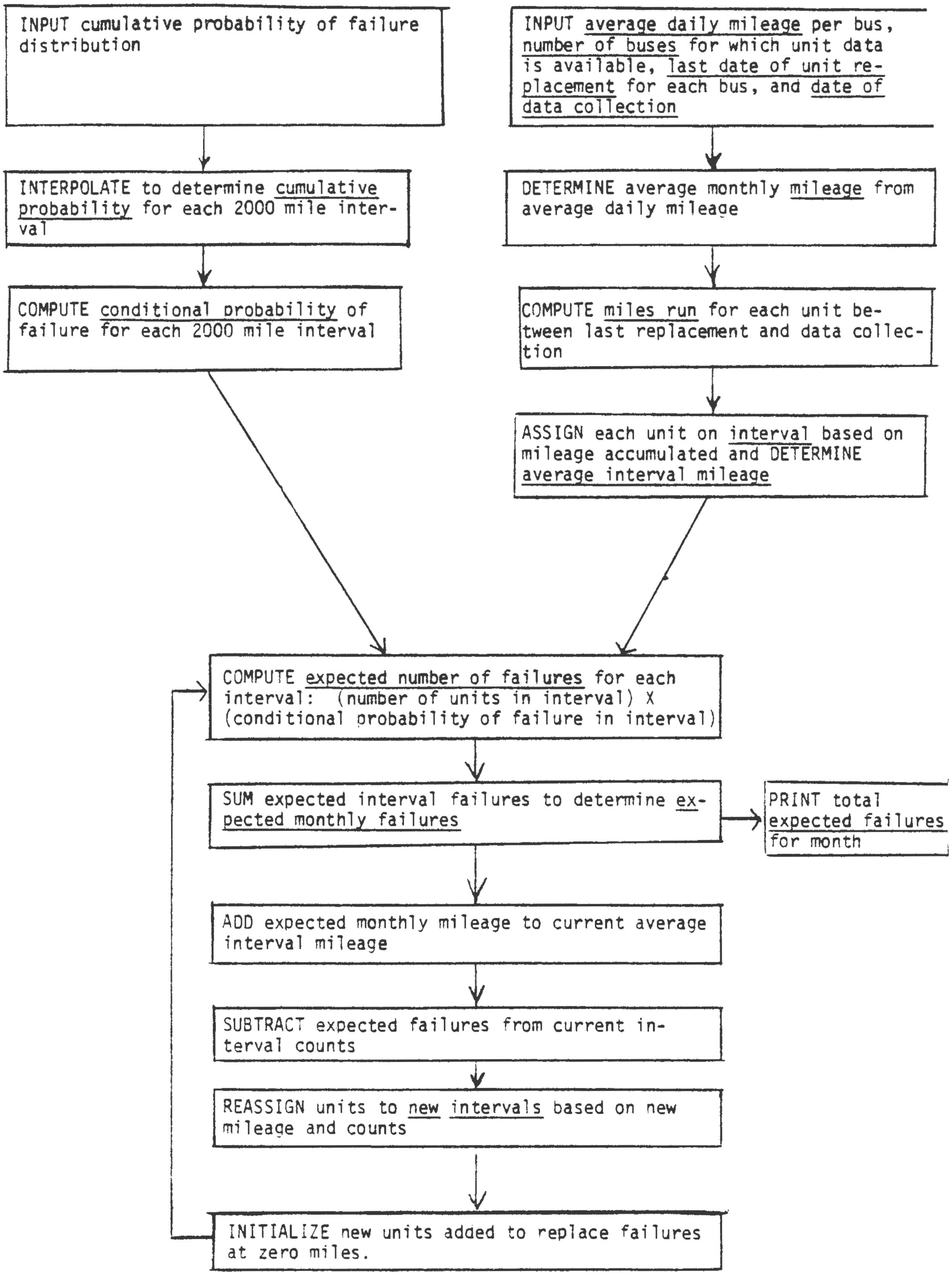
The most significant barrier to systematic analysis of this type has been the lack of methods or programs to permit transit managers to estimate the expected number of failures by specific components. Currently, estimates of failures are usually developed by seasoned personnel on the basis of historical trends, "experience" or special data analysis. The accuracy of such estimates is questionable.

One product of this project is a computer program to predict monthly expected component failures for any given component of a bus fleet. The component failure prediction program was designed to predict failures by component or major subsystem, for 36 months, using a data base that could be developed easily from bus maintenance records. It was also designed to use a minimum amount of computer time and storage and to be readily understood by the user. Detailed monthly information by component and subsystem is provided to estimate labor time and parts required for repairs. Simple estimates of total expected failures per month are less useful than this data because managers need to know the expected replacement times and parts requirements.

The 36-month projection figure was selected because most transit organizations work with two and five-year planning schemes, and the three-year period would provide sufficient information to fit into this time scheme and indicate possible trends. A data base that can be readily extracted from existing records is essential to permit use of the program. The program was designed for small and medium sized (10 to 500 bus) systems because these systems contain the majority of the buses on the road and because the least amount of research has been directed toward this size of property. However, the program does not limit the number of buses and is usable by transit properties of all sizes.

Exhibit IV.7

FUNCTIONAL FLOWCHART
QUARTERLY MAINTENANCE REQUIREMENTS MODELS



The computer program was written in FORTRAN using a WATFIV compiler. It requires 164K memory (as currently dimensioned) and should be readily adaptable to most medium-priced microcomputer systems which support FORTRAN. The program is divided into eight major parts: 1) entry of cumulative probability of failure distribution, 2) filling in of missing intervals in cumulative distribution, 3) conversion of cumulative probabilities to conditional probabilities, 4) entry of mileage and replacement data, 5) computing of miles run since replacement of each unit, 6) categorizing units into mileage intervals, 7) computing number of failures by interval and month, and 8) updating interval mileage and accounts. The functional flow chart of the program is illustrated in Exhibit IV.7.

The type of output produced is shown below:

Exhibit IV. 8
EXPECTED BLOWER REPLACEMENTS
BY TIME PERIOD

Period (months)	Number	Manpower and Material Cost
1-6	19.6	$ 2163
7-12	24.5	$ 2722
13-18	25.3	$ 2930
19-24	25.3	$ 2930
25-30	18.0	$ 3210
31-36	17.8	$ 3227

D. Maintenance Policy Testing

One perennial question facing maintenance managers is "Does mileage-based unit change save money?" The component failure prediction program described in Section C.2 can be used to address this question and to project cost levels under a variety of maintenance policy scenarios.

For example, Exhibit IV.9 shows the comparison of an existing AC Transit maintenance policy with two proposed alternative policies. The competing policies are: the current inspection based maintenance with replacement at failure, replacement at the current inspection mileages, replacement at 50% probability of failure. The program generated the following analysis based on a labor cost of $11.58 per hour, labor being 60% of total costs, and the cost of failures being 50% over replacement costs.

Exhibit IV. 9
POLICY COST COMPARISONS
FOR TRANSMISSION

	Inspection/ failure based maintenance	Replacement at inspection mileages (100,000 miles)	Replacement at 50% probability of failure (100,000 miles)
Cost			
3-year total	$46,378.30	$77,334.16	$77,334.16
Per quarter	$ 3,864.85	$ 6,444.50	$ 6,444.50

The costs for the second and third policies for transmissions are the same since the 100,000 mile inspection replacement interval corresponds to the mileage associated with a 50% probability of failure. Based on the above comparison, the inspection/failure replacement policy is by far the best, having a total cost 40% less than the cost of replacement at 100,000 miles or a 50% cumulative probability of failure.

A similar analysis of generator replacement is shown in Exhibit IV.10.

Exhibit IV. 10
POLICY COST COMPARISONS
FOR GENERATORS

Cost	Inspection/ failure-based maintenance	Replacement at inspection mileages (275,000 miles)	Replacement at 50% probability of failure (147,000 miles)
3 year total	$4,742.72	$2,205.75	$4,552.01
per quarter	$ 395.23	$ 183.81	$ 379.33

For generators, the replacement at inspection occurred at 275,000 miles. The mileage associated with a 50% failure probability is 147,000 miles. Replacement at 50% cumulative probability of failure is only slightly better than the replacement policy. Replacing generators at inspection mileages, however, would current result in a 53% savings over current practices.

An analysis of blowers is given in Exhibit IV.11.

Exhibit IV. 11
POLICY COST COMPARISONS
FOR BLOWERS

Cost	Failure/inspection based maintenance	Replacement at inspection mileage (90,000 miles)	Replacement at 50% probability (175,000 miles)
3-year total	$17,230.57	$11,747.78	$13,291.58
per quarter	$ 1,435.85	$ 978.98	$ 1,107.63

Blower inspection mileage is 90,000 miles. The 50% probability of failure mileage is 175,000 miles. Replacement at 50% cumulative probability of failure shows a savings of 23% over current practices, which indicates that some improvement could be made by changing policies. However, as with the generators, replacement of the blowers at the 90,000 inspection mileage appears to be the best policy with a 32% savings over current inspection/failure policies.

Brake policies are illustrated in Exhibit IV.12.

Exhibit IV. 12

POLICY COST COMPARISONS
FOR FRONT BRAKES

Cost	Failure/inspection based maintenance	Replacement at inspection mileage (50,000 miles)	Replacement at 50% probability (60,000 miles)
3-year total	$36,205.11	$102,796.35	$98,629.95
Per quarter	$ 3,017.09	$ 8,566.36	$ 8,219.16

The replacement mileages for front brakes for the second and third policies are 50,000 and 60,000 miles. As the table shows, the practice followed by AC Transit is substantially cheaper than either replacement at the specified inspection mileage or 50% cumulative probability of failure with a savings of 65% and 63%, respectively. As with the transmissions, AC Transit appears to be following the best policy.

The preceding exhibits show how the program can be used to compare various maintenance policies. Such comparisons could be used to resolve long-standing disputes about the cost-effectiveness of failure-based maintenance vs. mileage-dependent unit exchanges. The program may also be used to determine estimated monthly costs or labor requirements. If the cost and labor time needed to perform repairs are known or can be estimated, the monthly cost and time requirements may be approximated by multiplying total expected monthly failures by the unit cost or time.

Other possible areas for further development are: writing a companion program which would directly compute the conditional and cumulative probabilities of failure from historical bus maintenance data; translating the program into an interactive system; and eventually including the program in an inventory control system so that unit replacements could be monitored at the parts storeroom level and quarterly expected parts requirements could be used to maintain an economical inventory level.

E. Optimum Maintenance Interval Methods

Four models for determining maintenance intervals for components of transit buses were identified from the literature during preparation of this report. Their use is illustrated in the following section using data from AC Transit. The models are described in detail by Rueda and Miller (1982). They include the Jardine model, the Dynamic Programming model, the Bakr Maintenance Scheduling model, and the MASSTRAM system. A comparative analysis and assessment of their value as decision tools for bus maintenance is presented. The purpose of this effort is to inform the transit industry of various options for setting fleet maintenance policies. Bus replacement techniques are discussed in Appendix C. Discussion of each method includes its objective, input requirements, output applications, and evaluation of method.

1. Jardine model. The objective of this model is to calculate the optimal replacement interval for each bus component. The input requirements are cost of preventive component replacement, cost of replacement at failure, and component failure distribution per mile. The output is a listing of candidate preventive replacement intervals, expected number of in-service failures, and expected cost per mile.

Jardine's model evaluates trade-offs between the costs of preventive replacement and replacement at failure. This model is applicable only when components exhibit increasing failure rates over time and when replacement at failure is considered more costly than preventive replacement. The cost of failure may include penalty costs attributed to service interruptions. For the sake of example, labor costs were set at $11.58 per hour, and labor was assumed to be 60% of the total maintenance cost. A 50% penalty cost was assumed for in-service failures, although data on such penalty costs is not generally available. AC Transit data on component failures were used.

A computer program was developed by Rueda (1982) to facilitate computations. Exhibit IV.13 presents an example of the output for scheduling component replacement.

Exhibit IV.13

JARDINE MODEL: OPTIMAL REPLACEMENT MILEAGES AND COSTS

Component	Replacement Interval (000 mi)	Cost ($/000 mi)
Rear Brakes	42.0	6.7
Rear Brake Diaphragm	57.0	0.6
Front Brakes	62.0	3.4
Clutch	75.0	2.3
Front Brake Diaphragm	67.0	0.4
Brake Application Valve	92.0	0.4
Starter	107.0	0.3
Air Compressor	122.0	0.3
Transmission	152.0	1.9
Brake Relay Valve	221.0	0.2
Blower	165.0	0.9
Generator	240.0	0.1
Differential	333.0	0.8
Semi Engine Overhaul	263.0	4.8
Major Engine Overhaul	305.0	11.1

2. Dynamic Programming Model. The objective of this approach developed by Vergin and Scriabin (1977) is to schedule preventive, opportunistic, or breakdown replacement of a multi-component bus subsystem. The input requirements are cost of preventive replacement by component, penalty costs of replacement at failure, cost-savings associated with the preventive replacement of groups of components and survival probability by component mileage. The output is the replacement policy for every

combination of component ages. The methodology uses a dynamic programming approach to evaluate alternative maintenance policies. These policies are: a) replacement of a component only upon failure, b) replacement of a component before its failure, c) replacement of a group of components upon failure of one component, d) the replacement of a group of components upon preventive replacement of one component.

To illustate this method, suppose a system is composed of components 1, 2, 3, and 4. The dynamic programming stages would be the number of mileage intervals the components are expected to operate. The state would be the number of 40,000 mile intervals survived by each component and its specific stage. The transition cost would be the cost associated with a breakdown, preventive or opportunist replacement policy.

The penalty cost for replacement at failure was assumed to be a 50% increase over the cost of preventive replacement cost. Cost savings for group preventive replacement was evaluated over two sets of assumptions: 1) the group preventive replacement cost is the sum of the preventive replacement cost of each component, and 2) group replacement results in a 50% reduction in total replacement costs. Three sets of assumed accumulated mileages for the components were evaluated. A sample of the output from a program by Rueda (1982) is shown in Exhibit IV.14.

Exhibit IV. 14

SAMPLE DYNAMIC PROGRAMMING/GROUP REPLACEMENT ANALYSIS

Cumulative Failure Probabilities

component	40,000 mi	80,000 mi	120,000 mi
1	.263	.657	.876
2	.263	.657	.876
3	.438	.871	.976
4	.438	.871	.976

Optimal Replacement Strategies

Case	Mileage Accumulated by Component				Best Option Assuming	
	1	2	3	4	No cost savings for Group Action	Group Savings
1	40,000	0	80,000	120,000	Replace 4	Replace 1,4
2	40,000	0	120,000	80,000	Replace 3	Replace 1,3
3	80,000	120,000	80,000	80,000	Replace 2	Replace 1,2

This technique can be used to evaluate the cost trade-offs, frequencies of breakdown, and preventive and opportunistic policies for replacement of multi-component systems. In contrast to deriving replacement intervals for components on an individual basis, this method accounts for both the component's age and the ages of the other components in the subsystem. It tends to become computationally difficult as the number of componets under evaluation is increased, but sub-groups with a reasonable number of components exhibiting potential for preventive and opportunistic replacement can be considered. Components of such groups may be characterised by increasing failure costs, similar mean mileage lives, or similar failure functions. A significant disadvantage of the method is the amount of recordkeeping required to keep track of the components' ages to decide whether preventive, opportunistic or block replacement should take place at specific mileage intervals. This makes the model most appropriate for use in special studies to control high cost functions.

3. Bakr Maintenance Scheduling Model

The objective of this model is again to determine an economical bus maintenance schedule by accounting for preventive maintenance costs, costs of in service failures, and bus preparation costs. The input requirements are failure distributions by component, preventive replacement times by component, emergency replacement times by component, probability of bus accident upon in-service failure of component, costs and times for replacement, average cost of an accident and bus preparation costs. The output is the maintenance schedule and the total maintenance cost per mile. Bakr and Kretschmer (1974) use a search method to select least-cost bus maintenance schedules. The search begins by grouping components with similar mean mileage lives. These components are then kept as a group for scheduling purposes. The initial estimates of mileage intervals are derived by minimizing preventive replacement and in-service failure costs. The search method evaluates the cost of candidate mileage intervals within the range of the mean failure time of the components. Final service schedules are derived by minimizing preventive replacement, in-service failure and bus preparation costs. A moving-range search method is used.

Test applications of this model have generated solutions which are extremely sensitive to bus preparation time, accident cost, and the difference between scheduled and unscheduled repair costs. The method also tends to produce schedules which are incompatible with the objective of meeting peak hour service needs. Some of those problems are remedied in the approach discussed next.

4. MASSTRAM. The Maintenance Analysis and Scheduling System for Transit Management or MASSTRAM model was originally intended for rail maintenance scheduling. Its authors conducted initial runs of the model, using data collected from the Massachusetts Bay Transportation Authority (Herniter et al., 1977). Recently, Foerster et al. (1980) modified and tested the model using data from a bus transit system. The unique feature of MASSTRAM is that it is an interactive system. It is basically a more refined version of the Bakr model and has options allowing the user to define minimum and maximum preventive mileage intervals and the maximum allowable number of inservice failures. Peak fleet requiement became an additional constraint in the derivation of least-cost maintenance schedules. The user specifies the maximum number of different preventive mileage intervals to be considered during the evaluation and the model has the capability to differentiate regular and overtime requirements for any generated maintenance schedule. It searches for the maintenance schedule which minimizes preventive

maintenance and in-service failure costs, and which also satisfies user-provided constraints on peak fleet requirements and allowable numbers of in-service failures. Examples of MASSTRAM outputs are shown in Exhibit IV.15. It has the unique capability of analyzing the tradeoffs between cost and system reliability.

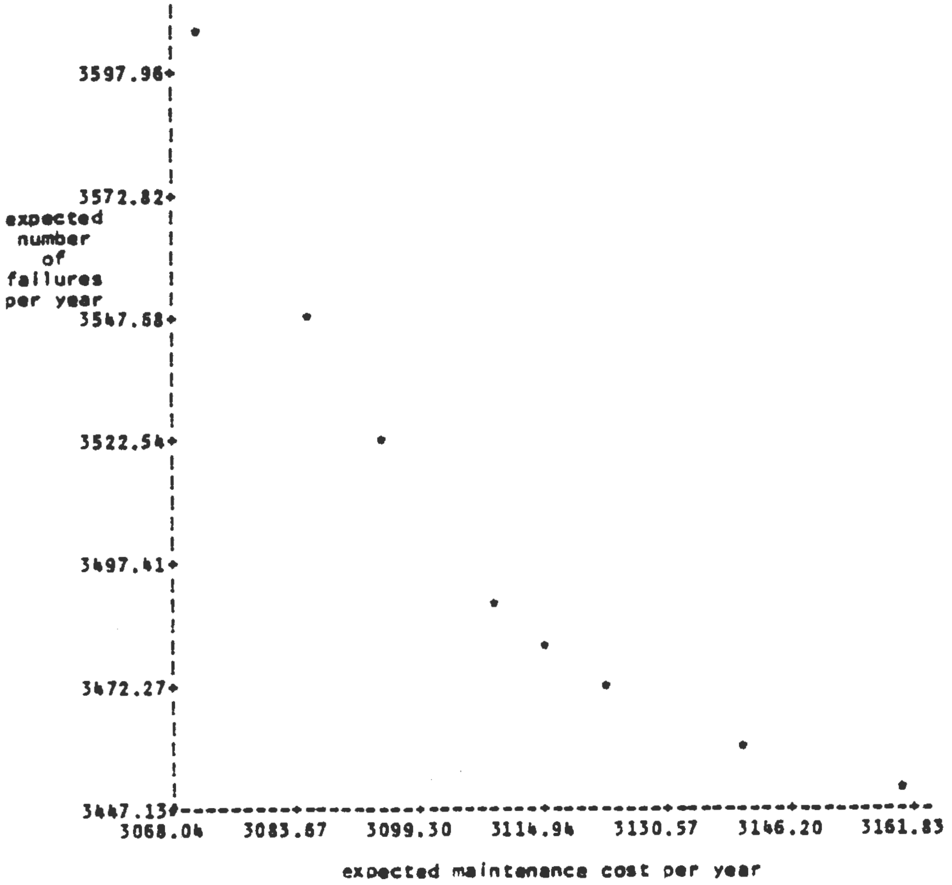
EXHIBIT IV.15

MASSTRAM MAINTENANCE SCHEDULE AND TRADEOFF OUTPUT

```
                                        *********************
                                        SUBSYSTEM EVALUATION
                                        *********************


                                           EXPECTED MAN-HOURS      VEH. HRS.        NO. OF
                                MAINT.        REQUIRED FOR          OUT OF         VEHICLE
SYSTEM DESCRIPTION             INTERVAL        MAINTENANCE          SERVICE        FAILURES
                               (MILES)    REG  EMERG.    TOTAL      PER YEAR       PER YEAR
********************           *******   *********************     ********       ********
  ENGINE BLOWER                 150000    934    224      1159        1837            41
  ENGINE INJECTORS               53000   3247    511      3758        6120           111
  ENGINE STARTER                158999    882    892      1774        3636           265
  FLUID FAN DRIVE               158999   2351    260      2611        4325            36
  TRANSMISSION                  158999   2351   3097      5447       22083           341
```

plot of expected number of failures per year
as a function of
expected maintenance cost per year



x scale: 100.00 y scale: 1.00

V. SUMMARY AND CONCLUSIONS

Vehicle maintenance is an extemely important and complex aspect of transit management. The efficiency and effectiveness of maintenance are influenced by a number of decisions about how to plan individual jobs, how to record daily activities, and how to allocate resources over both short and long term planning periods. Techniques for improving maintenance performance can be categorized according to their relevance to these concerns:

Technique	Issue Addressed
Job task design Component rebuilding procedures Daily fueling and servicing	Work methods issues
Preventive maintenance Recordkeeping Maintenance scheduling	Daily operating records
Maintenance scheduling Budgeting Vehicle replacement analysis	Strategic planning issues

Current maintenance management tools address routine operating concerns, principally daily servicing, scheduled inspections, and exception reporting. A checklist of these current tools is given in Exhibit V.1.

Opportunities for improving maintenance exist in both the work methods and strategic planning areas. The types of issues which arise in these areas are not immediately reflected in daily performance reports, but they have an important impact on long-term cost and on reliability trends.

Techniques for redesigning work methods which have potential for improving maintenance performance include:

- Standard job performance procedures
- Standard job time estimation
- Job performance bulletin
- Fault mode analysis

Strategic planning techniques which could improve management effectiveness include:

- Failure Analysis
- Cost and Manpower Forecasting Methods
- Maintenance Policy Testing Methods
- Maintenance Scheduling Tools
- Vehicle Replacement Analysis

Implementation of these new methods will require a commitment by management to long-term planning and organizational development. This commitment must be translated into improved maintenance recordkeeping

EXHIBIT V.1
CURRENT MAINTENANCE MANAGEMENT TOOLS

Item	Purpose	Reference	
		Page	Exhibit
Operator defect report	* Monitors vehicle condition * Establishes accountability of driver	14	III.1
Consumables report	* Monitors fuel and oil used * Provides data for cost analysis	55	B.1
Work order system	* Identifies items needing attention * Provides for accountability	56	B.2
Maintenance cost report	* Details and summarizes time and material used	57	B.3
Periodic inspection	* Monitors vehicle condition * Allows for routine adjustment	58-59	B.4
Vehicle history record	* Tracks mileage between repair * Documents periodic inspection	16	III.2
Roadcall reporting	* Identifies reliability problems * Insures corrective action	60	B.5
Performance summaries	* Monitors fleet condition and maintenance effectiveness	61	B.6
Vehicle cost summaries	* Tracks average cost levels * Identifies problem vehicles	62	B.7

Note: Exhibits B1-B7 are located in Appendix B.

and more systematic maintenance engineering studies to identify property-specific strategies for improving performance and controlling costs.

Experience in the work methods area has demonstrated that methods analysis and the use of job performance bulletins improve maintenance. The major need in this area is dissemination and transferability testing.

The idea of strategic planning methods is relatively new in transit maintenance but it has been standard practice in maintenance engineering for many years. This report documents a number of procedures for processing component reliability data, analyzing maintenance policies, and generating improved maintenance schedules. These techniques have been found to be practicable. They can be recommended to management as tools for simulating and evaluating the budgetary and staffing impacts of maintenance decisions.

The actual impacts of strategic planning tools currently cannot be quantified because their data requirements are not met by current recordkeeping practices. Adoption of these methods will require development of a data base which has component-level maintenance information including cost of materials and labor, reason for maintenance, and mileage of performance. This type of data is frequently kept in written records but at this time it is not summarized into useable form nor is it retained over the life of the individual vehicles. It is essential that historical component level records of this type be maintained to permit trend analysis and policy testing. It is not sufficient merely to record the mileage at which the last maintenance action was taken, as is now the practice for routine inspection scheduling.

The specific techniques identified in this study, their data requirements, and potential for improving transit maintenance are summarized in Exhibit V.2.

Exhibit V. 2
POTENTIAL APPLICATIONS AND DATA REQUIREMENTS OF NEW TECHNIQUES

Item	Objective	Data	Application
1. Work Methods Analysis	* Identify sources of error and inefficiency	* Special observation	* Reduce error * Produce reference for staff
	* Develop standard job procedures		* Improve performance time
	(reference: Section IV. A)		
2. Standard Job times	* Develop estimate of labor needed (reference: Section IV. A.1)	* Special observation	* Job scheduling * Employee performance monitoring
3. Standard Cost Analysis	* Determine material and labor cost of specific task	* Bill of materials *(1) and (2) above	* Costing job-out decisions
	(reference: Section IV. A.6)		
4. Failure Analysis	* Determine failure characteristics of key components (reference: Section IV.B)	* Component life miles * maintenance history	* Supplier comparison * Trend analysis comparison * Fleet/facility performance analysis * Policy testing and forecasts
5. Fault Mode Analysis	* Diagnose reasons for component failure	* Special engineering studies	* Develop remedial measures
	(reference: Section IV. B.3)		
6. Planned Maintenance Forecasting	* Allocate manpower to meet PM intervals	* Vehicle mileages * PM schedules * Vehicle and Labor availability	* Set PM policies
	(reference: Section IV. C.1)		

7. Non-Scheudlued Maintenance Forecasting	* Project future Failure-Based Maintenance	* Same as (5) above	* Budget forecasting * Inventory and manpower planning
	(reference: Section IV. C.2)		
8. Maintenance Policy Testing	* Predict Failures, Cost of Maintenance	* Same as (5) above * Unit change-out costs * failure-based unit replacement cost	* evaluate impact of PM and planned unit exchange policies on cost, workload
	(reference: Section IV.D)		
9. PM Scheduling	* Develop least cost Maintenance Plan for Entire Bus	* Same as (9) Except for for all systems	* Cost and Failure off analysis
	(reference: Section IV.E)		

REFERENCES

Abkowitz, Mark (1983) "Proceedings of the Transit Reliability Workshop" (Troy NY: Renssalear Polytechnic Institute).

Bakr, M. M. and Kretschmer, S. L., (1974) "Optimal Scheduling of Bus Maintenance." U.S. Department of Transportation, UMTA.

Foerster, James (1982) "Comparative Analysis of A/C Transit Component Life Expectancies," Technical Memo, University of Illinois at Chicago, Urban Transportation Center.

Foerster, J.F., Miller, F.G. and Muthukumaran, N. (1982) "Implementing Cost-Effective Service Interval Planning Methods for Bus Transit Vehicles: A Case Study," Final Report, Urban Mass Transportation Administration, DOT-IL-110028.

Haenisch, George and Miller, Floyd (1976) "Increasing Productivity in Bus Maintenance Functions," Proceedings of the Annual Conference of the American Institute of Industrial Engineers.

Herniter, J.D., Rosenthal, S.R., and Wellon, V.P. (1977) "The Development of a Computer System for the Cost-Effective Maintenance of Rail Equipment in Urban Mass Transit Systems," U.S. DOT Report No UMTA-MA-11-0027.

Jacobs, Michael (1982) "National Urban Mass Transportation Statistics: 1981 Section 15 Report" (Cambridge, Mass: Transportation Systems Center).

Kelly, A. and C. Ho (n.d.) "A Maintenance Plan for a Local Passenger Transport Fleet" (University of Manchester, Simon Engineering Laboratories).

Kosinski, Maria, James Foerster, and Floyd Miller (1982) "Development of Transit Bus Component Failure Statistics From Conventional Bus Card Records" Final Report U.S. Department of Transportation DOT-IL-11-0028 (Chicago: University of Illinois at Chicago, Urban Transportation Center)

Meyer, M. and Hemily, P. (1982) "Public Transportation in the 1980's: Responding to Pressures of Fiscal Austerity," (Cambridge, Mass: Massachusetts Institute of Technology, Center for Transportation Studies).

Miller, Floyd and Pat Lane (1982) "A Case History for Increasing Productivity in Transit Bus Maintenance" Maintenance Management International, V3, pp. 89-99.

MITRE (1973) "SIMS Overview," U.S. DOT Report No. UMTA-VA-06-0004-73-5.

Nie, Norman and C. Hull (1981) "SPSS Update 7-9" (New York: McGraw-Hill).

Preston, Charles (1980) "Maintenance Practices and Schedules" (Salt Lake City, Utah: Utah Transit Authority).

Rueda, Amelita (1982) "Comparative Analysis of Techniques for Determining Bus Replacement and Maintenance Intervals," Masters Thesis Dept of Systems Engineering, University of Illinois at Chicago.

Rueda, Amelita and Floyd Miller (1982) "A Comparative Analysis of Techniques for Determining Transit Bus Maintenance Intervals for Components" University of Illinois at Chicago, Department of Systems Engineering.

Transportation Research Board, (1983), "Bus Maintenance Improvement," Special Report 197, (Washington DC: Transportation Research Board).

Vergin, A.C. and Scriabin, M., "Maintenance Scheduling for Multi-Component Equipment," AIIE Transaction, September, 1977.

Wilson-Hill (1980) "Interactive Inspection Scheduling Program Users Guide," (Cambridge, Mass: Transportation Systems Center).

APPENDICES

APPENDIX A: RELATED REPORTS AND PAPERS

Complete versions of the items listed can be obtained from:

Urban Transportation Center
University of Illinois at Chicago
Box 4348
Chicago, Illinois 60680

A. "Implementing Cost-Effective Service Internal Planning Methods for Bus Transit Vehicles: A Case Study", James F. Foerster, Floyd G. Miller and Natarajan Muthukumaran, Final Report, Urban Mass Transportation Administration, Office by Policy Research, Nov. 1980.

B. "Development of Transit Bus Component Failure Statistics from Conventional Bus Card Records", Maria Kosinski, James F. Foerster, and Floyd G. Miller, Final Report, Urban Mass Transportation Administration, Office of Policy Research, Feb. 1982.

C. "A Predictive Method for Monthly Component Failures Using Available Bus Maintenance Data, "Maria Kosinski, Masters Thesis, Department of Systems Engineering, University of Illinois at Chicago, Feb. 1983.

D. "Maintenance Procedures and Standards for CTA Garages and Shops," Floyd G. Miller, Department of Systems Engineering, University of Illinois at Chicago.

E. "A Comparative Analysis of Techniques for Determining Transit Bus Maintenance Intervals for Components", Amelita Rueda and Floyd G. Miller, 1983.

F. "Transit Maintenance Research and Practice in the United Kingdom," Floyd G. Miller, 1983.

G. "A Methodology for Cost-Effective Maintenance Scheduling of Transit Buses", Natarajan Muthukumaram, Floyd G. Miller, and James F. Foerster, Terotechnica Vol 2, pp. 289-300, 1981.

Appendix B

EXAMPLES OF SHOP AND GARAGE REPORTS

EXHIBIT B.1

SAMPLE CONSUMABLES REPORT

DATE: ______________________

METER AND DIPSTICK

READINGS

	DIESEL FUEL	TRANS. OIL	MOTOR OIL
END			
START			
TOTAL			

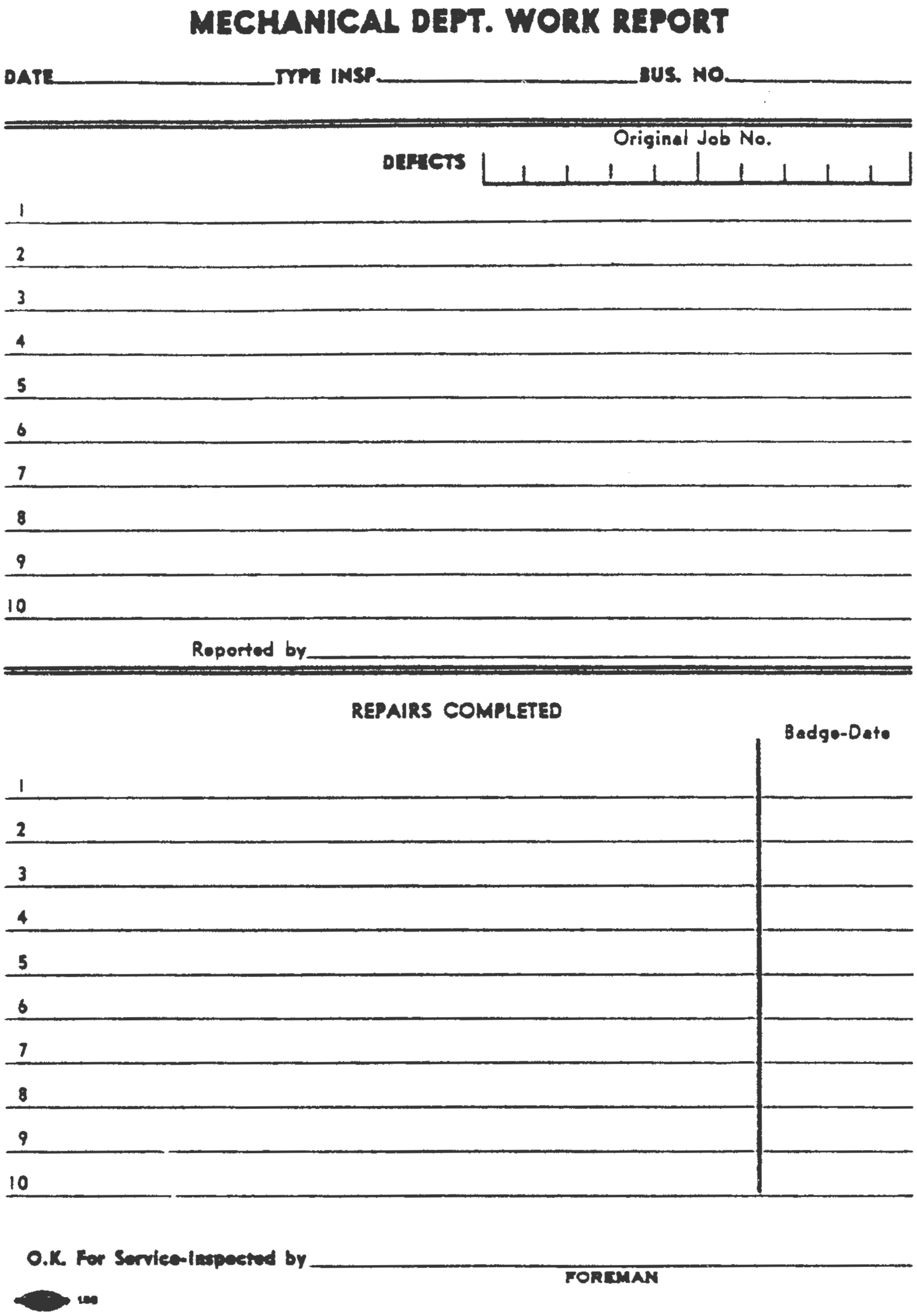
BUS	FUEL	TRANS.	OIL
1101			
1102			
1103			
1104			
1105			
1106			
1107			
1108			
1109			
1110			
1111			
1112			
1113			
1114			
1115			
1116			
1117			
1118			
1119			
1120			
1121			
1122			
1123			
1124			
1125			

BUS	FUEL	TRANS.	OIL
1126			
1127			
1128			
1129			
1130			
1131			
1132			
1133			
1201			
1202			
1203			
1204			
1205			
1206			
1207			
1208			
1209			
1210			
1301			
1302			
1303			
1304			
1401			
1402			
1403			

BUS	FUEL	TRANS.	OIL
1404			
1405			
1406			
1407			
1408			
1409			
1410			

EXHIBIT B.2

SAMPLE WORK ORDER



MECHANICAL DEPT. WORK REPORT

DATE__________ **TYPE INSP.**__________ **BUS. NO.**__________

DEFECTS Original Job No. ☐☐☐☐☐☐☐☐☐☐

1 __________

2 __________

3 __________

4 __________

5 __________

6 __________

7 __________

8 __________

9 __________

10 __________

Reported by __________

REPAIRS COMPLETED

	Badge-Date
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

O.K. For Service-Inspected by __________

FOREMAN

EXHIBIT B.3

MAINTENANCE COST REPORT

Account Distribution ______________________________ Type ______________

Description of Work ____

LABOR					PARTS AND MATERIALS					
Date	Clock No.	Hours	Rate	Amount	Date	Quan.	Part Number	Description	Unit Price	Amount
Total										

Total Parts	
Total Labor	

EXHIBIT B.4

SAMPLE PERIODIC MAINTENANCE SCHEDULE

QUAD-CITIES TRANSIT FACILITY

~~20,000~~ 21,000 MILE SERVICE INSPECTION

All **COACHES** equipped with **DIESEL HYDRAULIC**

Property ______________________________

Coach No. ____________ Inspection Miles ________________ Date ____________________

Symbol Definition:
☐ O.K.
☐ ADJUSTED
☐ REPAIRS NEEDED *

NOTE: REFER TO MANUFACTURER'S MAINTENANCE MANUALS FOR DETAILS OF INSPECTION PROCEDURES

Coach Interior Inspection

MECH NO — SYMBOL — **CHECK The Following:**

___ ☐ FREE PLAY IN STEERING WHEEL
___ ☐ BRAKES, ACCELERATOR-PEDAL OPERATION
___ ☐ HORN FOR SOUND & BUTTON OPERATION
___ ☐ AIR, OIL & GENERATOR GAUGES FOR PROPER READING & OPERATION
___ ☐ TEMPERATURE GAUGE OPERATION
___ ☐ SHIFT-TOWER & LEVER OPERATION
___ ☐ HAND BRAKE LEVER OPERATION
___ ☐ WINDSHIELD WIPER, SWITCHES & OPERATION
___ ☐ REAR VIEW MIRRORS
___ ☐ HEAD LIGHTS & DIMMER SWITCHES
___ ☐ DOME, DASH & STEPWELL LIGHTS
___ ☐ TURN SIGNAL OPERATION & LIGHTS
___ ☐ PASSENGER BUZZER FOR SOUND & OPERATION
___ ☐ DESTINATION SIGN FOR OPERATION & LIGHTS
___ ☐ FRONT & REAR DOOR OPERATION
___ ☐ INSTRUMENT PANEL SWITCHES
___ ☐ STOP & START SWITCHES
___ ☐ HEATER & BLOWER OPERATIONS (BLOW OUT CORES)
___ ☐ DRIVER'S SEAT & OPERATION
___ ☐ WINDOWS, LATCHES, OPERATION & GLASS
___ ☐ STANCHION & GRAB RAILS FOR DEFECTS
___ ☐ SEAT FRAMES & COVERING FOR DEFECTS
___ ☐ BUZZER CORD
___ ☐ EMERGENCY DOOR, LEVER & OPERATION
___ ☐ GENERAL INTERIOR CONDITION, PAINT, PANELS, ETC.
___ ☐ DOOR-ENGINES FOR AIR LEAKS, ETC
___ ☐ FIRE EXTINGUISHERS
___ ☐ FLOOR COVERING FOR LOOSENESS & DEFECTS
___ ☐ SAFETY DOOR EDGES, TREADLES, ETC.

Coach Exterior Inspection

___ ☐ MARKER, CLEARANCE, STOP & TAIL LIGHTS
___ ☐ DOOR & FENDER RUBBERS
___ ☐ GENERAL BODY & PAINT CONDITIONS
___ ☐ TIGHTEN WHEEL & AXLE FLANGE NUTS
___ ☐ VISUALLY, TIRES FOR UNEVEN WEAR, CUTS, ETC.
___ ☐ ADJUSTMENT ON WHEEL BEARINGS (RAISED WHEELS)
___ ☐ KING PIN WEAR (RAISED WHEELS)
___ ☐ CHECK AND SET TOE IN
___ ☐ CHECK AND SERVICE BATTERIES

Coach Exterior Inspection - CONTINUED

MECH NO — SYMBOL — **FILL IN The Following:**

VOLTAGE	BATTERY NO.	HYDROMETER
	BATTERY NO.	

CHECK VOLTAGE REGULATOR (IF NECESSARY)

Coach Under Chassis - Pit Inspection

___ ☐ DRAG LINE & TIE ROD FOR WEAR & ADJUSTMENT
___ ☐ PEDAL, SHIFTER, ACCELERATOR & HAND BRAKE RODS FOR WEAR
___ ☐ FRONT SPRINGS FOR BROKEN LEAVES CENTER BOLTS, LOOSE SHACKLES & "U" BOLTS
___ ☐ SHOCK ABSORBERS FOR FLUID & LINKAGE ADJUSTMENT
___ ☐ AIR TANKS, MOUNTING, "DRAIN TANKS"
___ ☐ FUEL TANKS FOR LEAKS, ETC.
___ ☐ REAR SPRINGS FOR BROKEN LEAVES, CENTER BOLTS, LOOSE SHACKLES & "U" BOLTS
___ ☐ HAND BRAKE LINKAGE & ADJUSTMENT OF SHOES
___ ☐ DRIVE SHAFT & "U" JOINTS FOR LOOSENESS, ETC.
___ ☐ DIFFERENTIAL PINION BEARING FOR EXCESSIVE LASH
___ ☐ DIFFERENTIAL-PINION-OIL-SEAL FOR LEAKS
___ ☐ BRAKE DIAPHRAGMS FOR LEAKS (BRAKES APPLIED)
___ ☐ BRAKE-CAM-TRAVEL & POSITION (BRAKES APPLIED)
___ ☐ RELEASE - ACTION & ADJUST BRAKES
___ ☐ BRAKE SHOE SPRING OPERATION
___ ☐ WHEEL SEALS FOR OIL OR GREASE LEAKS
___ ☐ ENTIRE UNDER CHASSIS OF COACH FOR DEFECTS
___ ☐ MUD SPLASH FLAPS
___ ☐ COMPLETE CHASSIS LUBRICATION, as per Mfgr's Spec
___ ☐ DIFFERENTIAL OIL LEVEL

NC An [illegible] cannot be made at the time of the Inspection should be listed under Remarks (On Rev[illegible]) [illegible] to Att'n of Shop Supt or Foremen

continued on next page

EXHIBIT B.4 continued

FLUID LEVELS

OIL: ____________________
TRANS: ____________________
REAR END LUBE: ____________________
COOLANT: ____________________
NALCOOL: ____________________
ALCOHOL: ____________________
W/S SOLVENT: ____________________

TIRE PRESSURES

LEFT FRONT ____________________
RIGHT FRONT ____________________
L. REAR INNER: ____________________
L. REAR OUTER: ____________________
R. REAR INNER: ____________________
R. REAR OUTER: ____________________

Coach Eng. Compartment Insp. (Cont.)

MECH. NO.	SYMBOL	CHECK The Following:
	☐	CHECK STARTER OPERATION, BRUSHES & SPRINGS
	☐	BLOWER BOX DRAINS FOR OBSTRUCTIONS
	☐	ENGINE GOVERNOR LINKAGE, ETC.
	☐	FRONT ENGINE SUPPORT
	☐	FAN AND FAN HUB
	☐	FAN SHROUD FOR LOOSENESS, CRACKS, ETC.
	☐	RADIATOR & SURGE TANKS FOR LEAKS, and
	☐	MOUNTINGS FOR LOOSENESS
	☐	BLOW OUT RADIATOR FINS FROM INNER SIDE
	☐	RADIATOR FILLER CAP AND GASKET
	☐	RADIATOR SHUTTER OPERATION
	☐	TAIL PIPE, MOUNTINGS
	☐	BULKHEAD BELLCRANKS, RODS, & CLEVISES
	☐	AIR COMPRESSOR SUPERCHARGER TUBE
	☐	MUFFLER & EXHAUST PIPE
	☐	WATER MANIFOLD FOR LEAKS
	☐	VALVE LASH - HOT ENGINE
	☐	INJECTORS & INJECTOR FLUID LINES FOR LEAKS
	☐	STALL TEST: TUNE ENGINE, IF NECESSARY
	☐	CHECK & AIR TIRES
	☐	ALL WIRING FOR BROKEN INSULATION, LOOSE TERMINALS, ETC.
	☐	ENGINE COMPARTMENT SWITCHES
	☐	ENGINE STOP, REAR STARTER, ETC.
	☐	ENGINE ALARMSTAT
	☐	ALL OIL, FUEL, AIR & WATER LINES FOR LEAKS & DEFECTS
	☐	ALL WATER HOSE & CLAMPS
	☐	TRANSMISSION OUTPUT BEARING FOR EXCESSIVE LASH
	☐	TRANSMISSION OUTPUT SEAL FOR LEAKAGE
	☐	NEUTRAL STOP ADJUSTMENT AND OPERATION
	☐	CLUTCH ADJUSTMENT
	☐	GENERATOR BRUSHES & SPRINGS (BLOW OUT DUST)
	☐	ENGINE INSULATORS
	☐	AIR COMPRESSOR-UNLOADER-VALVE-LASH
	☐	ASPIRATOR, IF SO EQUIPPED
	☐	FLUID-PUMP, IF SO EQUIPPED

Coach Eng. Compartment Lubrication

MECH. NO.	SYMBOL	CHECK The Following:
	☐	SHUTTER AIR CYLINDER (KYSOR FLUID)
	☐	SHUTTER AIR FILTER (KYSOR FLUID)
	☐	CLUTCH AIR CYLINDER (OIL)
	☐	THROTTLE AIR CYLINDER (OIL)
	☐	OIL - STARTER
	☐	GREASE - GENERATOR
	☐	CHANGE AIR COMPRESSOR OIL (WAGNER COMP.)
	☐	TRANSMISSION-GOVERNOR (OIL, IF NECESSARY)
	☐	CLUTCH RELEASE - BEARINGS (GREASE)
	☐	HYDRAULIC TRANS. BEARING-CAPS (GREASE)
	☐	CLUTCH RELEASE SHAFT - UPPER & LOWER (GREASE)
	☐	SHUTTER-LINKAGE & BLADE-BEARINGS (OIL)
	☐	CLEAN AIR COMPRESSOR AIR CLEANER, if equipped
	☐	CLEAN GENERATOR AIR STRAINERS, if equipped
	☐	CLEAN ENGINE AIR-CLEANERS & CHECK INTAKE SYSTEM
	☐	CLEAN ENGINE OIL STRAINER
	☐	CHANGE ENGINE OIL FILTER ELEMENT
	☐	CHANGE ENGINE LUBE OIL
	☐	CLEAN FUEL OIL STRAINERS
	☐	CHANGE FUEL OIL FILTER ELEMENT
	☐	CHANGE TRANS. FLUID & CLEAN STRAINER
	☐	CHANGE ANGLE-DRIVE OIL

REMARKS: ____________________

____

____

____

____
SIGNATURE OF SUPERINTENDENT OR FOREMAN

EXHIBIT B.5

SAMPLE ROADCALL SUMMARY

Bus Down

Shift ________ Date ________

BUS NO.	PROBLEM WITH BUS	WORK ORDER NO.	ASSIGNED TO	Rd Call	✓	Repeat
			Total			

Remarks:

EXHIBIT B.6

SAMPLE SUMMARY OF DAILY PERFORMANCE

Daily Maintenance Performance Indicators

Week Ending: ①

Indicator	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Target	Actual
Bad Order Buses	②						⑫	⑬
Spare Buses (at peak)	③							
Road Calls	④							
Service Delays	⑤							
Defects Reported by Operators	⑥							
Defects Repaired	⑦							
Interior Washes	⑧							
Engines Cleaned	⑨							
Minor Inspections	⑩							
Major Inspections	⑪							

EXHIBIT B.7

SAMPLE VEHICLE COST SUMMARY

RICMMTD
November - 1981
Page 2

QUAD CITY TRANSIT FACILITY

		CONSUMABLES									MAINTENANCE COST					
Bus#	Total Miles	Fuel	M.P.G.	Oil Qts.	M.P.Qt.	Torque Oil	Anti Freeze	Tire Cost	Total	Repair Hours	Parts Costs	Labor Costs	Direct Charge	Total	TOTAL COSTS	Cost Per Mile
8101	4360	1085	4.0	18(36)	242	4		$118.68	$1298.56	8.25	$ 25.44	$ 80.81	$ 53.04	$ 159.29	$1457.85	$.334
8102	4421	1138	3.9	17	260	2		120.34	1333.28	5.75	4.90	50.33	204.53	259.76	1593.04	.360
8103	4326	1126	3.8	13(36)	333	3		117.76	1337.14	7.25	212.23	66.71		278.94	1616.08	.374
8104	4099	1052	3.9	9(36)	455	3		111.58	1250.57	7.25	42.66	66.11		108.77	1359.34	.332
8105	3580	960	3.7	13	275	4		97.45	1122.10	16.25	799.02	144.57	286.55	1230.14	2352.24	.657
8106	4568	1147	4.0	6(36)	761	1		124.35	1360.03	6.25	25.44	62.59		88.03	1448.06	.317
8107	3810	989	3.9	6(36)	635			103.71	1171.64	22.25	176.36	216.21		392.57	1564.21	.411
8108	4120	1078	3.8	10(34)	412	1		112.15	1276.11	18.50	304.63	176.41		481.04	1757.15	.426
8109	3803	997	3.8	9(36)	423	1		103.52	1182.54	23.75	134.73	230.30		365.03	1547.57	.407
8110	4433	1164	3.8	12(36)	369	2		120.67	1378.64	17.00	35.55	158.04	144.36	337.95	1716.59	.387
8111	928	247	3.8	12	464			25.26	287.16	30.00	119.40	298.26	959.90	1377.56	1664.72	1.794
8112	4206	1100	3.8	8(36)	526	4		114.49	1304.53	24.00	81.08	221.18		302.26	1606.79	.382
8113	3934	989	4.0	7(36)	562	2		107.09	1177.48	18.75	145.87	187.09		332.96	1510.44	.384
8114	3554	930	3.8	9(36)	395	2	15	96.74	1105.98	38.50	204.82	376.20		581.02	1687.00	.475
8115	4242	1057	4.0	14(34)	303	2		115.47	1260.48	17.00	145.36	198.98	195.53	539.87	1800.35	.424
8116	4014	1054	3.8	10(36)	401	2		109.27	1249.99	24.50	220.63	246.09		466.72	1716.71	.428
8117	4592	1171	3.9	11(34)	417	29		125.00	1414.31	24.25	233.32	234.59		467.91	1882.22	.410
8118	4113	1044	3.9	15	274	3	6	111.96	1225.47	7.00	44.58	66.95	292.51	404.04	1629.51	.396
8119	3869	1002	3.9	10(36)	387	2		105.32	1191.14	19.00	152.33	182.89		335.22	1526.36	.395
8120	3990	1048	3.8	15	266	3		108.62	1226.92	26.75	138.80	275.65		414.45	1641.37	.411

RICMMTD ran a total of 97,632 miles, total cost was $47,651.66 which equals an average cost per mile of $.488.

Appendix C
Vehicle Replacement Decision-Making

Six methods for analyzing bus replacement were identified in the course of the maintenance project. These are Fleet Age Profile Analysis, Fleet Acquistion and Retirement Modeling, Maintenance Cost Trend Analysis, Life Cycle Cost Analysis, Average Cost Analysis, and the Annual Maintenance Cost Limit (AMCL) method. They are presented here to complement the main discussion of maintenance decision aids. The intent is to present a comparative analysis of maintenance decision aids for fleet replacement and to inform the transit industry of these various options. The methods are illustrated using actural component failure and estimated cost data. Discussion is organized around each method's objectives, input requirements, output information, and a brief evaluation.

Fleet Age Profile Analysis

The objective of this technique is to describe the effect of vehicle replacement schedules on fleet mix. The input requirements are the fleet age profiles at the start of the planning horizon, the length of the planning horizon and annual retirement and replacement plans. The output is a display of fleet composition on a yearly basis. The Tri-State Regional Planning Commission (1973) used this approach to study bus purchase decisions over a 20 year time frame, accounting to both changes in demand as well as bus fleet age. The fleet age profile is derived at the start of the planning period and the buses are retired annually with the oldest age groups getting higher priority than the more recent purchases.

The approach does not consider acquisition budget constraints and does not account for vehicle characteristics and mileage in the determination of the replacement schedule. Coming up with a stabilized replacement schedule may not be possible at all if many of the buses are "overaged" and the desired bus age is to be arrived at in a relatively short time frame. The method, however, is a quick and easy tool for looking at fleet modernization requirements. It is illustrated in Exhibit C.1.

Strategic Fleet Acquisition and Retirement Model

The objective of this methods is to generate a schedule of bus acquisitions over a five-year strategic planning period by evaluating the trade-off between bus acquisition and maintenance costs. The planning tool was developed by E. Hauer (1975) and was tested using data from the Ottawa Transit Commission, the Ottawa Carlton Regional Transit Commission, and the Guelph Transportation Commission. The input requirements are fleet age profile, annual miles run by buses in each age group, maintenance costs per mile of buses in each age group, required passenger miles per year, annual maintenance budgets, acquisition budget limits per year, and purchase cost of a new bus. The output is a listing of all feasible five year acquisition and retirement strategies with annual maintenance and acquisition costs and average fleet age at the end of five years. Each of these feasible strategies can be evaluated on the basis of acquisition and maintenance costs

Exhibit C.1
SAMPLE FLEET AGE ANALYSIS

Fleet Age Profile
(January, 1982)

Age	Number of Buses	% of Total
21	126	49.2
20	6	2.3
19	0	0.0
18	13	5.1
17	11	4.3
16	2	0.8
15	18	7.0
14	0	0.0
13	11	4.3
12	0	0.0
11	30	11.7
10	0	0.0
9	32	12.5
8	7	2.7

Bus Replacement Schedules

	Schedule 1		Schedule 2	
	Bus Age	Purchases	Bus Age	Purchases
1982	21	126	22	25
1983	20	6	23	25
1984	19	24	24	25
1985	17	20	25	25
1986	16	11	25	26
1987	15	30	22	30
1988	18	32	18	34
1989	8	7	17	34
1990	9	0	9	32

and/or average fleet age. A computer program was developed by Rueda (1982) using the methodology proposed by Hauer. Exhibit C.2 shows the type of output produced. Strategy one provides for the maximum number of acquisitions allowed by the annual budget, yielding an average fleet age of 15.2 years at the end of five years. This is in contrast to low cost strategy three, where no acquisitions are made over the five year time frame, resulting in an older fleet of 18.5 years. Strategy two has a cost saving of $2,709,316 over that of strategy one with an average fleet age of 17 years.

This technique is a good management tool for evaluating fleet performance over a project time horizon. One of its advantages is not considering replacements on an individual basis, so the replacement of an old bus will not assume the role of its predeceesor. The whole fleet performance is affected as new buses are assigned more mileage than the replaced older units. Maintenance cost as related to bus age must be determined, however.

Maintenance Cost Trend Analysis

The objective of this method is to determine the economical replacement age of a bus by analyzing the behavior of its maintenance costs. The data required is the maintenance cost per mile of a bus at various mileages or ages. The output is the replacement age of the bus resulting in lowerst total cost. This quick and easy method was discussed by Brown-West (1981) in his case study of the New York Transit Authority. The procedure is to plot the maintenance costs per mile versus bus age, and determine the equilibrium value by noting significant increases or decreases in maintenance costs. Exhibit C.3 shows a sample plot. It should be noted that significant cost increases occured at years 4, 5, 8, 9, 10, and 11. Cumulative mileage at years 5, 9 and 11 are 200,000, 360,000 and 440,000 miles respectively. At these points major and semi-engine overhauls are assumed to occur. This is supported by an analysis of AC Transit data which indicates a mean interval of 255,000 miles between semi-overhauls and 340,000 miles between major engine overhauls. Records also show that most of the other components were replaced along with these overhauls. One or two decreases in cost follow these overhauls due to increased system reliability until the wear-out effect is evident again. After three such overhauls, costs from year 13 start to fluctuate. Increases in maintenqnce cost are attributed to the rising failure rate. What seem to be cost decreases may be due to the minimal use of older buses because of their high failure potential. The trend analysis indicates an economic replacement age of 13 years.

The major advantage of this method is that it is easy to use. It is based on the retionale that the buses should be replaced when further maintenance becomes uneconomical. It does not consider the trade-off between acquisition and maintenance costs.

Aerage Cost Analysis

The objective here is to determine the most economical replacement age by minimizing average annual costs per mile. The input requirements are maintenance cost per year of operation, fuel costs per year of

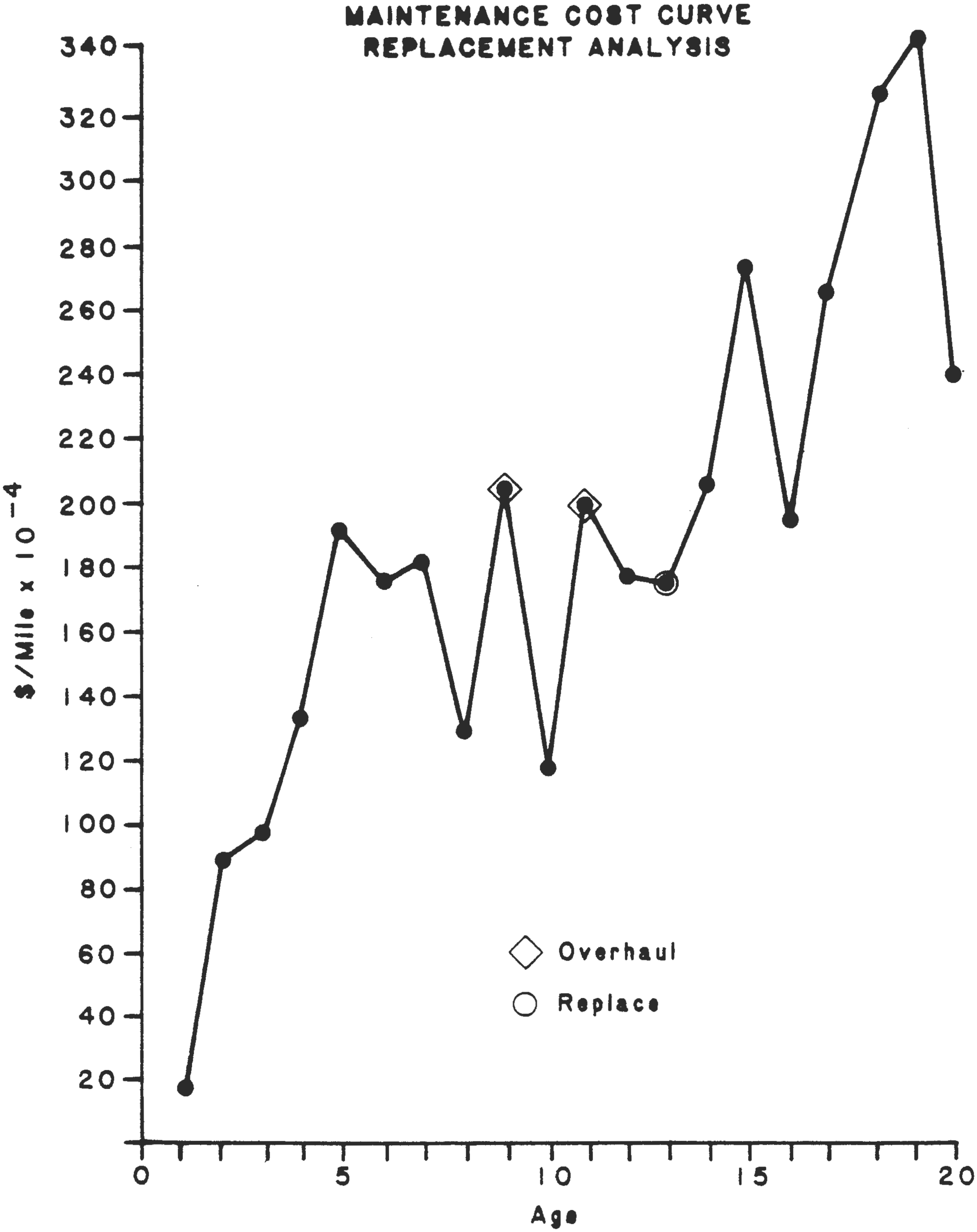
Exhibit C.2
SAMPLE FLEET ACQUISITION/REPLACEMENT OUTPUT

```
Strategy     Year        Acquisitions        Retirements   Totals ($) Cost
1              1              10                  10            1,252,374
               2              10                  10            1,278,230
               3              10                  10            1,272,058
               4              10                  10            1,278,730
               5              10                  10            1,265,330

2              1              10                  10            1,272,374
               2               9                   9            1,169,359
               3               6                   6              837,155
               4               0                   0              192,899
               5               0                   0              185,067

3              1               0                   0              183,655
               2               0                   0              195,351
               3               0                   0              194,699
               4               0                   0              205,451
               5               0                   0              198,351
```

EXHIBIT C.3



MAINTENANCE COST CURVE
REPLACEMENT ANALYSIS

operation, depreciation costs per year of operation, operating reliability costs per year of operation, and expected years of operation. The output is the optimal replacement age. The total annual cost is comprised of maintenance, operation, and depreciation costs. The average annual cost per mile is derived and the optimal replacement strategy is to retire vehicles at the point of the lowest average cost. Data from the LCC analysis (see below) assuming a constant mileage of 40,000 miles per year of operation were used. Exhibit C.4 shows the average cost curve. Minimum average cost per mile occurs at year 13. This is a very simple method and its results are comparable to the more complex LCC analysis when growth in cost and discount effects cancel out or are not considered.

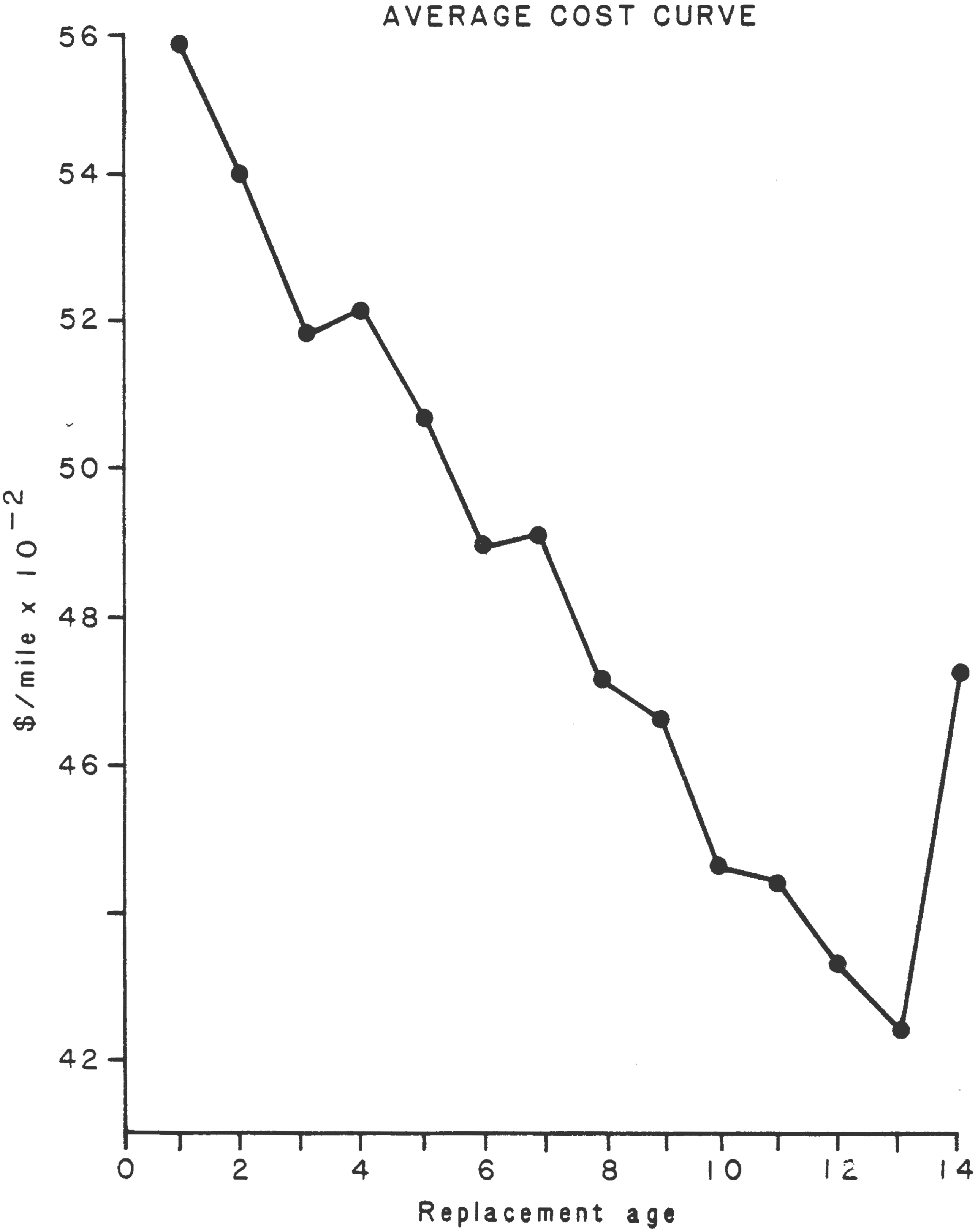
Life Cycle Costs (LCC) Analysis

The objective is to determine the replacement interval that minimizes the discounted value of future acquisition, operation and maintenance costs. A lengthy series of input requirements are required. They are: discount rate, maintenance cost growth rate, fuel cost growth rate, depreciation cost growth rate, operating reliability cost growth rate, miles per year of operation, maintenance costs per year of operation, operating reliability costs per year of operation, and expected years of operation. The output for each potential replacement interval is the replacement miles, the discounted maintenance, fuel, depreciation and operation reliability costs and the life cycle costs per life mile.

The method considers other cost elements in the bus life cycle in addition to maintenance costs. The bus acquisition cost is represented as depreciation costs per year of the bus life cycle. Relevant operational costs are likewise accounted for. Life cycle cost analysis examines the per mile discounted cost of the bus for various assumptions of annual miles, discount rates, and cost growth rates. It basically requires relevant costs to be calculated at current prices, adjusts them by means of cost growth rates, and discounts total costs to the base year.

Jhaveri (1978), however, proposes that instead of just discounting costs over the life cycle, the time horizons to be evaluated must be significantly longer than any of the candidate replacement intervals. This allows for a comparison of different replacement cycles and also evens out annual costs fluctuations that occur in short time horizons. Life cycle replacement analysis is a very useful quantitative tool, especially if the period under evaluation has irregular cost trends and a great deal of economic uncertainty. It accounts for all relevant costs related to vehicle ownership including those that vary as the years go by. LCC evaluates the interaction of effects of replacement decisions on various cost elements incurred throughout the bus life cycle and, aside from replacement analysis, can also evaluate buy/

EXHIBIT C.4


AVERAGE COST CURVE
56
54
52
50
48
46
42
$/mile x 10^-2
0
2
4
6
8
10
12
14
Replacement age

rehabilitate options as well as bus procurement bid selections. Growth and discount rates for all cost categories must be determined, however, and much computational time is involved in deriving the LCC increments. Lifecycle cost analysis is now being used by the National Bus Company which operates over 17,000 buses in the United Kingdom.

Annual Maintenance Cost Limit (AMCL) Method

The objective is to derive annual maintenance cost limits that will indicate if a vehicle of specified age should be replaced or be kept for another year. The input requirements are length of planning horizon, maximum bus age, purchase costs of a new bus, resale value of a bus at specified age at the end of the planning horizon, and the probability distribution of annual maintenance costs of a bus of specified age. This approach has been applied by Jardine (1976) for heavy duty transport vehicles. At the start of the year the expected maintenance cost is estimated. If the estimate exceeds the corresponding AMCL, the bus is replaced. Otherwise it can continue operating for the rest of the year and the evaluation is done new at year's end. The derived average maintenance cost limits should minimize the expected future costs of maintaining and replacing the bus until the planning period ends, when it assumed that the vehicle is sold.

A cost function is determined and is evaluated recursively until the initial year of the planning period is rearched. In this case an evaluation period of ten years was used as the planning horizon. The maximum age limit of a bus was set at 20 years. Buses reaching this age are automatically replaced. The purchase cost of a bus was the 1981 estimate of $109,728. Adopting the double declining depreciation policy, the net book value of the bus at the end of each year of operation was assumed to be its resale value. The procedure for deriving bus maintenance costs was previously discussed. The same method was adopted but the categories are by bus age regardless of annual mileage. A computer program was developed and was used to solve the recursive equation. Exhibit C.5 shows the resulting AMCLs from the application run. Derivation of these AMCLs considers the probability distribution of maintenance costs as the bus ages. An AMCL of $500 means that no more than this value should be allocated to maintenance for a bus of age one. If costs are foreseen to be greater than this at the start of the year, it is worthwhile replacing the vehicle.

The table also shows that a bus with eleven years of operation to data has an AMCL of zero at the end of the planning period. This is so because by then it would reach age 20, the maximim age limit that indicates certain replacement. Likewise, a bus of 12 years or more now has a starting AMCL of zero. This triggers replacement rather than a continued operation for another year. This result is consistent with that obtained from the life cycle cost and the average cost analysis. One of the weaknesses of pure economic life models is that they ignore the situation when a bus requires extensive repair before the end of its economical life. Contrary to the fixed economical life policy arrived at by the average cost or the life cycle cost analysis, this method allows for the evaluation of each bus at the start of the year. Replacement occurs only when it would be uneconomical to maintain the

Exhibit C.5
ANNUAL MAINTENANCE COST LIMITS ($00)

	Years Remaining									
Age Now	10	9	8	7	6	5	4	3	2	1
1	5	12	14	15	22	26	21	26	23	21
2	12	14	15	22	26	21	26	23	21	21
3	14	15	22	26	21	26	23	21	21	27
4	15	22	26	21	26	23	21	21	27	30
5	22	26	21	26	23	21	21	27	30	29
6	26	21	26	23	21	21	27	30	29	34
7	21	26	23	21	21	27	30	29	34	53
8	26	23	21	21	27	30	29	34	53	39
9	23	21	21	27	30	29	34	53	39	39
10	21	21	27	30	29	34	53	39	39	39
11	21	27	30	29	34	53	39	39	39	0
12	0	0	0	0	0	0	0	0	0	5
13	0	0	0	0	0	0	0	0	5	12
14	0	0	0	0	0	0	0	5	12	14
15	0	0	0	0	0	0	5	12	14	15

bus a year further. This approach allows the bus to be utilized for all its worth. Premature or very late replacements can be avoided. One of its disadvantages would be the significant man hours involved in evaluating buses on an individual basis. The model's data requirements might need more recordkeeping and analysis. Probability distributions of maintenanance cost by bus age need to be derived. Although no discount and inflation factors have been considered, the recursive equation can be modified accordingly.

References for Appendix C

Brown-West, O. G., (1981) "The Life Cycle Cost of a Bus - A New York City Case Study," Transit Journal, Winter.

Hauer, E. (1975) "Bus Maintenance and Retirement Decisions," Ph.D. Thesis, University of Toronto, April.

Jardine, A.K. S., (1976) "The Use of Annual Maintenqnce Cost Limits For Vehicle Fleet Replacements," Institution of Mechanical Engineers, Proceedings, Volume 190, No. 13.

Jhaveri, D. R. (1978) "When Shoule Rolling Stock be Replaced?" Transit Journal, Fall.

Rueda, Amelita (1982) "Comparative Analysis of Techniques for Determining Bus Replacement and Maintenance Intervals," Masters Thesis, Department of Systems Engineering, University of Illinois, Chicago.

Tri State Regional Planning Commission, (1973) "Interim Technical Report: Equipment Replacement Schedules for the Tri State Region's Bus Transit Fleet," September.