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Transit Bus Maintenance Management

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Summary: Research Needs in Transit Bus Maintenance

STEPHEN J. ANDRLE

ABSTRACT

Summarized in this Record are eleven areas in which research on transit bus maintenance would be beneficial. These eleven research areas were distilled from the papers and presentations offered at the 65th Annual Meeting of the Transportation Research Board in January 1986.

As a result of presentations made at the 65th Annual Meeting of the Transportation Research Board (TRB) in 1986, the Committee on Transit Bus Maintenance (A3C02) has identified areas in which additional research on bus maintenance would be useful. The Committee has also attempted to define research topics that (a) address the concerns of maintenance managers in the industry, and (b) address topics that are amenable to research by members of the transportation community who actively participate in the TRB. The Committee recognizes that other forums (such as the American Public Transit Association) are better able to address specific, day-to-day problems experienced by transit maintenance managers. The TRB provides a bridge between the transit industry and the academic-government-consultant community. As such, TRB-sponsored research should identify problems that take advantage of the research skills available to it.

Another theme that emerged during the Annual Meeting was the need to introduce to transit maintenance research the skills and methods of disciplines not traditionally associated with the industry. Many research issues revolve around people (e.g., training issues, motivation, quality control, and problem diagnosis). Researchers from fields such as industrial engineering, education, psychology, and management would have much to offer. Similarly, geographers possess skills in measurement of climate and terrain that can help explain the different maintenance requirements of transit properties. Sociologists and psychologists deal with the issues of community, belonging, motivation, and pride-in-performance that are so essential to a productive shop. It is the opinion of the Committee that an infusion of new people from different disciplines is important to the continuing vitality of research in this area.

It is recognized, however, that research conducted by those not in the transit industry must guard against the charge of irrelevance. The Committee has concluded that its proper role in maintenance research is to utilize the time and skills available to its members to identify basic principles, techniques, tools, and procedures that have merit. It is also the responsibility of the Committee to recruit talent from other fields and to clearly demonstrate the relevance of research and to suggest areas for implementation.

In the interest of relevance, the Committee has also concluded that research should avoid "data-hungry" techniques. The detailed empirical data required by some prior research efforts will probably never be available; if they are available, they will always be subject to dispute. If the data are not acceptable to the industry, the research results cannot be acceptable either. Accordingly, as inputs to research models or simulations, the Committee encourages the use of industry measures that exhibit stability over time and between properties. Alternatively, input data should be obtainable by the maintenance managers who are to benefit from the research effort. In the light of this discussion, eleven areas have been identified in which productive research can be conducted by TRB members in the area of transit bus maintenance.

1. DEMONSTRATE THE IMPORTANCE OF MAINTENANCE

Maintenance is not a glamourous topic, yet it accounts for approximately 20 percent of bus operating costs (1) and is responsible for preserving billions of dollars in capital investments. Research synthesis efforts that demonstrate this point are valuable. The primary audience that needs to be exposed to these facts are transit agency boards of directors, city councils, and the public.

2. QUALITY OF CURRENT MAINTENANCE

Some research work done in military maintenance and recent work in transit maintenance indicates that the error rate in repair work is between 30 percent and 50 percent. These figures have been derived from time series analyses of repeat repairs on the same component on the same vehicle. A top research priority should be to find out why this is the case and identify potential corrective actions.

3. INFORMATION SYSTEMS

To address item 2 as well as some items that follow, good data are required. As maintenance information systems come on line in various properties, the following types of reports are needed:

- Time series repair reports by vehicle,
- Total maintenance costs by vehicle,
- Repairs by type across all vehicles in a class, and
- Time to repair by type of repair.

These inputs are vital to both problem identification and problem solution. Developing a model information system at some property and, from it, developing a maintenance data base available to researchers would be a beneficial step. These data may be available already. If so, identifying their loca-

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tion and making the data available would be most beneficial.

4. MEASURES AND STANDARDS

It has been noted by others that the first step in advancing scientific knowledge in any area is the development of a measurement system. The transit maintenance industry has measures available to it, such as

- Miles between road calls (chargeable and non-chargeable),
- Mean time to repair,
- Incidence of repeat repair, and
- Average maintenance cost per vehicle.

Definitional problems plague attempts to use industry-wide data to develop standards of performance, however. Road call definitions vary from property to property; wage rates differ; maintenance policies differ; and the level of maintenance training also varies.

It may be unrealistic to expect the entire industry to adopt the same precise definitions, however, because the use of a term historically develops on a property and has meaning there but not necessarily somewhere else. Similarly, wage rate and maintenance policies will never be the same across the country. A positive advance in labor-related maintenance reporting would be the use of labor hours in place of dollars for cost items. Annual maintenance labor hours per vehicle is a more generic measure than cost per vehicle. Such data can be utilized by any transit property by applying prevailing local wage rates.

This is an area in which researchers with expertise from outside the transit industry can make a real contribution. Climate and terrain are noted by transit operators as reasons for differing maintenance practices. In informal discussions, transportation professionals talk of the "rust belt" and the "sun belt" and understand that maintaining a fleet of buses in these environments requires different procedures. Quantifying these terms in a useful way is not easy, but this problem can be addressed through geographical research. Measurement tools do exist to specify climatic and terrain variables that may, in turn, assist in the development of useful standards.

5. MAINTENANCE CONTRACTING

The development of internal standards of performance is essential if increased use is made of outside maintenance contractors as part of the privatization initiative. Acceptance testing of components rebuilt or repaired by outside contractors is essential. Clear specifications must be included in contracts if acceptable results are to be obtained. Performance standards developed for in-house performance evaluation become a tool for assuring satisfactory performance by contractors. A valuable research contribution can be made by synthesizing detailed standards used by the industry and making them available.

6. INCENTIVES

A critical management problem in maintenance facilities is the provision of personnel incentives. How should work be organized and good performance rewarded? How can pride be instilled for a job well done? How can the fear of failure on the part of junior personnel be overcome? The tools of management science and psychology could well be brought to bear on this issue.

This is an area that traditional transportation research has not covered, yet it is critical to achieving the elusive goal of improved productivity, the measurement of which has been the subject of extensive research and many papers. Productivity measurement does not suggest what to do if a problem is discovered; it simply provides a method of identifying the problem. Motivating the work force through a planned management program is possible and desirable. Research from other fields should be sought in this area.

7. TRAINING

Related to the provision of incentives is training. People like to do what they do well and they take pride in what they do well. Providing the training to enable people to perform well and to advance is an essential part of an incentive program and an essential part of addressing the problem of repair errors. Information is needed on effective training and incentive programs.

Training is the province of education, and there are some real educational research issues here. How can complex manual skills be effectively taught? Are manuals plus on-the-job training more effective than classroom work? What is the most effective mix of classroom and on-the-job training? The field of maintenance research would benefit from participation by professional educators.

State departments of transportation are beginning to play a role in maintenance training in some states in order to protect their financial investment in rolling stock (according to a statewide transit maintenance training plan being prepared by the Virginia Department of Highways and Transportation's Rail and Public Transportation Division). This is a new area that would benefit from information dissemination on model programs. The issues here involve the organization of maintenance training at the state level.

8. PROGRAMMED COMPONENT REPLACEMENT VERSUS FIX-ON-FAILURE

Programmed component replacement based on vehicle miles or hours of service is not a commonly used maintenance system in the transit industry because the fix-on-failure system is perceived as cheaper. Programmed replacement requires a comprehensive maintenance data system to identify the optimum replacement intervals. Even if such data were available, it is not clear if the programmed replacement system would be more economical than the fix-on-failure system. The failure rate of individual components can vary over such a wide range of service hours that a programmed replacement program runs the risk of increasing cost by replacing components that have considerable service life remaining. Definitive research on this topic would be welcome.

9. COMPUTERIZED SMART SYSTEMS

Correct problem diagnosis requires skilled personnel; personnel that are not always available. "Smart" systems aid mechanics in diagnosis by incorporating the knowledge of senior mechanics in computerized diagnostic routines. This makes maintenance shop performance less dependent on the skills of particular individuals. Retirement or job changes by senior personnel would have less of an impact on shop performance. An extension is electronic monitoring of vehicles coupled with problem diagnosis assisted by smart systems. Demonstrations have been conducted in this area with mixed success (2,3). Further development work is needed.

10. APPROPRIATE SCALE OF MAINTENANCE MANAGEMENT SYSTEMS

It is easy to conclude from this discussion that every maintenance shop should invest in the most advanced management systems. This is not the case, however. In small shops, mechanics know the idiosyncrasies of individual vehicles and mechanics often perform a wider variety of tasks. Very specialized tasks are often contracted to outside vendors. As maintenance shop size increases, so does specialization because (a) mechanics are less able to know vehicle idiosyncrasies and (b) the need for analytical management techniques increases. Research on what degree of maintenance management is appropriate for properties of various sizes would be beneficial.

11. INFORMATION SHARING

Finally, information sharing is important. Personal contact among managers cannot be replaced as a means of communication, but it can be enhanced by microcomputer information networks and by making data available to researchers. Any work that facilitates information sharing is useful.

These research topics emerged as priority items during the course of the 1986 TRB Annual Meeting. Individuals interested in conducting research in the area of transit bus maintenance should review the literature to see what has been done to date on these topics and then focus their efforts on developing tools, procedures, or guidelines that would be useful to maintenance managers.

ACKNOWLEDGMENTS

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Transit Bus Maintenance in New York State: Issues and Analysis

JOSEPH F. ZIMMERMAN

ABSTRACT

Under provisions of a cooperative agreement with the Urban Mass Transportation Administration (UMTA), the New York State Legislative Commission on Critical Transportation Choices conducted a study of transit bus maintenance in the state. Twenty site visits were made and questionnaires were completed and returned by 57 percent of the bus operators. Findings were made relative to spare ratios, mixed fleets, negotiated bidding, maintenance facilities, outdoor storage of vehicles, new mechanic and continuous mechanic training programs, performance measures, management, job aids, driver involvement in maintenance programs, preventive maintenance, record keeping, computer usage, diagnostic techniques, contract management, and parts procurement and inventories. Commission staff developed a series of 27 specific recommendations to (a) improve the effectiveness of bus maintenance practices and (b) preserve the large investment of funds by federal, state, and local governments in buses and bus maintenance facilities. These recommendations are currently under review by UMTA and the final report should be available in published form in the near future.

Inadequate maintenance of transit buses is a matter of grave concern for the federal and state governments because it is these governmental units that contributed a majority of the funding for the purchase of these vehicles. Concern about the adequacy of current bus maintenance programs prompted the Urban Mass Transportation Administration (UMTA) and the New York State Legislative Commission on Critical Transportation Choices to conduct a cooperative study in the state with the largest total number of buses, a significant diversity in types of systems, and the single largest bus system in the country--the New York City Transit Authority (the Authority).

METHODOLOGY

The study's methodology had three major components: a literature search and review, site visits to selected transit systems, and a questionnaire mailed to New York State's transit operators.

Twenty site visits were conducted to view maintenance facilities and to hold in-depth discussions with transit managers and maintenance personnel. Public, private, and "hybrid" (public-private elements) systems of varying sizes were visited. In selecting operators to be visited, a decision was made to include properties in most geographical areas of the state because conditions and problems vary significantly from area to area.

Fifty-four of the 95 (57 percent) bus organizations returned completed questionnaires containing information on

- The fleet,
- Facility age and condition,
- Work force,
- Work shifts,
- Maintenance program,
- Bus replacement,
- Level of computerization,
- Parts procurement policy,
- Maintenance performance measures utilized, and
- Percentage of operating costs devoted to maintenance.

FACTORS AFFECTING BUS MAINTENANCE

The key factors affecting the quality of a transit bus maintenance program are the fleet, maintenance facility, work force, and maintenance practices.

The Fleet

The characteristics of a transit system's fleet have an effect on the ability of the organization to carry out an effective maintenance program. A basic consideration is the number of buses an operator has over and above the number needed to meet peak service needs (commonly referred to as the spare ratio). The age of the fleet also affects maintenance needs with older fleets generally requiring more maintenance. Fleet mix (the number of types and manufacturers of buses that a system has), the quality of the equipment, and the degree to which an operator files manufacturer warranty claims on defective equipment and parts also have an impact on the maintenance costs of the fleet.

Spare Ratio

Spare ratios reported by survey respondents ranged from 0 percent to 60 percent. The larger operators had more consistent spare ratios than the smaller operators. The mean spare ratio for respondent operators with more than 100 buses ranged from 0.0 percent to 26.0 percent, with an average ratio of 13.4 percent.

An adequate spare ratio is essential for the es-

New York State Legislative Commission on Critical Transportation Choices, Legislative Office Building, Suite 811, Albany, N.Y. 12247.

tablishment of a sound preventive maintenance program (PM). Buses must be available to be worked on when mechanics are available. Although some preventive maintenance can be completed during off-peak hours, more time is required for maintenance work than is available between morning and evening peak service demands.

Another option, performing PMs at night, was investigated during site visits. Operators lacking a night shift indicated that considerable expense would be involved in starting one. A night shift would require management to schedule additional supervisory personnel to have a supervisor on duty at all times. Additional overhead would also be required to run the garage during night hours. Finally, a large number of buses stored inside would have to be shifted around to position them for maintenance work--creating a need for additional personnel to be on duty.

Analysis of survey data did not reveal that reported spare ratios were affected by differences in management structure, average annual snowfall, population density, or size of fleet. Because on-site interviewees suggested that some smaller operators tended to have difficulties meeting their scheduled service as a result of an apparent inadequate spare ratio, the survey responses were closely examined in relation to spare ratios.

Twenty-three out of the 27 small operators reported a spare-ratio figure ranging from 0 percent to 60 percent, with 11 operators indicating a figure of 15 percent or lower. A low spare ratio requirement applied to operators with fleets of all sizes would make it impossible for certain operators to adhere to a routine PM schedule, ultimately resulting in a shortened vehicle life.

Age of Fleet

Questionnaire results indicated that a correlation may exist between the spare bus ratio and two other variables--the age of the last bus replaced and the average fleet age. Operators with smaller fleets (25 buses or fewer) tended to replace buses more often than did their larger counterparts (fleet sizes of 101 to 200 and over 200), which had a mean last-replaced-bus age of 18 years. In comparison, the mean age of the last bus replaced for medium-sized operators (25 to 100 vehicles) was 15 years, and for small operators (25 buses or fewer), the mean age was 10 years. Furthermore, the larger operators had a higher mean fleet age than did medium- or small-sized operators. The mean fleet ages by size are as follows: over 200 buses, 9.0 years old; 101 to 200 buses, 10.3 years old; 26 to 100 buses, 7.2 years old; and 0 to 25 buses, 5.0 years old.

Private operators responding to the survey had a higher mean age for their bus fleet than public or "hybrid" operators. The mean fleet age for private companies was 8.1 years; for public operators, 6.2 years; and for hybrid operators, 5.0 years. The variance in average fleet age based on company ownership and management may be accounted for by the fact that, in many cases, privately owned and operated companies have not received federal or state funds for bus replacement, and, consequently, have elected to run their buses longer as a capital cost-saving measure.

Fleet Mix

A considerable body of literature on transit bus maintenance and many maintenance personnel who were visited agree that a mixed fleet hinders effective maintenance by placing added pressure on labor, inventory, inspection schedules, and record keeping. For each additional bus model, mechanics must be given specialized training, new parts ordered and stocked, operating schedules disrupted for different mileage inspection intervals, and separate books kept to monitor performance for each type of bus.

In order to avoid having a mixed fleet, several managers indicated that they would prefer to purchase buses from one manufacturer on a continuing basis when they had found a bus model meeting their needs. A fleet comprised of vehicles purchased from one manufacturer would reduce inventory needs, facilitate parts procurement, lessen the amount of mechanic training required, standardize inspection intervals, and enable the transit operator to establish an ongoing relationship with the manufacturer.

It was indicated during site visits that a deterrent to the continuing purchase of buses from one specified company has been the low bid requirement for capital purchases financed in part with federal funds. Implementation of negotiated bidding by UMTA was hailed as a positive step by transit managers participating in the study.

Quality Assurance

A factor contributing to the type and degree of complexity of the maintenance program is the original quality of the equipment. The Capital District Transportation Authority (CDTA), based in Albany, New York, has been cited by UMTA for a quality assurance program the authority implemented in connection with its recent purchase of 115 buses from Bus Industries of America (Orion), and which contains the following elements:

- On-site quality assurance reviews of welding equipment and processes,
- Stress testing of prototype equipment under actual field conditions to identify stress concentration points and to check design assumptions, and
- Destructive test analysis of main suspension assembly.

The buses subject to this quality assurance process have been in service for many months and show no evidence of structural damage; the CDTA is pleased with the program and plans to continue it when bus purchases are made in the future.

MAINTENANCE FACILITY

The adequacy of the maintenance facility is a primary factor determining whether the property will have the ability to carry out an effective preventive maintenance program. A poor facility can result in a greater number of bus breakdowns and concomitant safety problems for transit riders, lowered employee morale leading to a poorer work product, and ultimately, a shorter lifespan for the vehicles housed and serviced there. A properly designed facility does not ensure that the maintenance program will be an excellent one, but an inadequate facility makes the achievement of an effective PM program more costly and difficult. The most common problems with facilities visited by the project team were buildings not originally constructed for bus maintenance, deficiencies in garage design, and a facility too small to accommodate the increase in the number of buses in recent years.

A salient example of a garage designed for another purpose is that of the New York City Transit Authority's 132nd Street garage in Manhattan. The threestory building was erected in 1918 for double-decker buses that were shorter and narrower than current buses, thereby resulting in inadequate space for maneuvering and servicing modern transit vehicles. The problems of the facility are compounded by thick columns, located throughout the facility to support the upper stories, which cause difficulties in maneuvering buses through the garage and make it necessary to back up buses to service or park them. This problem is costly because extra personnel and time are required and a safety hazard caused by excessive backing up of the buses is created. In addition, the building lacks adequate drainage; bus maintainers and mechanics have difficult working conditions because they have to stand in water, oil, and grease to do their work, a situation that is causing safety problems.

Vehicle maintenance facilities initially constructed for other purposes exist throughout New York State. One upstate operator overhauls engines in a converted trolley barn, several garages are former factories, and one large operator is currently housed in a former United States Post Office building. Each of these facilities creates unique problems for the operators involved.

Many examples of inadequate garage design were discovered in the course of the study. Common problems were an insufficient number of service lanes and inadequate storage space for buses or parts. In addition, many older facilities were not designed for straight drive-through or for a minimum of right turns. A design allowing buses to be driven straight through the maintenance facility, with a minimum of backing up and right turns (which create a blind spot for the driver), is recognized as an efficient design and is incorporated into new facilities.

Bus Storage

Twenty surveyed bus operators reported that none of their buses is stored indoors. Outdoor bus storage in cold weather contributes to difficulty in starting buses and freezing of bus subsystems. Relative to the first problem, engines of buses stored outdoors during cold weather are difficult to start in the morning unless the engines are run all night, started every 2 or 3 hr, or attached to heater units. Outdoor storage in cold weather may also result in the freezing up of buses' air suspension system and brakes, thereby increasing maintenance needs and creating potential safety hazards for passengers.

The severity of the outdoor parking problem is illustrated by the Metropolitan Suburban Bus Authority, which stores its entire fleet outside on an unpaved lot. The tires of the buses become frozen into ice and slush during winter storms. Buses that are washed and stored outdoors in freezing temperatures, at this property and at others around the state, create a different type of undesirable situation: the water dripping off the buses freezes into ice puddles. Maneuvering buses on ice increases the potential for accidents.

Vandalism, in the form of physical damage to the bus or the writing of graffiti on the bus, is exacerbated by outdoor storage. Although few operators in the state have to contend with this problem, those who do have to contend with it find that vandalism is difficult to prevent.

Facility Sharing

Eleven transit systems in New York State, ranging in fleet size from 1 to 26 vehicles, share municipal garage facilities with a municipality. Provided adequate equipment and space for transit bus maintenance are available, this arrangement can have positive value.

THE WORK FORCE

The effectiveness of employees involved with the maintenance program--mechanics, bus cleaners, and shifters--is a major factor determining the ability of the transit system to adequately maintain its vehicles. Many variables influence the ability of these individuals to do their jobs, including the availability of training programs, attitude of management toward the maintenance function, adequate job descriptions, availability of job aids (including maintenance manuals), design of the workplace, and the driver's role in the maintenance program.

Training

Analysis of survey results revealed a significant difference in the mean percentage of operating costs devoted to maintenance for operators with a new mechanic training program and those operators without a training program. The mean percentage of operating costs devoted to maintenance for the former operators was 17 percent compared to 22 percent for the other operators. Furthermore, the mean percentage of operating costs devoted to maintenance was 18 percent for operators with a continuous training program and 25 percent for operators lacking such programs. Larger operators (101+) in New York are more apt to have training programs than are smaller systems (1 to 100). This greater commitment to mechanic training may be one reason that larger operators were found to operate an older fleet and to replace their last bus at an older age in comparison with smaller systems (1 to 100).

Despite the consensus within the industry on the positive effect that mechanic training has on maintenance programs, a large number of bus operators in New York lack training programs. Only 31 percent of the questionnaire respondents reported having a training program for new maintenance employees. Continuous training must be provided to upgrade maintenance skills and to orient mechanics to new equipment and state-of-the-art procedures. Although 61 percent of the responding operators had a continuous training program for experienced mechanics, 20 respondents did not.

Larger transit operators are better able to take advantage of training classes offered by bus and component manufacturers, in part because manufacturers may be unable to provide these sessions for systems with a small number of mechanics. Furthermore, smaller operators are not apt to have the time and extra personnel available to attend manufacturer-offered training sessions without shortchanging current maintenance operations. One solution to this problem may be the coordination of training programs on a regional basis.

Management

The success of the maintenance program depends in large measure on the support of top management in terms of setting clear and concise objectives for the maintenance department. Many suggestions have been advanced to improve the effectiveness of the work force. By assessing the exact nature of task requirements--such as cleaning and servicing, inspection schedules, and major repairs--maintenance managers can determine with precision the number and types of needed maintenance personnel.

Job Aids

Maintenance literature emphasizes the need for written job descriptions to enhance work expectations and employee accountability by helping employees to better understand their responsibilities and management to have more control over the maintenance process. Task descriptions and time standards are other methods used by management to increase human resource productivity. Several transit managers who were visited claimed that strictly applied time standards are detrimental to effective maintenance because mechanics concerned about completing a job in a specified amount of time may be less thorough, or may not be able to take the time to make other adjustments or repairs found to be necessary.

Properly designed manufacturer's maintenance manuals can enhance the efficiency and effectiveness ot bus repair. One transit manager reported that she would like to see "better, more graphic repair manuals provided by the manufacturer for quick reference for troubleshooting." London Regional Transport, for example, has translated manufacturers' manuals into easy-to-read English to help mechanics understand manufacturers' maintenance recommendations.

Another factor often overlooked when evaluating the ability of maintenance personnel to do an effective job is the work environment. Several interviewed transit managers mentioned that minor modifications in building design, such as providing adequate work space and an employee lounge, can create a more positive work environment and, as a result, a better work product. One recommendation on facility design made by transit managers to improve maintenance effectiveness is to have common lounge facilities for drivers and mechanics. A shared lounge would facilitate informal exchange between drivers and mechanics on general and specific bus problems and could help employees to perform their jobs more effectively and efficiently.

Driver Involvement in Maintenance Programs

Managers of transit systems interviewed indicated that driver involvement was a key element in the diagnosis of bus problems and, hence, in promoting a successful maintenance program.

A New York State Department of Transportation regulation requires public and private transit operators to direct drivers to turn in a bus defect card at the end of the work shift. These cards include spaces to indicate any bus malfunctions, and sometimes include a space to report bus body damage. Detailed and accurate card reports assist mechanics in determining the repair needs of a particular vehicle.

The Central New York Region Transportation Authority (CENTRO), located in Syracuse, has implemented an innovative program to register driver's post-trip reports. Because CENTRO's management believed that written drivers' reports often did not contain adequate information for mechanics to do the required repairs on the vehicles, a bus reporting booth was constructed as the initial stop of the bus servicing lane at CENTRO's new Syracuse facility. An individual trained to trouble-shoot bus problems is assigned to sit in this booth and to question drivers verbally as they return with the buses to obtain specific and detailed information on any problem(s) the driver had with the bus. This procedure provides more accurate reports and facilitates a more efficient work-flow pattern because it allows each bus to go immediately to the proper area of the garage for servicing. CENTRO is convinced that this system is superior to the card-reporting system utilized by all other operators in the state.

Training drivers in proper bus operation was mentioned by many interviewed transit managers as a desirable means for lengthening bus life because the vehicles last longer when drivers treat the buses with more care. One suggestion to increase the care drivers take with the bus is to pair each driver with the same vehicle every day. Thus, in the same way a driver gets to know the family car, the bus driver would become extremely familiar with the bus and could immediately identify potential problems on a day-to-day basis. In theory, the bus would become the driver's and would be apt to be treated with more care. Many operators reported they would prefer to utilize pairing, but do not have the extra parking space needed to allow a driver to have access to the same bus every day.

MAINTENANCE PRACTICES

Many characteristics that are unique to each transit system have an effect on the type of maintenance program implemented. Factors influencing maintenance needs include age of the fleet, type of routes the bus runs (express, local, charter), terrain over which the bus runs, climate, number of hours the bus runs per day, and "load factors" (i.e., the number of passengers the bus carries on each run). Each factor influences the types of needed repairs. For example, older buses typically require correction of corrosion damage or engine overhauls, and buses on routes requiring many stops need additional transmission and brake adjustments and repairs.

Certain types of buses require special treatment in order to ensure that they are well maintained. Many transit system managers operating small-sized vehicles contend that these buses require more complicated maintenance than standard-sized buses because of the chassis and body design of smaller buses. Managers also mentioned frequently that advanced-design buses require additional maintenance. Another special case has been the extra maintenance needs created by wheelchair lifts and kneeling mechanisms: lifts and kneelers tend to freeze in cold weather and become inoperable. If not tested once a day, the equipment may not work when needed. The problems of maintaining lifts and kneelers induced Westchester County to develop a demand-responsive paratransit system as an alternative to utilizing the lifts and kneelers on their fixed-route fleet. The New York City Transit Authority has addressed this problem by requiring mechanics who select the job of maintaining wheelchair lifts to stay with this job for 5 years.

Preventive Maintenance

The preventive maintenance schedules of most questionnaire respondents were based on set mileage intervals. However, several operators utilize schedules based on days (e.g., every other Tuesday, bus 346 is scheduled for a PM). Other properties based PMs on the number of hours a bus was in service. Interestingly, most operators using mileage intervals did not utilize odometers or hubometers as a part of the maintenance program, and relied instead on trip logs to estimate mileage.

The type of preventive maintenance schedule is not as important a factor in PM as is strict adherence to the schedule chosen. If inspections are not performed as scheduled and mileage intervals between inspections exceed the established schedules, the probability increases that buses will malfunction or break down, creating an unsafe situation for passengers and resulting in a shorter vehicle lifespan.

Manufacturer's specifications for inspection intervals should be used as a basis for the formation of the preventive maintenance schedule with adaptations made at each organization to accommodate unique operating conditions and needs. A written maintenance plan (outlining maintenance goals, PM schedules, and repair policy) helps to clearly identify the procedures and expected results and improves the maintenance effort.

Performance Measures

Goals for the maintenance program should be based on criteria that are capable of measuring the system's performance. There is a lack of consensus within the transit industry on the most accurate measures of maintenance performance. The questionnaire did not attempt to define the best measures, but was designed to determine which performance measures are currently used by transit properties in New York. Seventeen operators (31 percent of the sample) reported using no criteria, and thus were unable to measure the effectiveness of their maintenance effort. Twenty-six reporting systems utilized mean distance between failure (MDBF), eight used maintenance cost per service mile, two used cost per hour, one used percentage of scheduled trips completed, and one used miles per gallon of fuel.

The utilization of MDBF as a performance measure was considered to be undesirable by many transit managers who were interviewed. A common criticism of the measure was the inconsistent definition of "road call" from property to property. Several systems defined "road call" as any radio call requesting assistance, including those for broken mirrors and windshield wipers; other operators narrowed the term to any mechanical breakdown and still others reported a road call only when a bus was unable to continue in route service.

Record Keeping

A recurrent situation found during site visits is the need for improvements in record keeping. One measure of the quality of record keeping at a bus system is the ability to determine maintenance cost per bus. A survey question asked if operators compiled records that indicated maintenance costs for each bus. Of 51 respondents, 35 operators reported that they would be able to determine maintenance cost per bus. Nevertheless, site visits revealed records are not always organized in such a manner as to enable the operator to readily determine maintenance cost per vehicle or are not being used efficiently.

Analysis of questionnaire data revealed that there is a correlation between maintenance cost per bus and the percentage of operating cost devoted to maintenance. The mean percentage of operating cost devoted to maintenance was reported to be 18 percent for operators with records kept in such a manner that cost per bus could be determined compared to 26 percent for systems lacking records on cost per bus. Thus, it appears that maintenance efficiency could be enhanced by a record-keeping system capable of reporting maintenance cost for each bus.

Many transit operators have begun to use record-keeping data to strengthen the planning process of their maintenance program. If a system can predict more accurately when a bus component will fail, management may be able to avoid expensive emergency repair by replacing the component before breakdown. As record keeping is expanded to incorporate additional vehicle components, maintenance problems become more predictable and more activities can be added to PM checklists. Replacement of components before failure is not always cost effective. By utilizing vehicle and component records, the operators can compare the cost of the alternative maintenance methods, such as replace-at-failure and replace-before-failure, per component to determine the most efficient method.

Computer Usage

The computer is an essential part of a records management program, yet only 14 of 54 (26 percent) systems in New York have computerized maintenance programs. Six other systems were in the process of implementing a computerized maintenance system, and 16 systems indicated computerization would be desirable. The larger the system, the greater the propensity for the respondent to report that computerization would be a maintenance aid. Seventy percent of the smaller operators did not believe computerization would benefit their operation because their fleets were small enough that their maintenance programs could be managed manually.

The computer system should provide basic information on buses, maintenance work performed, and PM schedules. Before purchasing a computer, management should assess its objectives and search the market for the proper computer software.

Diagnostic Techniques

As an aid to proper planning and increased efficiency of maintenance, many operators in the United States take an oil sample from each bus on a regular basis and analyze the sample. The analysis allows managers to determine the optimal time for oil changes and to identify certain engine problems. Significant benefits include an extension of time between oil change intervals, a lengthening of the life of engine coolants, and enhancement of the ability of maintenance personnel to project the life span of engine components.

Diagnostic testing is another preventive maintenance technique. Computerized test equipment to monitor and diagnose bus component problems can often identify minor mechanical problems before major repairs are required. One system currently used is the Automated Bus Diagnostic System (ABDS), which can be used to perform 69 different tests and is designed to reduce unplanned maintenance and to verify that corrections have been made. Siemens, a West German company, has developed a similar diagnostic system that is capable of performing 120 to 170 tests and reducing the time required for inspections. Most bus operators in the United States do not have sophisticated diagnostic equipment because of its cost and the general belief that the equipment is not yet "perfected."

Contracting Out Maintenance Work

Two surveyed bus organizations contract out all maintenance work and 31 others contract out for some maintenance tasks. The smaller operators were most apt to contract work out because of the lack of facilities or equipment, or both. For example, Upstate Transit in Saratoga Springs, New York, hires a private contractor when major engine work must be done because it would not be cost-effective for an operator with 43 vehicles to have on hand the equipment necessary for this type of repair. Contracting out maintenance work may be a desirable approach to solving certain problems, but may create additional problems if the contractor is incapable of providing adequate service. One small property that was visited originally contracted out all of its maintenance work to a school bus operator, but discontinued this practice because the quality of the work was poor (e.g., brake shoes were put on backwards). Poorly done work can result in service interruptions and safety problems for transit riders.

Contract Management

Several municipalities have decided that the best means of providing transit service is to contract out the entire operation to a private operator. Westchester County contracts out all of its bus service to private operators, with Liberty Lines Transit, Incorporated, servicing the greater part of the county. The general principle behind such an arrangement is that a certain level of service is provided by the carrier for a price agreed to in the contract between the municipality and the operator. For example, the Westchester County agreement with Liberty Lines Transit, Incorporated, requires the company to provide the agreed level of service, regardless of the actual cost to the company with a few minor exceptions, such as an unexpectedly rapid rise in fuel costs.

A private operator entering into this type of arrangement has additional incentive to maintain an effective maintenance program to ensure that the profit margin is not eroded by high maintenance costs.

Parts Procurement and Inventory

Parts availability is important to the planning and efficiency of the maintenance operation. If parts are unavailable, the necessary repair work cannot be completed. A common occurrence during many site visits was that of buses waiting to be repaired because of specific part was not available. This problem occurs for two reasons--the part is too expensive for the property to keep in stock, or planning for inventory levels is inadequate. Relative to the lack of adequate inventory planning, a major problem is insufficient space for inventory, resulting in unorganized parts storage. Several visited operators had to stock parts outside the inventory room in a disorganized pile because of insufficient space, making efficient ordering, receiving, inspecting, locating, and dispensing of parts difficult. A second problem, often related to poor inventory practices, is overstocking of parts resulting from inadequate receiving and inventory control procedures. Valuable inventory space may be lost if parts are ordered without proper monitoring. Many bus systems utilize card systems to keep track of the parts in stock and to determine when to reorder a specific item. Other operators, however, employ computer systems for these purposes. The biggest problem with both methods, revealed by site visits, is the lack of constant updating of information on when parts had been used or reordered, producing incorrect records of inventory levels. It is important that management receive accurate and timely inventory reports to enable realistic projections of parts needs.

Computers are the most desirable method for keeping track of inventory because a large volume of information can be reviewed in a short period of time and part reordering can be facilitated in a timely fashion. Inventory practices also can be influenced by the fleet mix. Having a variety of bus makes and models in the fleet requires the purchase of a greater variety of parts, complicating inventory and its record keeping.

Establishing and following inventory practices proven to be effective is important to ensure that needed parts are available. It was recommended by transit managers and related literature that a locked parts area with access limited to few people be utilized and that a physical inventory of all parts be conducted at least once a year. The best parts procurement systems kept price quotations on file for frequently purchased items obtainable from more than one vendor, thereby allowing the inventory manager to quickly order the needed parts at the lowest price. CENTRO, in Syracuse, has a computer system that prints out price quotations from three vendors when it is necessary to order a specific part.

SUMMARY

This paper has highlighted the findings of a New York bus maintenance study conducted by the New York State Legislative Commission on Critical Transportation Choices under a cooperative agreement with UMTA. Specifically, the findings relative to the fleet, maintenance facilities, work force, and maintenance practices have been reported.

The commission staff developed a series of 27 specific recommendations, relative to the preceding topics, to improve the effectiveness of bus maintenance practices and preserve the large investment of funds of the federal, state, and local governments in buses and bus maintenance facilities. These recommendations are currently under review by UMTA and the final report should be available in published form in the near future.

Management of Transit Bus Prerun Inspections

JOHN DUFFY, JAMES F. FOERSTER, and SANTIAGO PUENTE

ABSTRACT

Described in this paper are the types of bus prerun inspection programs that are used at various transit systems within the United States. The information was obtained through mail-out questionnaires and phone interviews. The results indicate that there is a great deal of variety in how transit properties design and manage their prerun inspection programs. For instance, some agencies have formal procedures that utilize detailed checklists and constant management oversight while other agencies do not have any programs at all. Successful programs have visible support from management: if an agency's management believes in the efficacy of the program, it is much more likely that the inspection program will be undertaken and properly completed. The two greatest problems in utilizing prerun inspections are a lack of funds to pay for additional personnel time (principally supervisory time) and a lack of knowledge about how to operate and enforce inspection programs. The benefits of using prerun inspection programs include improved vehicle reliability, safer vehicles, and improved maintenance efficiency. Transit agencies should develop and use prerun inspection programs to improve vehicle reliability and possibly lower overall maintenance costs. If an agency does develop a program, management must offer visible support for the program; otherwise, inspections are unlikely to be performed properly.

Prerun inspection procedures are often cited as a key element of vehicle reliability programs, yet little has been written on the subject. Presented in this paper are the results of two surveys of transit bus inspection procedures in the United States. The goal is to document current practice and to summarize the characteristics of successful prerun inspection programs.

STUDY PROCEDURES

The study was conducted in two phases involving mail questionnaires and telephone interviews. The agencies consulted were selected to represent medium-sized systems (45 to 1,000 vehicles). Initial contact was made with system managers via letters stating the project's research goals and requesting participation in the project. A short questionnaire, printed on the back of a postcard, was included with each letter. In all, 119 letters and questionnaires were mailed, and 66 (56 percent) responses were received. The information obtained from the mail-out questionnaires was used to determine whether or not an agency had an inspection program. Questions were also asked about how drivers viewed the task and the use of prerun inspection forms.

The second phase of the study involved telephone interviews, which sought more specific information on prerun inspections. During this phase, 57 managers were interviewed by telephone. An open-ended questionnaire was used, and interview questions were tailored to the responses of the mail-out survey. Most interviews lasted between 20 and 35 min. Material used in the performance of prerun inspections, such as checklists, runcards, and company memoranda, were requested during each of the interviews.

OVERVIEW OF CURRENT INSPECTION PROGRAMS

Prerun vehicle inspections of some sort are conducted by most of the systems that responded to the survey. The general reasons for conducting inspections are that they

- Contribute to the safety of operators and passengers,
- Help maintain vehicle performance and reduce road calls,
- Increase efficiency, and
- Document body damage and improve driver accountability.

(In California and New York, prerun inspections are conducted to comply with state legal codes, which require vehicles to be maintained at a specified operating level).

Methods of prerun inspection vary greatly from system to system. Some systems utilize a formal checklist that must be completed and signed by drivers on a daily basis. Others merely provide drivers with verbal instructions during initial training and orientation sessions. Some systems' prerun checklists cover over 25 items, and others focus on only 10 or fewer items. All checklists typically require inspection of brakes, tires, lights, steering, doors, horn, and general vehicle condition. Supervision and disciplinary procedures vary from system to system.

CHARACTERISTICS OF THE SYSTEMS CONTACTED

Table 1 gives the fleet sizes of the systems that were contacted and those that responded. The sizes of the fleets for the systems participating in the

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J.D. Duffy and J.F. Foerster, School of Urban Planning and Policy, University of Illinois, P.O. Box 4348, Chicago, Ill. 60680. S. Puente, College of Business Administration, University of Illinois, Chicago, Ill. 60680.

TABLE 1 Number and Size of Systems Surveyed

System Size (number of vehicles)	Number of Systems Contacted	Number of Systems Responding[a]
<100	56	23
101-150	17	9
151-200	6	5
201-400	22	10
401-600	5	4
>601	5	6
Data not available	8	0
Total	119	57

[a] These systems responded to the postcard questionnaire and took part in the phone interviews.

study ranged from a high of 997 to a low of 47 vehicles. The largest group of responses was received from systems with fleets of fewer than 100 revenue vehicles. Although the data appear to imply that smaller systems were more willing to take part in the study, this is not the case because smaller systems made up a majority of the 119 transit systems originally contacted.

MAIL-OUT QUESTIONNAIRE RESULTS

Responses to the brief mail-out survey are given in Tables 2 through 4. As shown in Table 2, most systems that responded require prerun inspections and others have optional programs. As given in Table 3, however, most managers said that their drivers conduct superficial inspections. Table 4 gives documentation requirements. Twenty-nine of the 57 systems (51 percent) require driver sign-off on checklists or logbooks even if no defects are detected.

TELEPHONE INTERVIEWS

Telephone interviews indicated that some systems have more success with inspection procedures than others and identified several differences in checklist use and management supervision. Table 5 gives a typology of agency programs.

TABLE 2 Type of Prerun Inspection Program

System Size (number of vehicles)	Mandatory	Optional	None	No Answer
<100	18	3	1	1
101-150	8	0	1	0
151-200	4	1	0	0
201-400	9	1	0	0
401-600	3	1	1	0
>601	5	0	0	0
Total	47	6	3	1

TABLE 3 Thoroughness of Driver Prerun Inspections

System Size (number of vehicles)	Thorough	Superficial	None	No Answer
<100	10	11	1[a]	1
101-150	5	3	1	0
151-200	1	3	1	0
201-400	2	8	0	0
401-600	3	0	2	0
>601	1	3	1	0
Total	22	28	6	1

[a] Inspections performed by mechanics.

TABLE 4 Required Documentation for Inspections

System Size (number of vehicles)	Must Always Sign off	Sign-off—Defects Only	No Sign-off Required	No Answer
<100	10	9	3	1
101-150	6	1	2	0
151-200	0	1	4	0
201-400	8	1	1	0
401-600	3	1	1	0
>601	2	2	1	0
Total	29	15	12	1

TABLE 5 Approaches to Prerun Inspection Programs

	Approaches						
Program Description	1	2	3	4	5	6	7
Program in use	Yes	Yes	Yes	Yes	Yes	Yes	No
Performed by	D	D	D	D	D	M	NA
Checklist used	Yes	Yes	Yes	No	No	Y-1 N-2	NA
Degree of supervision	C	O	None	O	None	None	NA
Number of systems	8	11	6	13	14	3	2

Note: NA = not applicable, D = drivers, M = mechanics, C = constant, and O = occasional.

Fifty-five of the systems contacted by telephone reported having mandatory or optional prerun inspection programs in place. Most agencies ask drivers to perform inspections, but only about one-half of the systems issue daily checklists to drivers; checklist use is more common in small systems than in large systems.

During the telephone interviews, managers who use checklists stated that daily prerun inspection forms are desirable because they

- Serve as an inspection enforcement tool;
- Document the operating condition of the vehicles for safety purposes;
- Assist in the identification of damage;
- Contribute to the effectiveness of fleet maintenance;
- Serve as guides for the inspection of key items before pull-out (especially for those systems with different types of buses in their fleets); and
- Alert operators to minor defects detected by previous drivers of the same vehicle.

Other managers gave a variety of reasons for not issuing checklists including

- Lack of knowledge regarding the efficacy of checklists for their operations,
- Low priority for prerun inspections,
- Inclusion of inspection procedures in training and rule books,
- Reliance on disciplinary action,
- Excessive time requirements,
- Inability to process paperwork, and
- Lack of funds for printing checklists.

The most notable result of the telephone interviews is the diversity of the procedures used in administering prerun programs. Table 6 gives these data by showing how checklist and supervision choices have been made in systems of various sizes. It indicates that only 9 of the 57 systems employ constant supervision to ensure that the inspection is performed properly by operators or mechanics.

TABLE 6 Comparison of the Use of Checklists and the Degree of Supervision

System Size (number of vehicles)	Degree of Supervision		
	Constant	Occasional	None
<100			
Checklist	4	5	6
No checklist	0	5	3
101-150			
Checklist	3	1	0
No checklist	0	2	2
151-200			
Checklist	0	1	0
No checklist	0	1	3
201-400			
Checklist	2	1	0
No checklist	0	2	5
401-600			
Checklist	0	1	0
No checklist	0	1	2
>601			
Checklist	0	2	0
No checklist	0	1	2
All systems			
Checklist	9	11	6
No checklist	0	12	17

Forty-six systems reported using a minimal amount of supervision or said that supervision had been eliminated from their programs. Several reasons for low levels of supervision were offered:

- Prerun inspection procedures are not regarded as an important element in the preventive maintenance program;
- Follow-up discipline for superficial performance is sufficient to ensure proper completion;
- Personnel engaged in completing prerun inspections accept the task and there is no need for supervision;
- Limited funds prohibit the use of supervisors;
- New York and California legal codes are a sufficient inducement; and
- State highway patrol crews monitor the inspection.

During the course of the interviews, respondents were asked to classify their inspection programs as either successful or not successful. As given in Table 7, 34 transit agencies stated that they had successful prerun inspection programs. These systems reported the following benefits:

TABLE 7 Success of Inspection Program

System Size (number of vehicles)	Successful	Not Successful
<100	13[a]	11
101-150	5	2
151-200	3	2
201-400	6	4
401-600	2	2
>601	5	0
Total	34	21

[a] Performed by mechanics at three systems.

- Maintenance of a high degree of safety for the operators and passengers;
- Minimization of the number of road calls resulting from minor defects;
- Lessening of damage caused by operating faulty equipment;
- Reductions of equipment failure attributed to operating conditions; and
- Increased accountability for damage.

The remaining 22 systems cited several reasons to explain the low evaluations they gave of their inspection process. These included:

- A general disregard of prerun inspections as a result of customary nonenforcement;
- A low level of awareness of the usefulness of inspection programs;
- Insufficient funds to pay for daily checklists, supervision, and enforcement;
- Lack of knowledge regarding the proper enforcement of an inspection program; and
- Union contract constraints that reduced the degree of contribution the drivers could make to prerun inspections. (The most common restraints are work rules that confine mechanical tasks to mechanics and pull-out time limits.)

GAINING DRIVER COOPERATION

Driver attitudes varied considerably among the systems. Interviews indicated that driver attitudes are related to the importance placed on inspections by management, supervision of inspections, use of daily checklists to document inspections, and use of disciplinary measures to sanction faulty performance. The response of most managers to questions about driver involvement was "if management enforces the program, drivers complete it; and if management does not enforce the program, drivers do not complete it." Unfortunately, many systems do little to actively enforce their prerun inspection program. For example, 14 systems said they do not issue daily checklists and have not developed formal enforcement procedures because management regards prerun inspections as a low priority.

Four systems reported good driver cooperation in the absence of active management enforcement. The reasons for cooperation in the absence of formal programs include

- Use of simple "walk-around" inspection procedures;
- Assignment of drivers to the same buses on a daily basis;
- Driver interest in locating defects before pull-outs to avoid bus changes during runs; and
- Driver interest in not being blamed for damage caused by someone else.

Five of the nine systems that issue daily checklists to their drivers and that employ a constant degree of supervision over the task reported positive driver cooperation but the remaining three agencies did not. Driver cooperation in the five systems was explained as follows:

- Drivers want to operate safe equipment;
- Drivers believe that identifying defects will result in proper maintenance;
- Driver of the Year Award programs are used as an incentive for the operators to diligently perform all duties properly; and
- Management reinforces positive driver attitudes by emphasizing the importance of the task.

The three systems that reported poor driver cooperation said that they had recently adopted strong enforcement measures, now issue daily checklists, and are providing constant supervision to improve driver performance. Eleven systems were found to issue daily checklists to drivers and use occasional spot supervision as an enforcement measure. These systems reported that the majority of their operators accepts the task. Further, the managers of these systems said that the level of performance they have achieved is attributed to the inspection procedure being an established part of driver job requirements.

Some managers maintained that current disciplinary measures are not strong enough to ensure compliance. Six systems reported that although daily checklists are issued to their drivers for prerun inspections, no supervision is provided. The managers of these systems said that their drivers regarded prerun inspections as being useful, but they reported that drivers usually do not perform the inspections. These agencies said that they do not supervise the activity because they do not believe it is worth the effort. Therefore, it is not surprising that the drivers have a good opinion of the procedure but rarely do it; driver attitude and behavior simply reflect those of management.

Fourteen systems said that they do not issue daily checklists, do not use any method of supervision, and leave the inspection solely to the driver. The few agencies in this category that nevertheless mandate prerun inspections rely on strictly enforced disciplinary measures to ensure that the inspection is completed. For example, one system keeps lists of road calls for 30 days to identify the drivers that accumulate the most. Three road calls within 30 days lead to an operator's suspension.

SETTING UP A PRERUN INSPECTION PROGRAM

The development of a prerun inspection program involves

- Union constraints on prerun inspections,
- The personnel classification that will be responsible for the inspections,
- The degree of formality that the inspections will assume,
- The documentation that will be required, and
- The degree of supervision to be used.

As given in Table 5, transit systems have approached their prerun inspection methods in different ways. The four major approaches identified in the survey work were labeled 1, 5, 6, and 7 in Table 5. Approaches 1 and 5 are driver-oriented, and Approach 6 is mechanic-oriented. Approach 7 is the null case.

APPROACH 1: DAILY CHECKLISTS AND CONSTANT SUPERVISION

The eight systems that typify this approach stated that inspections are important components of their overall preventive maintenance program. To ensure driver compliance, the systems issue daily checklists to their operators. In addition, the systems monitor driver performance with constant supervision. Seven of these systems reported that operators making unnecessary road calls resulting from superficial prerun inspections are subject to disciplinary measures. The disciplinary procedure typically consists of a three-step process as follows:

1. An informal memorandum is given to the driver notifying him that his failure to properly inspect his vehicle had resulted in a road call and that this event had been noticed by the agency.
2. A second occurrence results in having the unnecessary road call recorded on the operator's record.
3. For the third occurrence within a year, the driver is suspended for several days.

These systems noted that they rarely suspend a driver for road calls attributed to superficial inspections because drivers seldom make more than 2 unnecessary road calls within a year.

To better illustrate how the Daily Checklist-Constant Supervision approach works, the experience of one system is described next. The agency in question has had a prerun inspection program since it began operation 8 years ago. The stated objectives of the program are to (a) maintain the working conditions of the older buses, which make up a majority of the fleet, (b) comply with state regulations requiring periodic inspections of all buses, and (c) obtain longer service lives from all vehicles. The drivers are issued checklists by dispatchers as they are assigned to their buses. The checklist, which was developed by the manager in conjunction with maintenance personnel, consists of 25 items that the drivers are to inspect. The checklist requires drivers to indicate whether or not each item is in proper working condition. The checklist focuses on mechanical operability, safety, and cleanliness. The completed inspection checklist is turned in to the dispatcher before starting the run. The checklist is kept on file for a period of approximately 90 days to satisfy state requirements. Periodic reviews of the checklist's accuracy and currency are conducted by the state highway patrol. Each driver is allotted 10 min to perform the inspection. (Time and motion studies of the entire inspection procedure have indicated that the actual time needed is approximately 6 min, but the drivers' union would not accept this time frame. Consequently, a 10-min inspection period was agreed on by both management and the union.)

If an item is found to be defective during the inspection, the driver notes it on the checklist and informs the dispatcher of the problem. The dispatcher, in turn, notifies the maintenance shop. At this point, if the defective item can be repaired in time for the scheduled pull-out, a service crew is dispatched to the bus. According to the system's operating policy and union rules, drivers are not allowed to repair any defective items.

The transit manager reported that even during inclement weather, and with the vehicles parked outside, the drivers inspect the vehicles without complaint. Positive driver response was attributed to two factors: (a) the Driver of the Year Award program, which recognizes drivers who perform all duties as diligently and professionally as possible, and (b) the assignment of a supervisor to walk the yard while the inspections are performed.

APPROACH 5: NO CHECKLIST AND NO SUPERVISION

Fourteen systems in the survey reported prerun procedures that did not involve daily checklists or performance supervision. These systems relied on either the drivers' self-interest in performing the task or follow-up discipline. Some of these agencies wanted to change their present policy of low enforcement but stated that insufficient funds prevented them from doing so. They said that if additional funds are allocated, they would be able to pay for the time required for operators to properly perform the inspections, the printing of checklists, and supervisory personnel.

Four systems had simply issued aids to drivers to help them memorize items requiring inspection but others reported that they use special enforcement measures. For instance, 6 of the 14 systems in this category noted that they have disciplinary procedures for unnecessary road calls resulting from superficial prerun inspections or for not informing management of body damage. The actual disciplinary measures are similar to those previously described.

Several variations of enforcement procedures were reported. One agency left supervision enforcement responsibilities to the state patrol because state laws specify that public vehicles must be properly maintained. (Drivers operating unsafe buses risk being ticketed by the state patrol for operating a potentially unsafe vehicle if they do not perform their prerun inspections and are caught with a faulty vehicle.) Another property assigned the maintenance department to perform the inspections because the operators there would not execute their inspections properly without supervision. Last, one system assigned individuals to inspection duty who could not be assigned to their regular duties because of minor injuries. Seven systems of the 14 in this group mentioned contract or union issues associated with operator involvement in minor repairs and the amount of time allocated to inspections.

One system that requires drivers to perform inspections provided further details about how agencies adopting the No Checklist-No Supervision approach operate their prerun inspection program. This system has required drivers to perform the inspections for approximately 20 years. The success of its program was attributed to management's attitude regarding prerun inspections. The system's drivers perform inspections after receiving their daily bus assignments. They are not issued checklists because they are expected to have memorized the items requiring inspection. In addition, there is no supervision of the inspections. Because the inspections are not supervised, drivers who do not perform the inspection can only be disciplined if their bus requires a road call for an item that should have been identified during the prerun inspection. The disciplinary procedure consists of a counseling memorandum for a first occurrence followed by a written reprimand for a second occurrence. Disciplining of drivers does not occur often because of the positive driver attitudes regarding the inspections and because minor defects are automatically charged to the driver.

Drivers at this system are not allowed to fix any defect they find, no matter how trivial it might appear, because of the union contract. If a driver finds a defect, he drives the vehicle to a special site on the property where it is inspected by maintenance personnel. The manager estimated that 3 or 4 out of the property's 200 buses are held for maintenance work each day because of defects or damage identified during the prerun inspections. Not all buses with defects are held out from service; if defects are not safety-related and the bus is needed for peak-hour service, the dispatcher has the authority to place the bus in service as a "tripper."

Drivers are required to note defects or damage that occurs during a run on a special defect card. After the driver ends a run, he completes the defect card and leaves it on the bus. These cards are then checked by service crews who notify the maintenance department of items needing attention. In addition, the information is included in vehicle history files for later use by the maintenance department in tracing chronic defects.

APPROACH 6: INSPECTIONS PERFORMED BY MECHANICS

Three systems among the 57 surveyed had mechanics perform prerun inspections. Each of these systems has different reasons for using mechanics. One manager said that his drivers do not want to perform prerun inspections and that he chose to use mechanics in their place. Another said it is more efficient to have mechanics perform inspection because they are better able to repair defects. The third noted that when drivers are assigned to the same bus on a daily basis, minor defects are not reported because drivers do not want their bus to be sidelined; therefore, mechanics must perform the inspections to ensure that they are properly completed.

All three systems stated that their drivers are informed during the initial training period of the items that the mechanics will check during the prerun inspections. Although the agencies require the mechanics to perform the task, they do allow their drivers the option of performing a second, more casual inspection. Two of the three systems within this group issue daily checklists to the mechanics to document the inspections. The system that does not issue checklists has them available for use but does not require them to be turned in.

The one system that best typifies the mechanic-oriented approach has fewer than 100 revenue vehicles. The system views prerun inspection as an important contribution to the maintenance of the coaches, and the inspections are considered by the manager to be working satisfactorily. The mechanics who perform the prerun inspections are part of the regular maintenance staff. They receive no formal inspection training because the transit agency does not consider this function to be overly complex.

The system's mechanics arrive approximately 1 to 1.5 hr before pull-out time to complete the inspections. To aid them in this task, the mechanics are issued checklists that describe the items to inspect on the different buses within the system's fleet. The inspection procedure requires the inspection of only those items that can be easily checked, such as mirrors, windshield wipers, and horns. The mechanics are allowed 10 min per bus to perform the inspection. If a defect is found, the mechanics decide whether the problem is serious enough to sideline the bus or if it can be corrected in time for scheduled pull-out. There is no supervision of the mechanics when they perform the inspection. On completion of the inspections, the buses are moved to a pull-out area for the drivers. At this time, drivers have the option of performing a second prerun inspection. This option is left entirely up to the drivers although the agency would prefer that they do it.

APPROACH 7: NO PRERUN INSPECTIONS PERFORMED

Prerun inspections were not performed at two of the agencies contacted. The transit managers at these properties were uncertain if such inspections had ever been used.

The manager of one system attributed his current situation to the union contract, which does not allow drivers to perform any task other than driving. The union's view regarding inspections is that it is a task strictly for the maintenance department to perform. However, the agency's mechanics do not perform prerun inspections because of a manpower shortage within the maintenance department. The manager of this system favored the institution of a prerun inspection program because of excessive road calls attributed to minor farebox and door defects. He stated that most of the defects can be identified before the bus leaves the garage. Hence, if the agency had a prerun inspection program, it is believed that maintenance costs would be lowered.

The manager for the other system indicated that the union contract is the principal obstacle to implementing such a program. His system's contract does not stipulate that drivers cannot conduct prerun inspections; however, it specifies that drivers must be allowed 5 min in which to leave their assembly area and receive their bus assignments. Prerun inspections cannot be completed because of the limited amount of time available for the inspection. Shortages of funds to pay the drivers for the additional inspection time were noted, and the agency does not want to renegotiate the contract to include the inspection provisions. As a consequence, the manager believes that the only way a prerun inspection program can be implemented is to prove that it will pay for itself by reducing overall maintenance costs. In place of prerun inspections, the mechanics of this system start the buses before pull-outs and drive them for a short distance. Any obvious problems are recorded by the mechanics. In addition, the drivers are issued defect cards that are used to inform the maintenance department of problems encountered during their runs.

COMPARISON OF INSPECTION PROGRAMS AND SYSTEM PERFORMANCE

Using Section 15 report data, the preceding four approaches (Checklist and Supervision, No Checklist-No Supervision, No Inspections Performed, and Inspections Performed by Mechanics) were compared on two dimensions of system performance. The specific measures used are mechanical failures per revenue mile and the number of mechanic labor hours per revenue mile. The results are given in Table 8. As can be seen, the number of labor hours per revenue mile increases as the inspection process becomes less formal or structured (i.e., agencies having the lowest mechanic labor utilization use checklists and a constant degree of supervision and agencies with the highest labor utilization do not have any inspection programs at all).

TABLE 8 Comparison of Program Type and System Performance

Program Category	Average Mechanical Failures per Thousand Revenue Miles	Average Labor Hours per Thousand Revenue Miles	
Checklist and supervision	0.5360	19.927	(N = 8)
Inspection performed by mechanics	0.5312	23.488	(N = 3)
No checklist or supervision	0.4124	27.854	(N = 14)
No inspection performed	0.9449	35.432	(N = 1)

The second measure chosen for comparison is the number of mechanical failures per revenue mile. Surprisingly, the agencies with the best performance in this area do not use checklists nor do they utilize constant supervision. This may be because of locational characteristics as many of the agencies in the No Checklist-No Supervision group are located in the southern United States. It might also reflect the fact that some systems do not have road call problems and, therefore, see no reason to institute inspections. The other three groups have indicators closer to what one would expect. That is, the No Inspection Performed category had the highest number of failures per revenue mile and the other two categories have lower mechanical failures per revenue mile.

CONCLUSIONS

Most transit managers believe that prerun inspections are useful tools for maintaining vehicle safety and operating efficiency. The benefits of prerun inspections are reduced road calls, more complete vehicle histories, increased driver accountability, and improved communication between drivers and maintenance staffs. Unfortunately, many managers feel that they are not realizing the full benefits of driver inspections. This is due to customary neglect of inspections and a lack of knowledge about implementation and enforcement mechanisms.

Systems that emphasize prerun inspections use several approaches to ensure that the task is performed properly. They encourage daily performance, adopt formal checklists, and discipline drivers for failure to comply with established procedures. Promoting inspections during initial orientation periods and communicating expectations about compliance are important for proper performance of the task. Several systems have successfully formalized their procedures via training, checklist documentation, and supervision. These practices result in improved inspections. Follow-up discipline for faulty inspections, although often not severe, demonstrates to drivers that the inspections are part of regular duty and are considered important by management.

The following guidelines were synthesized from interviews with managers experienced in the establishment of prerun inspection programs. The authors recommend that they be followed by systems interested in improving the effectiveness of their own operation.

1. The importance of prerun checks to the system's overall maintenance program should be made explicit to all personnel involved in prerun inspection programs.
2. Detailed checklists should be used on a daily basis.
3. The items selected for inspection should not overburden the inspection staff. Inspection lists should be limited to those items that are most important to the reliability, efficiency, and safety of the bus fleet.
4. Checklists should be turned in by drivers to aid in enforcement of the inspection procedures.
5. Managers should not allow prerun inspections to be performed in a superficial manner. Management should take an active role in the entire prerun inspection process and provide appropriate supervision.
6. Disciplinary consequences for failing to comply with inspection procedures should be made explicit and applied uniformly.
7. Procedures for reporting problems or defects identified during the inspections should be made known to all transit personnel.
8. Quick follow-up procedures for fixing minor defects found during the inspections should be developed.
9. Incentives for the personnel involved in the inspections should be explored to encourage good performance and to improve the "esprit de corps" within the agency.

Application of a Transit Maintenance Management Evaluation Procedure

BRUCE E. PAKE, MICHAEL J. DEMETSKY, and LESTER A. HOEL

ABSTRACT

The application at the Tidewater Transportation District Commission of a framework for evaluating a transit agency's maintenance program is described. This method views the maintenance department's mission as a set of management activities that are associated with functional tasks that comprise the total bus maintenance process. A structured data collection procedure was developed and used to provide the information necessary to perform the analysis. A step-by-step discussion of each of seven management elements cites the data used for the analysis and interprets measures of the level of activity provided. Utilization of Section 15-type data supplements the management unit evaluations to provide an overall measure of the maintenance operation's effectiveness, particularly in terms of vehicle miles per road call and vehicle maintenance cost per vehicle mile. The study results are presented as a summary matrix that shows general performance patterns. This application provides transit agencies with a guide for using the method. The framework suggests promise for promoting comparability among transit maintenance departments.

A practical method for evaluating a transit agency's maintenance program has been developed (1,2). This approach to transit maintenance management views the maintenance department's mission as a set of management activities that are associated with the functional tasks that comprise the total bus maintenance process as shown in Figure 1. The influence of environmental features and organizational characteristics is represented as "external factors" in Figure 1.

Table 1 gives levels of each activity for increasing levels of sophistication and resource dedication. When a transit agency's maintenance program is evaluated, its performance for each level is assigned a value (A to D) along a spectrum. In general, the basic arrangement of A represents a package appropriate for small transit systems. As an agency moves toward D, its operation becomes elaborate and complicated, as represented by larger properties. The derivation of this framework for evaluating bus transit maintenance operations has been described elsewhere (1,2). The rationale for the set of activities used and the established levels are included in the earlier publications on this method. Described in this paper is an application of maintenance management evaluation techniques in the Tidewater Transportation District Commission (TTDC). This agency was selected because it lies within the size range of a small-to-medium property and because it was willing to cooperate with the study team.

The TTDC is a special administrative arrangement that provides public transportation services for five municipalities (Norfolk, Virginia Beach, Portsmouth, Chesapeake, and Suffolk) in the southeastern corner of Virginia. There are 180 motorbuses in the agency fleet, and the agency has an extraordinary commitment to vanpools and minibuses (another 165 vehicles). The annual cost for the bus operation in FY 1983 was $13,274,422, 19.8 percent of which was dedicated to bus maintenance.

A structured data collection procedure was developed and used to provide the information necessary to perform the analysis (1). The evaluation form was completed through the following three levels of effort:

1. A general analysis of available information;
2. A preliminary visit and discussion with various TTDC officers; and
3. A process of feedback and review during the final stages of a site visit, during which contacts were made with the assistant superintendent of equipment I, the assistant superintendent of equipment (and maintenance training) II, the administrative assistant, an equipment office representative, the purchasing manager, a transportation planner, and a computer operator.

The following discussions address how information is translated into the analysis framework. The evaluation requires establishing values for the elements in a row of Figure 1. This case study is to be considered a starting point for (a) practical application of the method, (b) motivation toward using the framework for peer comparisons (descriptive information), (c) assessing the potential for refining the subjective measurement system into an objective technique, and (d) suggesting further research to relate the rating information to system performance.

DESCRIPTION OF COMMUNITY AND EXTERNAL CONDITIONS

From a review of environmental factors external to the organization, pertinent information can be summarized for the left column of the matrix of Figure 1. The TTDC serves an area characterized by a

- Large community (900,000),
- Moderate population density,
- Moderate-to-light transit reliance,
- Flat terrain,
- Mild-to-warm, variable climate, and
- Moderately priced labor market.

B.E. Pake, City of Tampa, 3208 Fair Oaks Avenue, Tampa, Fla. 33611. M.J. Demetsky and L.A. Hoel, Department of Civil Engineering, University of Virginia, Charlottesville, Va. 22901.

DESCRIPTION (EXTERNAL FACTORS)	WORK ASSIGNMENT	MAINTENANCE SCHEDULING	WORKFORCE DEVELOPMENT	LABOR ALLOCATION	INVENTORY MANAGEMENT	EQUIPMENT MANAGEMENT	INFORMATION SYSTEMS
BASE CASE: Small Community (50,000) Dispersed Community Light Transit Reliance Flat Terrain Warm, Moderate Climate Inexpensive Labor Market New Road Surfaces 15-Bus Fleet 72 Hrs. Revenue Service/wk. Homogeneous Fleet Abundant Capacity in Facility Nonunionized Workforce	A	AorB	AorB	A	A	A	A
Moderately Small Community (120,000) Dense Community Moderate Transit Reliance Flat Terrain Moderate Climate Expensive Labor Market New Road Surfaces 40-Bus Fleet 90 Hrs. Revenue Service/wk. Heterogeneous Fleet Abundant Capacity in Facility Unionized Workforce	B	B	B	BorC	BorC	B	B
Moderately Large Community (500,000) Dense Community Moderate Transit Dependence Flat Terrain Warm, Moderate Climate Expensive Labor Market New Road Surfaces 200-Bus Fleet 105 Hrs. Revenue Service/wk. Heterogeneous Fleet Abundant Capacity Facility Unionized Workforce	C	BorC	C	C	C	C	C
Large Community (1,000,000) Dense Community Moderate Transit Reliance Flat Terrain Warm, Moderate Climate Expensive Labor Market New Road Surfaces 450-Bus Fleet 120 Hrs. Revenue Service/wk. Heterogeneous Fleet Abundant Capacity Facility Unionized Workforce	D	CorD	D	D	D	D	D

FIGURE 1 Composite profiles of maintenance departments.

Of this group, the factors that would most influence maintenance performance are the almost ideal operating conditions of mild weather and flat terrain, and these factors are not significantly mitigated by any adverse conditions in the labor market or by road conditions.

The organization pursues its objectives through a management-by-objectives system that stresses that, at the highest level, the budget deficit should not exceed $1.00 per passenger. The resulting charge to the maintenance department is to support "running equipment as efficiently, economically, and effectively as possible," although the objectives become more specific as they filter down through the organization. Informally, maintenance managers state that "cleanliness and a mechanically stable fleet [not a lot of breakdowns]" are stressed. The bus fleet has to be characterized as diverse, or heterogeneous, with the breakdown given in Table 2.

From a review of organizational policies, pertinent information can be summarized to complete the left-hand column of the matrix as follows:

- A 180-bus fleet, 129-bus peak fleet,
- 154-hr of revenue service per week,
- A diverse fleet,
- An abundant capacity in facility,
- A new fleet, 6.0-year average age,
- A unionized work force, and
- A total of 28 percent spare vehicles.

WORK ASSIGNMENT

Work assignment throughout the day is executed in the following sequence. Buses receive a brief inspection by operators at the beginning of the run, and extended preventive maintenance inspections take

TABLE 1 Maintenance Activity Level Definitions

	Level			
Activity	A	B	C	D
Work assignment	Contract out heavy repairs, in-house inspection; first-come, first-served.	Some heavy repairs in-house; maintain and repair quickest item first.	Spectroanalysis augments inspection; priority for scheduled work over breakdown.	All repairs in-house.
Maintenance scheduling	No scheduled inspections on most items.	Manufacturer's inspection guidelines.	Individually tailored inspection intervals.	Scheduled replacement intervals.
Work force development	No training, seniority promotion, no incentives, no work standards.	Outside training; nonmonetary incentives.	Merit promotion, monetary incentives, work standards.	In-house training.
Labor allocation	All crews responsible for all duties; no specialized mechanics; no specialized crews; no specialized teams; one shift.	Specialized mechanics; two shifts.	Specialized crews; three shifts.	Specialized teams.
Inventory management	No formal structure except minimum safety levels.	Manual systems; defined order quantities; defined reorder points; safety stock defined through service levels.	Computerized system.	Computerized system directly integrated with maintenance scheduling; order quantities and reorder points contingent on scheduling.
Equipment management	Low capital intensity.	Moderate capital intensity with minimum special equipment.	Moderate capital intensity with selected special equipment items.	High capital intensity with specialized equipment.
Information	Aggregate; manual; direct entry; nonintegrated.	Automated; microcomputer.	Micro/mini; indirect entry.	Disaggregate information; automated; mainframe computer; integrated.

TABLE 2 TTDC Motor Bus Fleet

Number	Year	Vehicle Model
47	1973	Grumman Flxible 53102
10	1978	Bluebird
72	1979	Grumman Flxible 53096
20	1980	GMC RTS-II
7	1981	Ford "Trolley"
13	1983	Flxette
9	1983	GMC "Trolley"
2	1980	Chevrolet Transliner

place chiefly during the day (the first shift is from 7:00 a.m. to 3:30 p.m.), unit overhaul and other shop activities take place during the day (7:00 a.m. to 3:30 p.m.), running repair (which responds to breakdowns and operator-generated or inspection-generated work orders) takes place during all shifts (7:00 a.m. to 3:30 p.m., 3:30 p.m. to 12:00 midnight, and 10:30 p.m. to 7:00 a.m.), and the servicing operation (6:00 p.m. to 2:00 a.m.) occurs between shifts.

The work load is determined by the inspection intervals (see section on Maintenance Scheduling elsewhere in this paper) and the resulting work orders, and by in-service breakdowns or operator complaints. Essentially, six buses per day receive a preventive maintenance inspection. All vehicles pass through the daily servicing cycle, which averages 15 to 20 min per vehicle. During this cycle, the farebox is removed, oil and transmission fluids are checked, tires and lights are checked, the fuel tank is filled, and the vehicle is vacuumed, washed, and parked.

Shop activities consist of unit overhaul (rebuilds and other work that requires removal of components), body work, and painting. All these activities take place in the first shift (7:00 a.m. to 3:30 p.m.).

The preceding describes the routine assignment of work tasks. However, events in the day are frequently not routine and certain issues must be confronted in the assignment of work tasks. One such issue is contracting work outside the agency. Some repair tasks are contracted out, but it is the policy of the maintenance department that no item be automatically contracted. Essentially, only 1 percent of engine and transmission work is contracted out at times when shops become overloaded (when shortage occurs in specialized personnel for those time-consuming tasks); otherwise, there is no contracting. In cases such as seasonal peaks of air conditioning repair work, the policy of the department is to use overtime instead of contracting, so as to ensure control over operations.

Another issue of work assignment is whether to execute inspection procedures entirely on-site. The department does administer regular on-site inspections, but, in addition, some oil analysis is conducted by an outside firm, which effectively amounts to contracting some inspection. In this case, oil spectroanalysis is performed by the vendor that supplies oil to the department. This service is furnished free to advise on the condition and performance of oil stocks. The officers believed that this service did not appreciably assist or augment on-site inspections. They suggested that it was accepted because it was a free service and the results were not incorporated into the inspection routine. Maintenance work is scheduled at the beginning of the day subject to change as events occur. However, the department does try to schedule the heavy work of the unit overhaul shop as much as 1 week in advance.

Last, the rule of queue discipline determines the sequence of work of the maintenance shop. Maintenance duties at the TTDC are largely dispatched on the basis of "quickest tasks to be done first." In the running repair shop, a secondary rule was also suggested: "put new buses on the road before old buses" to promote attractiveness of service.

A summary of the preceding discussion can be compared to the performance scale for work assignment given in Table 1. The TTDC does almost all heavy repair in-house, which would place the TTDC at a position a degree higher than C on the spectrum of work assignment. The TTDC also conducts some off-site spectroanalysis inspections, but the spectroanalysis plays a minor role in operations, so this feature would place the TTDC a little lower than C on the spectrum. The queue discipline policy of "quickest items first" indicates that operations have not yet attained the size where scheduling difficulties would make "scheduled work over breakdown work" the dominant policy. Thus, the TTDC's queue discipline would place it on the B point of the spectrum. In considering all of the factors, and giving weight to the first point of minimal contract work, the TTDC's collective work assignment policy can be summarized as C.

MAINTENANCE SCHEDULING

The primary policy decision that a maintenance department faces concerns the balance between a preventive maintenance schedule and attending to maintenance needs that result from breakdowns. The TTDC maintenance department has opted to select a preventive maintenance schedule, which revolves around basic inspection intervals of 6,000 mi for most vehicle models (or units of 3,000 mi for the smaller "trolleys" and Flxettes). This schedule is adhered to conscientiously, except for some special seasonal campaigns, such as air conditioner and alternators in the spring and water pumps and heaters in the fall. Furthermore, prerun (check water, windshield wiper, signals, accident damage, and loose mirrors) and postrun inspections are executed by drivers on each vehicle run.

The specification of mileage for inspection intervals is crucial. The TTDC bases its schedule primarily on the guidelines suggested by manufacturers, although this base is frequently modified to suit agency experience. As an example of adjustment, the manufacturer of the smaller Flxettes recommended 6,000 mi as a basic unit for inspection. Using this schedule, the TTDC experienced repeated problems, such as oil leaks and dirty transmission fluids. The department reacted to this experience by adjusting its basic inspection interval to 3,000 mi. The new interval was arrived at through an informal process of judgment and analysis of records. Maintenance officers judge that since this adjustment was made, the system has worked fine. The department estimates that from 8.5 percent to 10 percent of items that are listed for inspection have received revised interval values.

The TTDC maintenance department has not established a strict program for scheduled replacement of components, however. Major components are frequently rebuilt when they are judged to be performing poorly, but precise mileage intervals are not observed. In reevaluating inspection intervals or arriving at a decision to pull and rehabilitate a component, the department refers to monthly computer reports. These reports display incidents of in-service troubles, either according to individual bus vehicles or according to component type. When it is judged that extraordinary problems are occurring with a component, action can be taken either to rebuild it or to revise the inspection interval.

At the time of the site visit, most of the maintenance scheduling had been computerized. The computer information system traces which vehicles are approaching their inspection time by comparing the number of miles since the last inspection with the basic inspection interval (usually 6,000 mi).

A comparison of the TTDC maintenance department's long-term scheduling policies with Table 1 indicates that the TTDC has opted to implement a preventive maintenance inspection system, which is to be expected from all but the smallest agencies. In developing the inspection schedule, manufacturer's guidelines for mileage intervals are used as a base, but this base is adjusted considerably according to departmental records and judgment. The TTDC maintenance department does not, however, employ statistical studies to establish interval values, but has instead found success with an informal analytical process. The TTDC maintenance scheduling policy has not emphasized optimal intervals for automatic replacement of components instead of inspection intervals. Because of the informal analytic process that accompanies interval values, and because scheduling has not been taken to the extreme of studying optimal replacement intervals, one would place TTDC's maintenance scheduling policy at C on the spectrum of Table 1.

WORK FORCE DEVELOPMENT

The personnel functions of the maintenance department are guided chiefly by labor union agreements and explicit written procedures. The subjects that are considered in this evaluation are recruitment policy, training programs, criteria for promotion, discipline and grievance procedure, motivation programs, and work standards. At the entry level, no one is hired without mechanical experience despite a low starting wage ($4.33/hr) and despite the fact that some career paths (bus cleaners, for example) do not make great use of a mechanical background. The training policy is such that once an employee is recruited, he receives unsupervised on-the-job training, supervised on-the-job training, some classroom training with industry manufacturers, and some on-site classroom instruction.

When positions above the entry level are to be filled, the department's promotion policy takes effect. Senior positions are filled only from within the organization. As soon as a senior position opens, the department goes through a bidding process whereby the job is awarded to that individual who has the most seniority for the job classification. Merit tests are not applied at each level of advancement, although merit is considered in the form of a review of an applicant's records (e.g., absenteeism and discipline problems).

The TTDC maintenance department has developed incentive programs. One fundamental incentive is provided through differential pay scales. Many transit agencies are hindered by pay levels that provide little difference between entry level and the most senior positions, but this is not the case for the TTDC. The lowest pay for the lowest positions is $4.33/hr, and the highest pay for the highest positions reaches $10.94/hr. Thus, the prospect of promotion and accompanying pay raises provides a strong financial incentive for TTDC maintenance personnel to seek advancement. Progressing from the lowest to the highest pay scale would provide a pay increase of 153 percent, which is a greater differential than many agencies offer.

Other pay incentives are a premium of $0.15/hr for working the 10:30 p.m. to 7:00 a.m. "graveyard" shift, which is not highly effective in attracting interest in the shift, and the time-and-a-half pay premium for overtime, which is effective. Seniority is the key criterion for the assignment to shifts. Senior workers get first preference in shifts, which amounts to the least senior workers staffing the second and third shifts. The system for assigning overtime gives equal consideration to all workers; seniority is not a factor. Priority for overtime is assigned according to a rotating board system in which the name at the top of the list is offered first choice.

The standard for comparison is given in Table 1. Because the development of the maintenance department's training program relies heavily on outside training and on-the-job experience, the TTDC's training program falls between B and C on the spectrum. The seniority system of promotion would place the TTDC at B, and special monetary incentives puts it between B and C. The absence of monitoring task completion times (no work methods or standards) places it at B or lower. Altogether, the composite work force development program of the TTDC could be summarized as B or B/C, with noticeably low development of training, promotion, and work methods policies.

LABOR ALLOCATION

According to Fiscal Year 1983 Section 15 reports, the TTDC's motorbus transit operations had 67 maintenance labor equivalents or 2.70 vehicles per maintenance employee. These figures compare favorably to the 1982 Section 15 averages for the industry. Motorbus fleets of TTDC's size bracket (100-249 buses) average 2.4 vehicles per maintenance employee, although industry-wide averages are 1.8 vehicles per maintenance employee. The TTDC's favorable employee-to-vehicle ratios may be attributable in part to the ratio of spare vehicle to required vehicles. Reliance on overtime is commonplace in the maintenance department, but it is controlled. Overtime hours are estimated at 6.6 percent of regularly scheduled hours.

The TTDC's evaluation relative to Table 1 is as follows. It clearly supports three shifts of maintenance operations, thus placing it toward the C/D range on the spectrum. Inspection crews, furthermore, are effectively separated from repair crews. However, road crews are not regularly staffed but are improvised according to worker availability. Thus, crew organization at the TTDC would be squarely placed at C on the spectrum. Although functional teams are nominally set up in the maintenance department, the separation is flexible over the long run (new sign-ups every 6 months) and very flexible over the short run (idle team members being temporarily assigned to other productive tasks). Thus, the TTDC's policy of administering specialized teams would place it just slightly above C on the spectrum. Individual mechanics (such as electricians and welders) do receive specialized status and training, thus the TTDC's orientation of mechanics would qualify as "specialized" and would place the TTDC in the C/D range of the spectrum. Altogether, the combined profile of the labor allocation system would be classified as C: specialized mechanics, somewhat specialized crews, minimally specialized teams, and three shifts.

INVENTORY MANAGEMENT

The inventory system of TTDC is one of the sequestered stockroom with the flow of stock being directly monitored by purchasing personnel, both at the point of receiving and at release for work orders. Parts are ordered by the purchasing office when a computer review indicates that the number on hand is at or below the minimum level. Orders are entered on the part profiles on the computer, and they remain on an outstanding status until the parts arrive. The receipt of stock is also entered on the part profile in the computer, and the outstanding status is amended. The stock is placed in the stockroom and is issued when maintenance employees present work order release forms.

The TTDC employs a reorder point system. Projected usage rates for parts are based on records when possible, and the reorder point for parts is generally 30 days' worth of on-hand inventory. Order quantities are generally 90 days' worth of stock--but this order quantity may be larger if an exceptional volume discount is available. Thus, fixed order quantities are established for each part, but these quantities are "recommended rather than mandatory." Because parts are ordered according to usage, orders are issued at irregular intervals and are not placed at predetermined intervals.

The preceding description applies to all parts costing over $2.00. For the many high-volume, low-cost parts (such as screws, nuts, washers), storage is provided outside the stockroom, in bins on the garage floor. Each of these "pink tag" items occupies a bin, and the bin stock is simply regulated by "eyeballing." When the bin is nearly empty, it is replenished from bulk storage in the storage room. Except for the matter of storage location and the requisition process, the inventory cycle for these low-cost items is similar to that for other stock.

At present, the inventory system is monitored both manually and by computer. The manual component consists of request forms (work order release forms that later are entered into the terminal), purchase order forms, copious vendor records, and 97 interchangeable "strip files." The computerized component consists of a profile of each part, which provides the following information:

- Part number assigned by the TTDC,
- List of vendors who supply the part, with preferred (lowest priced or fastest fulfillment) source listed first,
- Order point for part,
- Order quantity for part,
- Lead time for part order,
- On-hand inventory,
- On-order inventory, and
- Cost of part.

Certain measures of performance for the TTDC's inventory management are available. The total parts inventory taken on Sept. 29, 1984, showed a value of $567,800, which amounts to $3,138 per vehicle. Furthermore, stock-outs occur on the average of three or four times a day. This incidence is greater than that for the previous year, and it is seen as a problem. But the increase in stock-outs may be due to the diversity of the TTDC's fleet or the burden of maintaining both manual and computerized information systems during the trial period. Overall, the performance of the inventory office is perceived as sound.

The TTDC inventory can be summarized as computerized, despite the many manual procedures that are being carried through the trial period of the computer system. The computerization of inventory would place the TTDC at C on the spectrum. The agency also has a formally developed inventory cycle using reorder points and order quantities. The determination of these quantities remains somewhat informal, as does the practice of incorporating safety levels of stock into the system. This array of features places the TTDC at the overall C level of development. The system is below the D level of development because of the informal determination of order points, quantities, and safety levels, and because the inventory computer program has not yet been directly integrated with a maintenance scheduling computer program.

EQUIPMENT MANAGEMENT

The maintenance department carries most of the equipment generally found in larger agencies, such as automatic bus washers, large bus vacuum systems, automatic farebox removal equipment, transmission and engine stands, heavy-duty press, brake lathe and grinder, transmission test stand, valve body tester, and TIG and MIG (tungsten and metal inert gas, respectively) welder. However, the department still does not possess its own dynamometers, frame straighteners, shapers, or mill. There was no strong indication among officers that these items are necessary, although some, like dynamometers, were regarded as "nice to have."

Considering the equipment that has been identified at the TTDC, the agency's maintenance department should be classified as significantly capital intensive. It possesses the equipment necessary to execute almost all maintenance operations on-site (less than 1 percent of work is contracted out--see section Work Assignment elsewhere in this paper), but it still does not have some highly specialized equipment (such as dynamometers). In conclusion, the TTDC equipment management system can be summarized as C/D on the spectrum.

INFORMATION SYSTEMS

As indicated previously, the TTDC maintenance department relies on both manual and automated information. At present, there is a significant overlap of the two, but, in the future, more and more reliance will be placed on the automated system, as more program features are brought on-line and as present computer programs prove themselves. The computer system utilizes minicomputers with several terminals available in the bus maintenance facility. The software is a "turnkey" system supplied by a vendor who acts as a consultant in programming new features or attending to problems. Although minicomputer capabilities are broad and execution occurs rapidly, the TTDC's information program can be distinguished from other, more elaborate, automated systems in a number of key ways.

First, the level of detail in the TTDC's maintenance information system is still somewhat aggregated. Specifically, two key benchmarks of information disaggregation are not present. The TTDC does not as yet track and analyze individualized work time records of personnel on the computer--nor does it do so manually. The TTDC is, however, planning to introduce such a program "perhaps in a year or so." Second, failure histories of mechanical components are not kept. Although the monthly printout generates a record of breakdown failures related to specific components, it does not record inspection-generated observations of component failure. Failure information is permanently recorded in manual records, but not in a form that is easily retrieved. Although the TTDC is considering putting all past records on computer storage, such a transcription will be time consuming. If such a system were ever brought on-line, there would be good possibilities for the analysis of inspection intervals based on precise historical data.

In another sense, the department's automated information system is a simple one in that, as yet, only specific maintenance personnel (clerks and administrators) interface with the computer terminals. Terminals are not present at work sites nor are portable recorders employed at work sites. Thus, all information generated from work sites must still be recorded indirectly (i.e., be entered on paper forms to be input later to a terminal by a clerk).

Last, the TTDC has not implemented a system for integrating information programs. The maintenance department employs computer programs for monitoring inspection schedules and inventory, but these programs remain independent of each other. Officers indicate that they are trying to implement a system where the occurrence of certain parts needs will automatically be tied to parts requisition. However, such an integrated information system is extremely advanced for the industry, and it is not likely in the TTDC's immediate future.

The maintenance department's information system can be summarized as using aggregated information, minicomputer hardware, and indirect entry. This configuration comes closest to the C level on the spectrum, with the indirect data entry being a notable exception. Although this exception is significant, the TTDC information system is on the verge of pursuing the disaggregation of worker time information and, in general, supports a fairly sophisticated reporting system. Therefore, the TTDC's information system could be summarized as being between B and C, and as favoring C somewhat.

MONITORING AND EVALUATION

The evaluation framework used in this paper focuses on general measures that can be obtained from Section 15 information, with primary emphasis on the measures of vehicle miles per road call and maintenance cost per vehicle mile. The values are presented in Table 3 for fiscal years 1981, 1982, and 1983. For each year, the values for the TTDC are presented; but, in the last year, comparative information is lacking.

The TTDC's vehicle miles per road call improved slightly from FY 1981 to FY 1983, but, even so, values were less than the average for its class size for 1981 and 1982, and there is every reason to believe that the 1983 data would bear the same relationship. Based on the preceding values, the TTDC's performance may be somewhat unfavorable, although further considerations must be weighed.

Interpreters should be aware that the measurement of vehicle miles per total road calls may still include some factors that are out of the maintenance department's control. Nonmechanical road calls (as distinguished by Section 15) may account for a significant number of road calls, and, by definition, this category of road calls (bus vandalism, illness on buses, farebox problems) may not be a direct responsibility of vehicle maintenance. A general interview with the assistant superintendent of equipment I indicated that nonmechanical road calls may have been an exceptional problem and, therefore, further investigation was conducted.

When performance was adjusted to reflect vehicle miles per mechanical road call only, the TTDC's per-

TABLE 3 TTDC Evaluation by Fiscal Year

	FY 1981			FY 1982			FY 1983
Evaluation Category	Agency	Class	Industry	Agency	Class	Industry	Agency
Vehicle miles per road call	1,386.7	1,687.2	1,461.5	1,453.4	1,748.2	1,265.2	1,450.9
Vehicle maintenance cost (cents) per vehicle mile	34.6	41.7	58.8	36.8	47.6	66.7	50.3
Vehicle miles per mechanical road call	1,947.6	2,095.9	1,850.0	2,195.5	2,372.0	1,554.3	2,292.1

formance improved. The value of miles per incident increased considerably each year (from 1,947.6 to 2,195.5 to 2,292.1). However, in the latest available year for peer comparison (1982), the value still compared unfavorably to the class size average. But one should also note that the TTDC's value of vehicle miles per mechanical road call is above the industry-wide average for both 1981 and 1982. Thus, indications are that the TTDC maintenance department's road call performance is acceptable, but it remains an area to consider for improvements.

The TTDC's performance in vehicle maintenance cost per vehicle mile exhibits a trend that is the opposite of its road call performance, however. In 1981 and 1982, the maintenance cost was low, at 34.6 and 36.8 cents per vehicle mile, respectively. In comparison to both class size and industry averages, the TTDC delivered its services at an impressively low cost. However, in 1983, that status changed; the cost figure jumped to 50.3 cents per vehicle, which was at or just below the class-size average, and which certainly exhibited a sharp rise from the 1981 value of 34.6 cents.

Surely, a small part of this cost rise was attributable to inflation, but further investigation is necessary. Likely causes are increased fleet diversity with increasing emphasis on smaller and "trolley-type" buses, which require more frequent inspection and repair; increased inventory costs associated with fleet diversity; farebox problems; and the burden of maintaining overlapping manual and automatic information systems during the computerization trial period. Nevertheless, the TTDC's low base wage must be regarded as extremely favorable for low-cost operating expenses, and the recent growth in expense must be explained in the light of this advantage.

In conclusion, it might be observed that both road call and cost performance have been moving from extreme values toward more conventional, central values over the 3 years. The TTDC maintenance department experiences a road call incidence within acceptable levels, and it appears to enjoy a cost schedule that is slightly better than acceptable levels. It might also be suggested that some tradeoff has existed between these values; perhaps vehicle miles per mechanical road call has been improved through an increase in vehicle maintenance cost per vehicle mile. However, such an assertion requires further investigation. The most important outcome is to recognize the values of these two measures, their relationship to other values in the industry, and their trends. The decision as to whether these values are acceptable remains one of policy.

CASE STUDY SUMMARY

Based on the review of the different categories, the TTDC maintenance department is shown in Figure 2. Through this summary, general patterns and relationships are shown. Furthermore, the TTDC's maintenance department could be compared with the maintenance departments of other agencies described in the same framework.

Figure 2 indicates that the TTDC operates a fairly large fleet of 181 vehicles and serves a comparatively large urban area. Furthermore, it has many favorable conditions affecting bus maintenance: the fleet is young, the present maintenance facility

Description	WORK ASSIGNMENT	MAINTENANCE SCHEDULING	WORK FORCE DEVELOPMENT	LABOR ALLOCATION	INVENTORY MANAGEMENT	EQUIPMENT MANAGEMENT	INFO SYSTEMS	MONITORING & EVALUATION
Large community (900,000) Moderate population density Moderate-to-light transit reliance Flat terrain Mild-to-warm, variable climate Moderately priced labor market 180 bus fleet, 129 peak fleet 154 hrs. revenue service/wk Heterogeneous (diverse) fleet Abundant capacity in facility New fleet (5.9 yr. avg. age) Unionized workforce	C	C	B	C	C	C/D	B/C	1450.9 vehicle miles per road call. 2292.1 vehicle miles per mechanical road call 50.3¢ vehicle maintenance cost per vehicle mile.

FIGURE 2 TTDC profile.

accommodates operations easily, ample spare vehicles are provided, and terrain and weather are nearly ideal. Countering these positive conditions are the diverse character of the fleet and an almost around-the-clock delivery of revenue service. Overall, the conditions appear to be quite favorable, but each management activity area is differently affected by each listed characteristic. For instance, the heterogeneous character of the fleet places special burdens on maintenance scheduling, work force development (training), and inventory management.

Using Figure 2, one can compare the development of the different management areas with the expected impacts. For instance, one might expect a general level of development approaching C for operations of 180 buses--a size of operations that is considerably far along the size scale of 15 to 500 considered in this study. In general, this pattern is strikingly borne out: the array of C-C-B-C-C-C/D-B/C focuses around the C level; but the condition of a heterogeneous fleet may lead one to expect a fairly developed structure for training when, in fact, work force development is indicated as somewhat modestly developed--at level B. From this observation, a reviewer may wish to probe further into the details of the work force development system, to judge whether the arrangements are properly matched to the needs of the agency.

The performance of one management area can also be directly compared with another. For instance, it would be unusual for an inventory system to be out of step with the development of an information system. If such a situation were observed, then perhaps a reviewer would wish to examine these two areas of management activity together. In the case of the TTDC, the development of inventory management policies (C) does appear to be closely matched with information system development (B/C).

Finally, Figure 2 offers some key, general measures for the performance of the maintenance department. If the values appear disappointing, then a close look may be warranted at the possibility of either overdeveloped or underdeveloped areas of the maintenance management system. For instance, a high maintenance cost per vehicle mile might cause a reviewer to consider whether an equipment management system is overdeveloped (i.e., carrying too much specialized equipment when the size of operations or some other factor may argue for relying more heavily on contracting work out for specialized tasks) or underdeveloped (i.e., arguing for the acquisition of further specialized equipment so as to achieve economies or to increase control by reducing reliance on outside contractors).

Performance measures can also be interpreted in another way. Particularly strong values may caution a reviewer to take moderate action on perceived imbalances in a management area. For instance, in another study, one large agency (650 buses) was documented as having a maintenance information system that would measure A in this framework (3). Nevertheless, the performance of the maintenance department was strong according to indicators, due partly to strong informal practices that had been built up over time. Although the A level of development in information appears to be inappropriate for that agency, any actions that might upset the present informal systems should be carefully considered.

In the case of the TTDC, the performance measures of vehicle maintenance cost per vehicle mile and vehicle miles per mechanical road call both approach intermediate values. Therefore, no immediate action is prompted by either measure, but recent trends might be kept in mind: that is, maintenance cost has been worsening recently, while mechanical road calls have been improving. Ultimately, the decisions based on performance values will depend heavily on the policies of the agency involved, for that agency will determine which performance values are acceptable.

When the matrix is reviewed collectively, the elements of TTDC's maintenance department appear to be compatible with each other and well-suited to its environmental conditions. The values of performance measures for road calls and maintenance cost indicate acceptable performance, but both measures also suggest room for improvement--especially in light of recent trends of cost and a road call value that still remains somewhat low despite recent improvement.

The array of symbols would indicate that the management activities that should be given further attention are work-force development and information systems. At values of B and B/C, respectively, these levels of development may appear somewhat low for an agency the size of the TTDC. However, the deviation for information systems is slight, and the rating of B/C is not unusual for an agency that has already begun automation of its information system. Furthermore, the TTDC maintenance department appears to be firmly committed to further development of information systems, including the imminent introduction of a monitoring program for worker task times. Therefore, no recommendations appear to be required by the present state of the department's information system. In contrast, the work force development area appears to be a strong candidate for improvement.

Certain circumstances, such as the many vehicle models with newer, complex design features, make special demands on the skill and knowledge of the work force. Furthermore, as more and more new recruits are absorbed into the organization, added burden will be placed on the department's ability to train personnel. The new pay scales will most likely accentuate the need for training, as it cannot be expected that applicants of significant mechanical experience will be attracted by the low wages that are offered to all new recruits. Although some of the problems associated with applicants could be lessened through a revision of the recruitment policies, attention still needs to be directed to the present training structure. A program for monitoring worker task times should also greatly assist the development of personnel.

EVALUATION OF METHODOLOGY

The evaluation method applied in this paper has hypothesized a relationship between selected activities and transit organizational performance resulting from the maintenance effort. Resources are shown in terms of levels for each of seven activities. When a transit agency increases the sophistication of its maintenance effort, the cost per unit served can be expected to rise, but the fleet reliability as expressed in vehicle miles per road call will decrease. This was the case of the results shown in Table 3. Over a 3-year period, as related in the discussion, the TTDC enhanced their maintenance program using automation, modern equipment, labor incentives, and other positive changes. This increased cost was shown in the vehicle maintenance dollars spent per vehicle mile. The enhanced performance was noted by the increase in vehicle miles per road call.

If a broad set of applications similar to that described in this paper were conducted, researchers would have data to study the formulation of relationships between maintenance activity levels and performance. Quantifiable criteria governing each activity level would be desirable. Such criteria could evolve from those provided for this rather subjective application as given in Table 1 into specific measures that are associated with a score between 0 and 100. Such a score could be derived from concepts of the normal probability distribution to indicate Z-scores and associated cumulative probabilities. The Z-score is defined as

$$Z = (x - \mu)/\sigma \qquad (1)$$

where

x = measure on a 0 to 10 scale for a transit property,
μ = average peer group measure from sampled properties,
σ = standard deviation of peer group measure, and
Z = normalized maintenance activity level score.

The Z-score is the abcissa value for a standard normal distribution. The Z-value is converted into a probability measure by integrating the standard normal density function.

$$P(X \leq x) = \partial\ 1/2\pi^{1/2} \int_{-\infty}^{(x-\mu)/\partial} e^{-1/2Z^2} \sigma dZ \qquad (2)$$

Using tables for the standard normal distribution, Z becomes

$$P(X \leq x) = \phi[(x - \mu)/\sigma] \qquad (3)$$

Equation 3 can be converted to a performance score that shows performance relative to the expected measure for the peer group as follows:

$$\text{Performance} = \phi[(x - \mu)/\sigma] \times 100 \qquad (4)$$

where performance is the percent of peer properties performing below the operator under consideration on the scale.

The next step is the estimate of an aggregate score for the seven activity measures (Z_i; $i = 1, \ldots 7$). Here, each score would be weighted for the overall score. Then

$$P_T = \sum_{i=1}^{7} W_i P_i \qquad (5)$$

where

W_i = weight for ith activity ($o \leq W \leq 1$) $\sum_{i=1}^{7} W_i = 1$, and
P_i = performance score for ith activity.

In addition to the P-score approach, there are the aggregated performance measures, vehicle miles per road call, and maintenance cost per vehicle mile. There are different ways that these measures can be disaggregated and related to the activity level scores. One proposal uses either of the performance measures as a dependent variable and multiple linear regression or a transformed nonlinear form using the seven levels as explanatory variables.

$$Y = b_1P_1 + b_2P_{-2} + \ldots b_7P_7 \qquad (6)$$

where

Y = vehicle miles per road call,
b_i = regression coefficients, and
P_i = activity level P-scores.

Or, a single regression on the aggregate score can be attempted as

$$Y = bP_T \qquad (7)$$

The preceding are ideas that can be researched along with others to reach the objectives of (a) providing for the numerical measurement of activity levels, (b) calculating combined scores for all activity levels, and (c) relating activity resources to maintenance performance. These objectives could be attained by a state agency with transit properties under its jurisdiction and then extended to agencies in other states. The key is uniform data among agencies.

CONCLUSIONS

This paper has demonstrated a practical application of a procedure for evaluating transit maintenance activities. The application to a typical property has shown an organized way to characterize the performance levels of a maintenance organization's elements. The information used and its interpretation relative to Table 1 serve as a guide to transit agencies for using the evaluation framework. The framework suggests promise for promoting comparability among maintenance departments--something that has been elusive in the study of maintenance so far. Extensions to a more objective method appear possible if the framework presented here is refined to provide numerical scores and quantified relationships with performance. Approaches to this end have been provided and should be tested.

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Analysis of Bus Transit's Maintenance Efficiency Using Section 15 Data

ATHANASSIOS K. BLADIKAS and CHARLES PAPADIMITRIOU

ABSTRACT

Vehicle maintenance expenses contribute approximately 21 percent to the total operating expenses and are the second highest expense category after vehicle operations. In addition, the cost efficiency of vehicle maintenance is declining. If maintenance becomes more cost efficient, overall cost reductions and service quality improvements are possible. Direct comparisons among systems are not generally useful, because cost variations are largely a function of factors that are determined by system operating characteristics and the environment in which the system operates, and are mostly outside the system operator's control. In this paper, the relationship and effect of these factors on vehicle maintenance efficiency and productivity components are explored. A cross-sectional analysis is performed through a set of regression equations that may be used by transit managers as a tool to identify and diagnose the sources of their inefficiencies, and assist them in the development or modification of their maintenance policies.

Rapidly increasing costs and declining productivity made the majority of the nation's transit systems increasingly more dependent on public subsidies over the last 2 decades (1). Furthermore, transit has been given the assignment to accomplish an array of social objectives, ranging from energy conservation to providing mobility for the poor and the handicapped. All this has led to an increased interest in the performance evaluation of the nation's transit systems.

There is no general agreement on how to define and measure the performance of a transit system, because the goals to be accomplished are often vague and conflicting. However, most researchers agree that transit performance is a multidimensional concept consisting of some or all of the following elements (2-4):

- Efficiency,
- Effectiveness,
- Quality of service, and
- Societal impacts.

In this paper, not all of these elements of performance are dealt with; rather, the focus is on only the cost-efficiency concept as it relates to the vehicle-maintenance function.

Vehicle maintenance expenses contribute approximately 21 percent to total operating expenses and are the second highest expense category after vehicle operations (5). Transit managers and policy makers have not given the maintenance function the interest and attention that its importance warrants. This was mainly the result of the "80-20" federal share for capital assistance, which allows transit properties to buy new vehicles at a cost to them of only 20 cents on the dollar, and often much less, because local and state governments provide additional capital funds. Thus, most systems find it more cost-effective to defer maintenance and replace vehicles prematurely. However, as federal sources of funds become less certain, increased attention has been paid not only to the costs associated with maintenance, but also to the quality and effectiveness of the maintenance practices, as road calls and missed runs contribute heavily to the quality of service offered and consequently affect the number of passengers attracted and, therefore, the fare revenues collected by the system.

Vehicle maintenance cost efficiency as measured by vehicle-miles per dollar spent is declining whether expenses are measured in actual or constant dollars (5). If maintenance becomes more cost efficient, overall cost reductions and, more important, service quality improvements are possible. Direct comparisons among systems are not generally useful (because cost variations are largely a function of factors that are determined by system operating characteristics and the environment in which the system operates and are mostly outside the system operator's control). In this paper, the relationship and effect of these factors on vehicle maintenance efficiency and productivity components are explored.

PREVIOUS STUDIES ON VEHICLE MAINTENANCE

A number of studies have dealt with vehicle maintenance and have identified the following major critical issues:

- Transit systems do not have adequate preventive maintenance programs and, in many systems, the established preventive maintenance schedule is not adhered to (6,7).
- Although vehicles have become highly complex technologically, there is little progress in vehicle mechanic training, promotion, and recruitment practices (6,8).
- Most systems do not have proper inventory control methods for spare parts and supplies, which

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A.K. Bladikas, The City College of New York, Institute for Transportation Systems, Convent Ave. at 138th Street, New York, N.Y. 10031. C. Papadimitriou, Department of Transportation and Industrial Engineering, Polytechnic Institute of New York, 333 Jay Street, Brooklyn, N.Y. 11201.

results in overstocking or maintenance work being held up while waiting for delivery of replacement units (6,8).

- Bus maintenance facility needs have not been properly addressed. Most garage, storage, and main maintenance facilities have become antiquated and are not geared to efficiently servicing the needs of the bus fleets (8).
- Vehicle history and status information recording methods are mostly inadequate for diagnostic purposes, often resulting in incomplete repairs (8,9).
- Quality assurance (QA) methods are not being extensively used in evaluating the degree to which established standards of performance are being attained (10).
- Most systems do not have an adequate maintenance information system (MIS), which is a prerequisite for the proper scheduling of maintenance activities, and which enables the correct usage of labor and material resources (9-11).

It is obvious from the studies just outlined that a wide range of problems exists in all areas of the vehicle maintenance function. Improvements in facilities, equipment, personnel, and procedures can make the delivery of the maintenance function more effective and efficient and reduce costs, as well as improve fleet reliability and quality of service. Realizing all this, Pake et al. (12) developed a generalized, descriptive managerial framework for bus maintenance. They defined the maintenance function as a set of eight component activities (work assignment, maintenance scheduling, work force development, labor allocation, inventory management, equipment management, information systems, and monitoring and evaluation) and classified transit systems according to the degree of sophistication with which they perform each activity. They also concluded that activity sophistication should be a function of the environment in which a system operates. Unfortunately, there are few studies that deal quantitatively with the effects of environmental factors.

Meyer et al. (13), in their analysis of mass transportation productivity, used a sample of 42 bus systems for 1970 to develop a formula that explains the variance in the maintenance costs as follows:

$$\begin{aligned} \text{mc} = {} & 0.331 - 0.017\ \text{mph} + 0.00003\ \text{size} \\ & - 0.00021\ \text{age} + 0.00008\ \text{temp} \end{aligned} \qquad \text{adj.}R^2 = 0.42$$

where

mc = maintenance costs (\$/bus-mile),
mph = average speed,
size = number of vehicles owned,
age = percent of buses over 10 years old, and
temp = the average number of days temperatures fell below zero per year.

The only variables found significant in the preceding regression equation were speed and fleet size, although the addition of the operator wage rate as an independent variable acting as an index for the maintenance wage rates only slightly increased the explanatory power of the equation (adj.R^2 = 0.50). This led the authors to conclude that most of the unexplained variation is attributable to differences in the skill of the maintenance personnel.

In two similar studies, Foerster et al. (7,14) survey the factors that influence transit bus maintenance costs and labor requirements. Employing multiple regression analysis and using Section 15 data from 107 transit systems, they produce the following model:

$$\begin{aligned} \text{LH} = {} & -2.9 + 0.0009\ \text{VEH} + 0.88/\text{SPEED} + 0.80\ \text{AGE} \\ & + 9.3\ \text{RC} - 6.1\ \text{SPARE} \end{aligned} \qquad R^2 = 0.37$$

where

LH = hours of maintenance labor per 1,000 revenue miles,
VEH = revenue vehicles,
SPEED = average speed,
AGE = mean age of fleet,
RC = roadcalls due to mechanical failure per 1,000 revenue miles, and
SPARE = revenue vehicles per peak vehicle.

The regression equation is able to explain only a small percentage of the variation, and the coefficient of the age variable is insignificant. The effect of fleet size and speed variables is in agreement with Meyer's earlier findings.

Wilson (15), in his examination of operating cost categories, developed a model for forecasting repair man-hours per thousand bus-miles. His findings show that the value of this resource consumption index is negatively influenced by the system's output as measured by the square root of bus-miles. This leads the author to conclude that there are economies of scale in this component and that positive impacts are found by the variables representing private ownership and annual snowfall, which are attributed to the poor financial state of private systems and to the increased care required for transit systems operating in colder climates. Wilson's model achieves a high coefficient of determination (0.861) when the regression is run on weighted data, but it explains only 50 percent of the variation when it is fitted to the raw data. Its major weakness, however, is that it is based on a small data base (only 20 transit properties).

STUDY APPROACH AND DATA SOURCES

Most of the data used in the analyses were obtained from the fourth year of statistics reported under Section 15 of the Urban Mass Transportation Act of 1964 as amended, which established a Uniform System of Accounts and Records and Reporting System, which required transit systems that receive federal operating assistance to annually submit financial and operating information.

The vehicle maintenance function costs are, according to Section 15, about 21 percent of the total operating costs as given in Table 1. In examining the cost efficiency of maintenance, regression equations can be developed that have as their dependent variable the ratio of a maintenance function input over a system output unit. Input units can be either employees or dollars. Vehicle-miles or platform (vehicle operating) hours can represent system outputs. Cost efficiency ratios can also be derived for the entire function, an individual object class, or a combination of object classes.

By combining inputs, outputs, and object classes, 12 vehicle maintenance efficiency elements were developed. They are given in Table 2 with all independent variables and are shown in Figure 1. The first six measures describe the efficiency of the most important object class--the salaries of maintenance employees, which accounts for about one-half of the maintenance function expenses. The first two elements use salaries in the numerator and the next four use actual employee hours as an input and can

TABLE 1 Vehicle Maintenance Expenses by Object Class

Object Class	Operating Costs (% of total)	VM Function (% within)
Salaries of maintenance employees	10.11	48.0
Fringe benefits	4.19	19.9
Services	0.72	3.4
Materials and supplies	5.79	27.5
Other (utilities, taxes, casualty and liability, expense transfers)	0.25	1.2
Total	21.06	100.0

TABLE 2 Dependent and Independent Variables

Variable	Description
Dependent	
SALPH	Salaries, vehicles, and maintenance/platform hour
SALVM	Salaries, vehicles, and maintenance/vehicle mile
EMPPH	Vehicle maintenance employees/platform hour
EMPVM	Vehicle maintenance employees/vehicle mile
MECPH	Vehicle mechanics/platform hour
MECVM	Vehicle mechanics/vehicle mile
SAFPH	Salaries + fringes in VM/platform hour
SAFVM	Salaries + fringes in VM/vehicle mile
SFSPH	Salaries + fringes + services in VM/platform hour
SFSVM	Salaries + fringes + services in VM/vehicle mile
TOTPH	Total vehicle maintenance/platform hour
TOTVM	Total vehicle maintenance/vehicle mile
Independent	
X1	Average monthly earnings of city employees
X2	Percentage of work trips made utilizing public transportation
X3	Mean January temperature (°F)
X4	Average seating capacity
X5	Ln (revenue vehicles)
X6	Total vehicle capacity—mileage weighted
X7	Platform hours/vehicle mile
X8	Vehicle mile/platform hour
X9	(Active vehicles*annual hours of operation)/platform hour
X10	Active vehicles/platform hour
X11	Active vehicles/vehicle mile
X12	Mean July temperature (°F)
X13	Fleet age—mileage weighted
X14	Active vehicle/vehicle in maximum service period
X15	Median county family income (1980)
X16	Ln (operating employees total)
X17	Platform hours/active vehicle
X18	Average capacity—vehicle weighted
X19	Active vehicles/vehicle midday
X20	Ln (total fleet capacity)
X21	Passenger miles/passenger

be considered as measures of employee productivity. The last six elements gradually add all other object classes to the salaries, starting with fringes. Services are added again to investigate possible tradeoffs between salaries and maintenance contracting. Finally, all expenses are included in the last two elements. Half of the elements use platform hours as a unit of output, and the other half are expressed per vehicle mile. They are distinguished by having a "PH" or "VM" as the last characters in their abbreviated description.

In addition to Section 15, which provided data for all dependent and most of the independent variables, the 1983 edition of the County and City Data Book (16) was used to extract information on the

- Percent of persons using public transportation for the work trip for both the county and city area,
- Percent of the unemployed civilian labor force in the county and city,
- Percent of area (county) that is urbanized,
- Mean temperature (in degrees Farenheit) in January and July, and
- Heating and cooling degree-days in a year.

(Note that items 1 and 3 are from the 1980 census and item 2 is a Bureau of Labor Statistics figure for 1982.)

Data on average monthly earnings of city employees were derived from government statistics reports on city employment (17). These reports provide data for the month of October of each year. Reports for 1980, 1981, and 1982 were used to extrapolate data and make them coincidental with the sixth month of each system's fiscal year.

ANALYSIS OF VEHICLE MAINTENANCE COST ELEMENTS

Basic Salary and Productivity Ratios

Salaries per platform hour (SALPH) and vehicle mile (SALVM) that represent the overall cost efficiency of the first and major vehicle maintenance object class should be influenced by the average basic maintenance wage rate and the productivity of the

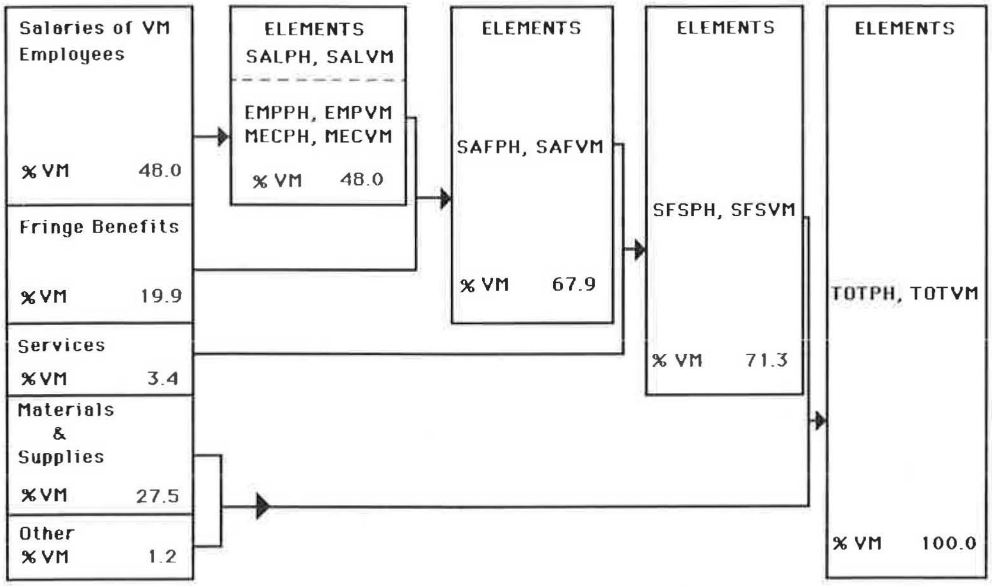

FIGURE 1 Derivation of analyzed elements in the VM function.

maintenance personnel. The basic wage rate can be computed from Section 15 information and expressed as salaries for maintenance employees/employee hours of vehicle maintenance personnel. Maintenance personnel productivity was defined for the purpose of this paper as employees per platform hour (EMPPH) and vehicle mile (EMPVM), and mechanics per platform hour (MECPH) and vehicle mile (MECVM).

The variables that are hypothesized to influence the productivity ratios are

1. Vehicle capacity--This variable should affect employee productivity ratios because systems with higher capacity vehicles will require more maintenance employees to perform the necessary maintenance tasks. The per-vehicle-mile and per-platform-hour productivity ratios hide the capacity factor because vehicles produce the same vehicle miles and platform hours regardless of their capacity.
2. Speed (miles/hour) and Slowness (hours/mile)--The assumption regarding these variables is that in the mileage equations, lower speeds will result in more maintenance employees per mile although in the hourly equations, higher speeds could result in more employees per hour. The reasoning behind these assumptions is that in the mileage equations, systems with lower speeds have their vehicles operating for a greater period of time for the same mileage, thus creating the need for more maintenance and, consequently, employees. By applying the same logic in the hourly equations, systems with higher speeds produced more vehicle miles for the same hours of operation, thus requiring more employees. It is much more likely, however, that the speed variable will be predominant in the mileage equations because maintenance employees (supervisory and support staff as well as mechanics) are hired more on the basis of annual hours of operation and number of vehicles in service than on the mileage vehicles accumulated. This creates an inherent distortion because systems with lower speeds would seem more unproductive in the mileage equations.
3. Degree of fleet and vehicle underutilization as measured by (a) (active vehicles x annual hours of operation) per platform hour, (b) active vehicles per vehicle mile, and (c) active vehicles per platform hour--It is assumed that low utilization factors would result in more maintenance employees per vehicle mile and platform hour. Certain maintenance functions are dependent on the number of vehicles, as all vehicles must be inspected, cleaned, repaired, painted, and so forth. Thus, the higher the values of the preceding variables, the higher the need for maintenance employees.
4. Climatic conditions--Systems operating in warmer areas are more likely to experience air-conditioning problems and systems in the colder regions will be affected by cold starts, heating system breakdowns, and corrosion caused by the melting snow and ice dripping from the undercarriage. Thus, the overall effect of the climatic factors is uncertain.
5. Vehicle age--The effect of this variable is also uncertain. Maintenance needs increase for older vehicles because of their time and mileage wear, and the sophistication and complexity of newer vehicles may also cause an increase in the amount of time required for their maintenance.
6. Spare ratio (measured by active vehicles/vehicles in maximum scheduled service period)--The impact of the spare ratio on the productivity factors could also be adverse. On one hand, large spare ratios allow for a greater time span for the maintenance of vehicles and a less intensive use of vehicle mechanics. On the other hand, the spare ratio, being closely related to the degree of the fleet's utilization, could increase the need for maintenance employees as more vehicles have to be maintained at any time. The effect of a similar variable, active vehicles per vehicles midday, which incorporates the degree of "peakness" in service was examined as well as active vehicles per vehicles midday = (active vehicles/vehicles in maximum service) x (vehicles in maximum service/vehicles midday).
7. System size--The main purpose for the inclusion of this variable was to detect possible economies or diseconomies of scale.

The wage rate of the vehicle maintenance employees was assumed to be influenced by the same factors that affect the operators' wage rate (4). They are as follows:

- City employee wages in the system's area of operation.
- Income per capita in the county of operation.
- Transit system size (i.e., fleet size, number of employees, annual hours of operation).
- Public transportation's degree of utilization in the city of operation.
- Geographical region of system's operation.
- Vehicle capacity (seating, total).

Various linear and nonlinear functional forms for all independent variables were tested. Variables were checked for multicollinearity problems and were included in the equations only if they entered at a 0.05 level of significance or better. The number of cases (N) is indicated for all regressions, and includes the maximum number of bus-only systems that had clean data. The standardized regression coefficient, along with the F-value of each independent variable, are presented in brackets and parentheses, respectively.

RESULTS

The analysis of the productivity ratios (EMPPH, EMPVM, MECPH, and MECVM) and the wage rate was impeded by the questionable values of the Section 15 data on employee equivalents, which were involved in the calculation of the wage and all productivity ratios.

The variables hypothesized to influence the wage rate of the maintenance employees were indeed correlated with the dependent variable. The strongest relationships exhibited by variables were average monthly earning of city employees (X1, $r = 0.555$), the percentage of people using public transportation for the work trip (X2, $r = 0.577$), and the average vehicle-seating capacity (X4, $r = 0.461$). However, none of the regression equations was able to explain more than about one-half of the variation in the wage rate. A reason for this may be that maintenance employee wages are, to a large degree, related to operating personnel wages or system-wide contracts. The following two equations were the best predictors of the maintenance personnel wage rate:

$$\text{Wage Rate} = 0.644 + \underset{\substack{\{0.29\}\\(9.0)}}{0.192*10^{-2}*X1} + \underset{\substack{\{0.44\}\\(29.3)}}{0.682*10^{-1}*X2} + \underset{\substack{\{0.25\}\\(7.1)}}{0.168*10^{-3}*X15} \qquad (1)$$

$$R^2 = 0.520 \text{ (adjusted} = 0.502\text{) } N=84$$

$$\text{Wage Rate} = -2.057 + \underset{\substack{\{0.42\}\\(22.1)}}{0.282*10^{-2}*X1} + \underset{\substack{\{0.21\}\\(\ 5.0)}}{0.911*10^{-1}*X4} + \underset{\substack{\{0.23\}\\(\ 6.2)}}{0.583*X9} \tag{2}$$

$$R^2 = 0.434 \ (\text{adjusted} = 0.412) \ N=84$$

The correlation matrix of the productivity ratios (EMPPH, EMPVM, MECPH, and MECVM) and the independent variables in Table 3 show that the slowness variable (X7) exhibited the strongest positive relationship in the mileage-related ratios (EMPVM and MECVM), confirming the assumption made. Speed (X8) showed a conflicting but nonsignificant relationship with the hourly productivity ratios (EMPPH and MECPH). Fleet age (X13) produced a weak negative relation and positive influence was found to be exerted by the vehicle capacity (X6) and fleet underutilization factors (X9, X10, X11). In addition, some positive influence is denoted by the coefficient of the spare ratio variable (X14), and the sign of the temperature variable (X12) suggests the usage of more maintenance employees for systems operating in warmer areas.

TABLE 3 Correlation Matrix of Elements EMPPH, EMPV, MECPH, and MECVM with Independent Variables

	Simple r			
Variable	EMPPH	EMPVM	MECPH	MECVM
X6	0.220	0.399	0.286	0.435
X7	–	0.644	–	0.586
X8	0.021	–	-0.128	–
X9	0.369	0.288	0.302	0.254
X10	0.219	–	0.165	–
X11	–	0.533	–	0.480
X12	0.237	0.138	0.12	0.044
X13	-0.167	-0.041	-0.101	-0.005
X14	0.248	0.271	0.061	0.098

The regression equations did not have satisfactory coefficients of determination. Nothing satisfactory could be obtained for MECPH, and the best equations for the other three productivity ratios are as follows:

$$\text{EMPVM} = -0.278*10^{-1} + \underset{\substack{\{0.28\}\\(10.6)}}{0.265*10^{-3}*X6} + \underset{\substack{\{0.51\}\\(36.7)}}{0.293*X7} + \underset{\substack{\{0.27\}\\(10.9)}}{0.118*10^{-1}*X14} \tag{3}$$

$$R^2 = 0.516 \ (\text{adjusted} = 0.498) \ N=84$$

$$\text{EMPPH} = -0.153 + \underset{\substack{\{0.20\}\\(\ 4.3)}}{0.172*10^{-2}*X6} + \underset{\substack{\{0.30\}\\(\ 9.6)}}{0.563*10^{-2}*X12} + \underset{\substack{\{0.32\}\\(10.4)}}{0.302*10^{-1}*X16} - \underset{\substack{\{-0.37\}\\(\ 13.9)}}{0.755*10^{-4}*X17} \tag{4}$$

$$R^2 = 0.287 \ (\text{adjusted} = 0.251) \ N=84$$

$$\text{MECVM} = -0.148*10^{-1} + \underset{\substack{\{0.43\}\\(23.1)}}{0.179*X7} + \underset{\substack{\{0.25\}\\(\ 8.1)}}{0.170*10^{-3}*X18} + \underset{\substack{\{0.24\}\\(\ 7.9)}}{0.244*10^{-2}*X19} \tag{5}$$

$$R^2 = 0.460 \ (\text{adjusted} = 0.440) \ N=84$$

The regression equations explaining maintenance salaries per platform hour (SALPH) and vehicle mile (SALVM) have much higher coefficients of determination than those just shown for the wage rate and the productivity elements because the values of these elements are not influenced by the questionable entries in the employee equivalent data. The best regressions are

$$\text{SALPH} = -3.49 + \underset{\substack{\{0.55\}\\(48.4)}}{0.49*10^{-1}*X2} + \underset{\substack{\{0.23\}\\(10.3)}}{2464.44*X10} + \underset{\substack{\{0.15\}\\(\ 4.1)}}{0.77*10^{-1}*X8} + \underset{\substack{\{0.37\}\\(23.6)}}{0.42*X20} \tag{6}$$

$$R^2 = 0.603 \ (\text{adjusted} = 0.583) \ N=85$$

$$\text{SALVM} = -0.28 + \underset{\substack{\{0.54\}\\(74.7)}}{0.49*10^{-2}*X2} + \underset{\substack{\{0.19\}\\(\ 7.8)}}{1.22*X7} + \underset{\substack{\{0.28\}\\(11.8)}}{2357.72*X11} + \underset{\substack{\{0.27\}\\(21.2)}}{0.31*10^{-1}*X20} \tag{7}$$

$$R^2 = 0.766 \ (\text{adjusted} = 0.755) \ N=85$$

As expected, the independent variables represent factors that were found to be related to the components (i.e., wage rate and productivity) of the preceding elements such as X2 (the degree of usage of public transportation in the area), X20 (a system size variable), X10 and X11 (the underutilization factors), and X8 and X7 (the speed and slowness variables) in the mileage and hourly equations, respectively. All have positive coefficients indicating that labor maintenance costs should be increasing as they do.

Composite Elements and Total Costs

Total vehicle maintenance costs can be obtained if fringes, services, and other miscellaneous expenses are added to the basic wages. Because these additional elements are relatively small in proportion to the maintenance salaries, the structure of the regression equations should not be altered substantially, and all earlier hypotheses should still be valid.

RESULTS

The results obtained from the analysis of the composite and total maintenance function elements are presented below:

$$\text{SAFPH} = -4.39 + \underset{\substack{\{0.47\}\\(38.9)}}{0.59*10^{-1}*X2} + \underset{\substack{\{0.24\}\\(11.2)}}{3614.82*X10} + \underset{\substack{\{0.42\}\\(32.1)}}{0.69*X20} \tag{8}$$

$$R^2 = 0.599 \ (\text{adjusted} = 0.584) \ N=85$$

$$\text{SAFVM} = -0.48 + \underset{\substack{\{0.50\}\\(65.0)}}{0.66*10^{-2}*X2} + \underset{\substack{\{0.20\}\\(\ 8.4)}}{1.84*X7} + \underset{\substack{\{0.24\}\\(12.3)}}{3553.00*X11} + \underset{\substack{\{0.30\}\\(26.5)}}{0.51*10^{-1}*X20} \tag{9}$$

$$R^2 = 0.764 \ (\text{adjusted} = 0.753) \ N=85$$

$$\begin{aligned}\text{SFSPH} = {}& -4.49 + \underset{\substack{\{0.33\}\\(16.9)}}{0.17*10^{-2}*X1} + \underset{\substack{\{0.42\}\\(29.0)}}{0.55*10^{-1}*X2}\\ &+ \underset{\substack{\{0.23\}\\(10.2)}}{3617.18*X10} + \underset{\substack{\{0.25\}\\(\ 9.7)}}{0.43*X20}\end{aligned} \tag{10}$$

$$R^2 = 0.592 \text{ (adjusted} = 0.572\text{) } N=86$$

$$\begin{aligned}\text{SFSVM} = {}& -0.47 + \underset{\substack{\{0.20\}\\(\ 9.1)}}{0.11*10^{-3}*X1} + \underset{\substack{\{0.49\}\\(51.4)}}{0.64*10^{-2}*X2} + \underset{\substack{\{0.25\}\\(0.67)}}{1.84*X7}\\ &+ \underset{\substack{\{0.25\}\\(12.0)}}{3612.12*X11} + \underset{\substack{\{0.20\}\\(\ 9.8)}}{0.34*10^{-1}*X20}\end{aligned} \tag{11}$$

$$R^2 = 0.746 \text{ (adjusted} = 0.731\text{) } N=86$$

$$\begin{aligned}\text{TOTPH} = {}& -7.58 + \underset{\substack{\{0.37\}\\(25.2)}}{0.29*10^{-2}*X1} + \underset{\substack{\{0.34\}\\(13.5)}}{0.64*10^{-1}*X2}\\ &+ \underset{\substack{\{0.29\}\\(16.1)}}{6511.82*X10} + \underset{\substack{\{0.26\}\\(\ 7.7)}}{0.13*X4}\end{aligned} \tag{12}$$

$$R^2 = 0.609 \text{ (adjusted} = 0.590\text{) } N=86$$

$$\begin{aligned}\text{TOTVM} = {}& -0.74 + \underset{\substack{\{0.24\}\\(15.0)}}{0.19*10^{-3}*X1} + \underset{\substack{\{0.41\}\\(23.0)}}{0.77*10^{-2}*X2}\\ &+ \underset{\substack{\{0.18\}\\(\ 6.0)}}{2.37*X7} + \underset{\substack{\{0.19\}\\(\ 6.2)}}{0.95*10^{-2}*X4} + \underset{\substack{\{0.32\}\\(19.7)}}{6960.71*X11}\end{aligned} \tag{13}$$

$$R^2 = 0.745 \text{ (adjusted} = 0.729\text{) } N=86$$

The findings are supportive of the earlier hypotheses, as they demonstrate that vehicle maintenance costs are associated with the

- Degree of public transportation utilization (X2),
- Transit system size (X20),
- Wages of city employees (X1),
- Number of vehicles utilized in the provision of services (X10, X11),
- Slowness factor (inverse of speed) in the mileage equations (X7), and
- Average seating capacity of the vehicles in the fleet (X4).

MAINTENANCE EFFECTIVENESS

Although the analysis of the vehicle maintenance costs provided some insights on the influence of the environmental variables on these functional elements, it should be noted that the overall success or effectiveness of vehicle maintenance is measured by the ability to keep the fleet running at all times without missing trips, avoiding mechanical breakdowns, and, at the same time, minimizing the associated costs.

Although it is not in the scope of this paper to examine the effectiveness of vehicle maintenance actions, an effort was undertaken nevertheless to link the effectiveness measure of vehicle miles or platform hours per road call (mechanical failure) to a number of system characteristics and environmental variables. However, the Section 15 data on road calls caused by mechanical failure proved to be unreliable and produced regressions with low coefficients of determination, the best of which follows.

Road calls/vehicle mile =

$$0.442*10^{-3} + \underset{\substack{\{0.62\}\\(47.4)}}{0.162*10^{-4}*X2} - \underset{\substack{\{-0.40\}\\(\ 19.5)}}{0.598*10^{-4}*X21} \tag{14}$$

$$R^2 = 0.400 \text{ (adjusted} = 0.385\text{) } N=84$$

Others were equally unsuccessful in producing reasonable regression fits. For example, Foerster (7,14) produced the following two models that explained less than 20 percent of the variation in road calls per revenue and vehicle mile, respectively. In Model I

$$RC = -0.802 + 0.114 \text{ Ln(VEH)} + 8.905/\text{SPEED}$$

$$R^2 = 0.175 \quad F = 11.48$$

where

RC = road calls due to mechanical failure per 1,000 revenue miles,
VEH = revenue vehicles, and
SPEED = average speed (mph).

In Model II the dependent variable is mechanical failures per vehicle mile

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

The independent variables are as follows:

Independent Variables	Coefficient	Significance Level
Constant	.00012	
Labor hours per vehicle mile	+.0046	.21
Annual per peak mileage per vehicle	$+.922*10^{-10}$	.009
Annual total system mileage per vehicle	$-.666*10^{-10}$	.07
Section 5 (dollars per bus mile)	$-.038*10^{2}$	.06

Road calls appear to be unpredictable because of their inconsistent definition among systems that chose not to follow the Section 15 standard, as well as reporting inaccuracies. For 86 fourth-year Section 15 systems, the variable vehicle miles per road call had a mean of 6,839, a standard deviation of 10,565 and ranged from 459 to 60,047. Similarly, the variable platform hours per road call had a mean of 525, a standard deviation of 803, and ranged from 58 to 4,942. Obviously, it is impossible to predict variables that are distributed so widely. Vehicles miles per road call are computed and given in Table 4 for all bus systems and each of the five Section 15 annual reports currently available. During the first 4 years, vehicle miles per road call kept declining and, in the fifth year, they increased sud-

TABLE 4 Trend in Vehicle Miles per Road Call

Year	Vehicle Miles	Road Calls (number of mechanical failures)	Vehicle Miles per Road Call
1	1,328.9	504,519	2,634
2	1,461.1	766,636	1,906
3	1,541.1	825,412	1,867
4	1,523.6	980,091	1,554
5	1,554.4	612,920	2,520

denly to reach practically the first-year level. This sudden increase could be partially attributed to overestimates of vehicle miles because this variable is used to allocate a portion of federal subsidies. Vehicle miles did increase in the fifth year, but the sharp decline in road calls was responsible for the jump in vehicle miles per road call. Whether this is an aberration or a new trend will be determined as more Section 15 data become available in the future.

CASE STUDY AND SUGGESTIONS FOR FURTHER RESEARCH

It was shown that system characteristics and environmental conditions influence, to a large extent, the amount of maintenance resources consumed by a transit system. Given the environment in which they have to provide service, transit managers can use the regression models of this paper to evaluate their relative position among their peers. The results of an application case study are given in Table 5. A system was picked at random, and the values of the environmental variables pertaining to it were substituted in Equations 6 through 13 to obtain the predicted column. The values of the observed column were derived from the system's Section 15 report. The absolute and percent differences between the observed and predicted values are presented in the last two columns, with positive values indicating that the predicted values are exceeded and, therefore, that the system underperforms.

TABLE 5 Case Study Results

Element	Equation Number	Predicted	Observed	Difference	Difference (%)
SALPH	6	2.63	2.83	0.2002	7.611
SALVM	7	0.17	0.19	0.0247	14.908
SAFPH	8	3.54	3.61	0.0716	2.023
SAFVM	9	0.23	0.24	0.0127	5.576
SFSPH	10	3.95	3.70	-0.2547	-6.439
SFSVM	11	0.27	0.25	-0.0208	-7.688
TOTPH	12	5.88	6.25	0.3678	6.252
TOTVM	13	0.37	0.42	0.0458N	12.234

The results of Table 5 indicate that the system is spending more than was anticipated on the basis of its environmental setting for the salaries and fringe benefit components (SALPH, SAFPH, SALVM, SAFPM). However, this course is reversed and cost savings are realized when the service component is added (SFSPH, SFSVM). This seems to indicate that the system achieved an overall reduction in costs by conducting a large portion of the maintenance work in-house as opposed to contracting it out. But these cost savings are short-lived, as the addition of the other maintenance component costs (mainly materials and supplies) produces total vehicle maintenance unit costs (TOTPH, TOTVM) that are higher than expected, resulting in an overall inefficiency in the vehicle maintenance function.

The model's usefulness and ability to pinpoint inefficiencies in the maintenance function ends at the object class level. In addition, no corrective action can be immediately devised by just inspecting the results. The case study system, for example, underperforms when materials and supplies and other expenses are added. This could be the result of a chaotic inventory control system, unusually high utility bills and liability premiums, or wasteful employees. The exact cause(s) can be identified only by the system's management that has an intimate knowledge of its operating and procedural details.

Combining the models' results with the degree of sophistication to which each of the eight previously mentioned component activities of maintenance are performed will probably be the best direction that future research efforts could take. Successful results in that area will not only refine the models presented here, but, in addition, a quantification of the descriptive framework of Pake et al. (12) will become possible. Another research area could be the establishment of a relationship between environmental factors and maintenance effectiveness either by using future years of cleaner Section 15 data or through an independent data collection effort. Finally, if the models are to be refined, in order to be able to determine the effects of environmental factors at a level more detailed than the object class, Section 15 information will be insufficient. For that purpose, additional and extensive data collection efforts will have to be undertaken, although the desirability of such an effort may be doubtful because wages will totally overshadow any minor expense category.

Recognizing the importance of the maintenance function, ways must be found to improve all of its aspects. Opportunities must be identified, trends should be examined, and policies formulated that will lead to the more efficient and effective use of resources, so that the transit industry can provide dependable and reliable service to the public, while simultaneously achieving operating expense reductions.

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Climatic Effects on Bus Durability

SANDRA L. ARLINGHAUS and JOHN D. NYSTUEN

ABSTRACT

The purpose of this paper is to provide climate peer groups that may be used in combination with any set of Section 15 indicators as a guide to understanding the impact of climate on participating transit authorities. The method of deriving these climate peer groups involves applying three climatic indicators to partition 203 transit authorities into "harsh," "intermediate," and "benign" climate peer groups. The results are mapped and are displayed in tabular form. The simple numerical procedure is checked using elementary linear algebra, and the resulting climate peer groups are again mapped and displayed in tabular form. The hypothesis that bus durability is adversely affected in harsh climates is then tested, using data from Section 15 indicators, to illustrate the method of employing these climate peer groups. Section 15 indicators on "age distribution," "distance between road calls," and "vehicle miles per maintenance dollar," partitioned by climate class, provide support for this hypothesis. Implications resulting from the testing of this hypothesis suggest which climate peer groups might benefit from additional evaluation of their maintenance strategy and which climate peer groups might serve as maintenance models for others.

Cars and buses heavily scarred from rusty sores are a familiar sight to residents of the Great Lakes Basin as well as to those in other regions that experience heavy concentrations of snow and road salt, or heat and airborne salt, near urban surface routes. Other environmental stresses that contribute to the aging of a bus fleet might involve the steepness of the underlying terrain and the density of traffic congestion. Steep grades produce extra strain on the motor and power-train, and frequent stopping and starting wear the brakes, the engine, and the drive train. However, major "surgery" often fixes component breakdowns, via brake transplant or electrical bypass, resulting from the various strains on the visceral bus system. Distintegration of the bus skin, however, is irreparable and often forces vehicle replacement; one response to this problem is to build rust-proof buses of stainless steel that resist corrosion from road and airborne salt. This change in material could extend bus life, thereby presenting transit authorities, in adversely affected climatic regions, with an opportunity to build healthier, more efficient bus fleets.

The major contribution of this work is to derive measures of climatic conditions that can be used in the analysis of several factors related to vehicle performance. This exploits the "Potential Data Applications" suggested in the Fourth Annual Section 15 Report of National Urban Mass Transportation Sta-

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S.L. Arlinghaus, Institute of Mathematical Geography, 1441 Wisteria Drive, Ann Arbor, Mich. 48104. J.D. Nystuen, College of Architecture and Urban Planning, The University of Michigan, Ann Arbor, Mich. 48109.

tistics that "Peer groups could be formed based on mode, fleet size, annual operating expenses, and/or such other factors not contained in this report as climate and collective bargaining agreements. Comparisons can be made to the individual transit systems in the group, or to overall group averages" (1). These climate peer groups are then used to show how an increased understanding of other factors, such as age profile and performance data on bus fleets, might result.

CLIMATE PEER GROUPS

The mechanics of constructing climate peer groups involves incorporating material from climatic atlases into the Section 15 data and using the resulting climatic indicators to sort transit authorities into "harsh," "intermediate," or "benign" climatic peer groups. These peer groups are determined first according to a simple numerical procedure based only on climatic indicators above, below, or equal to a mean value, and are checked with an approach using linear algebra to associate a climate vector with each transit authority. The latter approach also generates a rank-ordering of transit authorities in each climate peer group. It does so using the lengths of climate vectors (vector norms) measured in a coordinate system with the national average as the origin.

Peer Groups Formed by a Simple Numerical Procedure

It is assumed that when road salt is used as an aid in snow removal, it speeds bus body corrosion; it is not assumed that all corrosion is caused by road salt, however, nor is it assumed that all communities employ road salt in snow removal. Thus, the measures that follow include transit authorities in which airborne salt in warm, humid climates promotes corrosion of buses that travel coastal routes, as well as transit authorities in agricultural states that do not use road salt in snow removal. Inclusion of these transit authorities provides a broad spectrum of positions for data points to partition into peer groups on relatively unchanging, purely climatic, bases. Changes in policy, involving decisions to salt, or changes in bus route position, involving nearness to salt water, are more closely spaced in time than are changes in climate. Although these are issues that could be superimposed on the results of this study, they are beyond its scope as they do not contribute, at the fundamental level, to sorting transit authorities by climatic type; it is the typology that is dominant here.

The following climatic indicators will be used to link snow to road salt. First, the "total amount of annual snowfall" is significant as a rough measure of total volume of road salt to which bus bodies are subjected in a single winter. Second, the "mean number of days of one inch or more of snow and sleet" uses frequency of snow events to measure the extent to which bus bodies are exposed to road salt on a continuing basis. Third, the "average number of times per year of an alternation of freezing and thawing" gives a general indication of the number of days that are optimal for applying salt to melt snow and accumulated ice. These factors are assumed to have roughly the same weight in describing winter adversity at the national scale, as suggested by groupings of variables of this sort to describe national climate patterns in climate atlases; however, individual transit authorities may see one factor as more significant than another. Further, these climatic indicators measure trends over time and may thus differ from local weather patterns in any single year. Therefore, individual transit authorities should exercise caution in using current weather statistics. To understand the range of possible weather patterns, it is necessary to supplement current weather observations with a longer view of the climatic history of the region.

Data for the first two climatic indicators is available on a city-by-city basis in the tables of "Normals, Means, and Extremes" in Climates of the States (2). These tables report data only from locations with complete weather stations. Only data from those weather stations in cities with bus systems were included. Cities with bus systems, but not with reporting weather stations, were grouped with the weather station in their climatic zone as shown in maps of "Climatic Zones" in Climates of the States. Data for the third variable come from the maps in Figures 1A, B, and C, which appeared originally in Stephen Visher's Climatic Atlas of the United States (3). To form the isolines in this map, Figure 1A, Visher used the differences found by subtracting "Normal annual number of days with temperature continuously below freezing" (Figure 1B) from "Normal annual number of nights with frost (minimum of 32°F or lower)" (Figure 1C). For example, Detroit, Michigan, has about 135 nights with frost in a year. Of those, about 45 are associated with days where the temperature is already below freezing; on these days, little benefit comes from applying salt to the roads. That leaves 135 - 45 = 90 times per year with frost at night when the day temperature is not continuously below freezing; hence, an alternation occurs across the freeze line. Locations between isolines were assigned the value of the lower of the two isolines. Interpolation was not employed because these climate values generally do not vary linearly between isolines. Numerical values for this climatic indicator range from 0 to 130 days. High values of this Visher index should be expected in alpine areas, due to daily temperature fluctuation. Low values should appear in southern cities, and these values will increase more rapidly away from large bodies of water because the land temperature responds more quickly than does the water temperature to changes in the surrounding air temperature.

The three climatic indicators were calculated for each of 193 cities associated with 203 transit authorities of more than 25 buses that filed Section 15 reports for at least two of the four years under study. The national mean for these indicators, rounded to the nearest integer and expressed as an ordered triple (number of inches of snow per year, number of snow events per year, and number of alternations of freeze-thaw per year), was (23, 7, 50). An ordered triple that represents the climatic indicators for a particular city has entries of positive sign to represent deviation above the mean, of negative sign to represent deviation below the mean, or of 0 to represent no deviation from the mean. The following list classifies the 193 cities according to the signs of their ordered triples. No city received a score of (0, 0, 0), the national mean. Cities in which all three climatic indicators are above the mean are represented by triples with sign (+, +, +). These cities are grouped in the "harsh" climate class in the list (ordered by longitude). Similarly, cities in which all three climatic indicators are below the mean are represented by ordered triples with sign (-, -, -). These are grouped as the "benign" climate class of entries in the list (ordered by longitude). The cities associated with the remaining sign possibilities are grouped in the "intermediate" climate class of the list (ordered by longitude).

Class

Harsh

- Portland, Maine
- Haverhill, Mass.
- Boston, Mass.
- Lowell, Mass.
- Manchester, N.H.
- Worcester, Mass.
- Springfield, Mass.
- Hartford, Conn.
- New Haven, Conn.
- White Plains, N.Y.
- Albany, N.Y.
- Yonkers, N.Y.
- Newark, N.J.
- Utica, N.Y.
- Allentown, Pa.
- Scranton, Pa.
- Kingston, Pa.
- Binghamton, N.Y.
- Syracuse, N.Y.
- Harrisburg, Pa.
- Rochester, N.Y.
- Altoona, Pa.
- Johnstown, Pa.
- Buffalo, N.Y.
- Pittsburgh, Pa.
- Erie, Pa.
- Youngstown, Ohio
- Kent, Ohio
- Canton, Ohio
- Akron, Ohio
- Cleveland, Ohio
- Detroit, Mich.
- Toledo, Ohio
- Saginaw, Mich.
- Ann Arbor, Mich.
- Flint, Mich.
- Bay City, Mich.
- Jackson, Mich.
- Fort Wayne, Ind.
- Kalamazoo, Mich.
- South Bend, Ind.
- Gary, Ind.
- Chicago, Ill.
- Racine, Wis.
- Kenosha, Wis.
- Waukegan, Ill.
- Des Plaines, Ill.
- Milwaukee, Wis.
- Joliet, Ill.
- Elgin, Ill.
- Aurora, Ill.
- Appleton, Wis.
- Oshkosh, Wis.
- Rockford, Ill.
- Madison, Wis.
- Rock Island, Ill.
- Davenport, Iowa
- Dubuque, Iowa
- La Crosse, Wis.
- Cedar Rapids, Iowa
- Duluth, Minn.
- Waterloo, Iowa
- St. Paul, Minn.
- Des Moines, Iowa
- St. Cloud, Minn.
- Sioux City, Iowa
- Lincoln, Nebr.
- Fargo, N.Dak.
- Omaha, Nebr.
- Colorado Springs, Colo.
- Denver, Colo.
- Salt Lake City, Utah
- Spokane, Wash.

Benign

- Norfolk, Va.
- Hampton, Va.
- Raleigh, N.C.
- Fayetteville, N.C.
- West Palm Beach, Fla.
- Fort Lauderdale, Fla.
- Miami, Fla.
- South Daytona, Fla.
- Savannah, Ga.
- Orlando, Fla.
- Jacksonville, Fla.
- Augusta, Ga.
- Gainesville, Fla.
- Tampa, Fla.
- St. Petersburg, Fla.
- Bradenton, Fla.
- Clearwater, Fla.
- Tallahassee, Fla.
- Columbus, Ga.
- Montgomery, Ala.
- Pensacola, Fla.
- Mobile, Ala.
- Harahan, La.
- Gretna, La.
- New Orleans, La.
- Jackson, Miss.
- Baton Rouge, La.
- Shreveport, La.
- Houston, Tex.
- Dallas, Tex.
- San Antonio, Tex.
- Fort Worth, Tex.
- Corpus Christi, Tex.
- Austin, Tex.
- Laredo, Tex.
- El Paso, Tex.
- Tucson, Ariz.
- Phoenix, Ariz.
- San Diego, Calif.
- San Bernardino, Calif.
- Riverside, Calif.
- Oceanside, Calif.
- Garden Grove, Calif.
- Norwalk, Calif.
- Montebello, Calif.
- Long Beach, Calif.
- Los Angeles, Calif.
- Santa Monica, Calif.
- Gardena, Calif.
- Torrance, Calif.
- Bakersfield, Calif.
- Ventura, Calif.
- Santa Barbara, Calif.
- Fresno, Calif.
- Stockton, Calif.
- Sacramento, Calif.
- Monterey, Calif.
- San Jose, Calif.
- Santa Cruz, Calif.
- Oakland, Calif.
- Seattle, Wash.
- San Mateo, Calif.
- San Francisco, Calif.
- Tacoma, Wash.
- Salem, Oreg.
- Eugene, Oreg.
- Portland, Oreg.

Intermediate

- Class (-, -, +)
  - Philadelphia, Pa.
  - Wilmington, Del.
  - Lancaster, Pa.
  - Washington, D.C.
  - Lynchburg, Va.
  - Columbus, Ohio

Knoxville, Tenn.
Chattanooga, Tenn.
Kansas City, Mo.
Topeka, Kans.
Tulsa, Okla.
Wichita, Kans.
Oklahoma City, Okla.
Amarillo, Tex.
Lubbock, Tex.
Albuquerque, N.M.

Class (-, -, 0)
Richmond, Va.
Winston-Salem, N.C.
Charlotte, N.C.
Dayton, Ohio
Atlanta, Ga.
Cincinnati, Ohio
Newport, Ky.
Lexington, Ky.
Nashville, Tenn.
Birmingham, Ala.
Memphis, Tenn.
St. Louis, Mo.
Little Rock, Ark.

Class (+, +, 0)
New Bedford, Mass.
Brockton, Mass.
Providence, R.I.
Flushing, N.Y.
Jamaica, N.Y.
Jackson Heights, N.Y.
New York, N.Y.
East Meadow, N.Y.
Brooklyn, N.Y.
West Coxsackie, N.Y.
Louisville, Ky.

Class (-, 0, 0)
Indianapolis, Ind.
Urbana, Ill.
Decatur, Ill.
Peoria, Ill.
Springfield, Ill.

Class (+, -, +)
Bridgeport, Conn.
Stamford, Conn.
Asheville, N.C.

Class (-, 0, +)
Huntington, W.Va.
Charleston, W.Va.

Class (0, -, +)
Baltimore, Md.

Class (+, 0, +)
Roanoke, Va.

Class (-, +, +)
Boise, Idaho

Note that some cities may have more than one transit authority associated with them. Also note that the cities with the harshest climates are as follows (ordered by longitude): Portland, Maine; Manchester, New Hampshire; Springfield, Massachusetts; Albany, Utica, Binghamton, Syracuse, Rochester, and Buffalo, New York; Erie, Pennsylvania; Duluth, Minnesota; Colorado Springs and Denver, Colorado; Salt Lake City, Utah; and Spokane, Washington. The cities whose climate was closest to the average were as follows (ordered by longitude): Indianapolis, Indiana; Urbana, Peoria, Springfield, and Decatur, Illinois; Baltimore, Maryland; and Charleston and Huntington, West Virginia.

Figure 1 partitions the continental United States into harsh, benign, and intermediate climate peer groups of transit authorities. Peer group boundaries were drawn to separate transit authorities in, or near, cities of harsh climate (see the preceding list) from transit authorities in, or near, cities of intermediate climate (see the preceding list). The latter were separated, in turn, from transit authorities in, or near, cities of benign climate (see the preceding list). As is evident from the underlying scatter of dots in Figure 2, the accuracy with which these climate peer group boundaries were placed is greater in the east than in the west. In much of the western mountainous region, the boundary follows topographic features such as mountain ranges and river basins. Because the climatic indicators that formed the basis for delineating climate peer groups were chosen for their capability to link road salt to snow, Figure 2 also shows the position of the Salina Basin, a major subsurface rock salt deposit near many of the transit authorities in the Great Lakes portion of the harsh climate peer group.

The Distribution of Climate Vectors

The three climate peer groups shown in Figure 2 exhibit a great deal of variation within each group; this section shows how to determine the peers most closely related, in both climate and geographic position, to an arbitrarily chosen transit authority. The map in Figure 3 displays the grid generally employed for the polar case of an azimuthal equidistant map projection (on which distances measured from the center are true). In maps of this sort, the radials generally represent longitude and the arcs represent latitude. Because latitude and climate are related, climate is substituted for latitude; the column "climate vector norms" in Table 1 gives single climate values, based on all three climatic indicators, used in place of latitude in the map of Figure 3. Then, dots on that map that are close have both climate and longitude (geographic position) that are close. Hence, the nearest neighbors within a semi-circular band of a given point are its geographically proximate climate peers. Table 2 gives the names of each transit authority represented in Figure 2 and its nearest climate peers. For example, there is no transit authority with winters as severe as those in Duluth, Minnesota, nearer than Springfield, Massachusetts, on the east, or than Denver, Colorado, on the west. Thus, Springfield and Denver are Duluth's geographically nearest climate peers.

The detail of constructing this map and these tables rests in viewing the ordered triples of climate indicators as vectors in three-dimensional space. The components of the vectors are numerical measures of different ranges, but are of equal weight in describing severity of winter (as previously explained). Thus, to compare vectors, adjustment is required of the set of values over which individual components may range. A variety of strategies is available for this purpose, and each could lead to the means for determining climate peer groups based on the climate vectors associated with individual transit authorities.

Suppose that the ordered triples are referenced to three mutually orthogonal axes. The x-axis measures the number of inches of snow, and values along it range from -23 in. below to 86 in. above the national mean; the y-axis measures the number of events, and values on it range from -7 events below to 25 events above the national mean, and the z-axis measures the Visher index, and values on it range from -50 alternations below to 80 alternations above the national mean. The origin (0, 0, 0) represents the national mean. To standardize the units, any arbitrary scale, including those already on the axes, might have been used. Because the Visher scale has the finest mesh of the three scales already present, the authors chose, for ease in matching units, to convert each of the scales on the x and y axes to

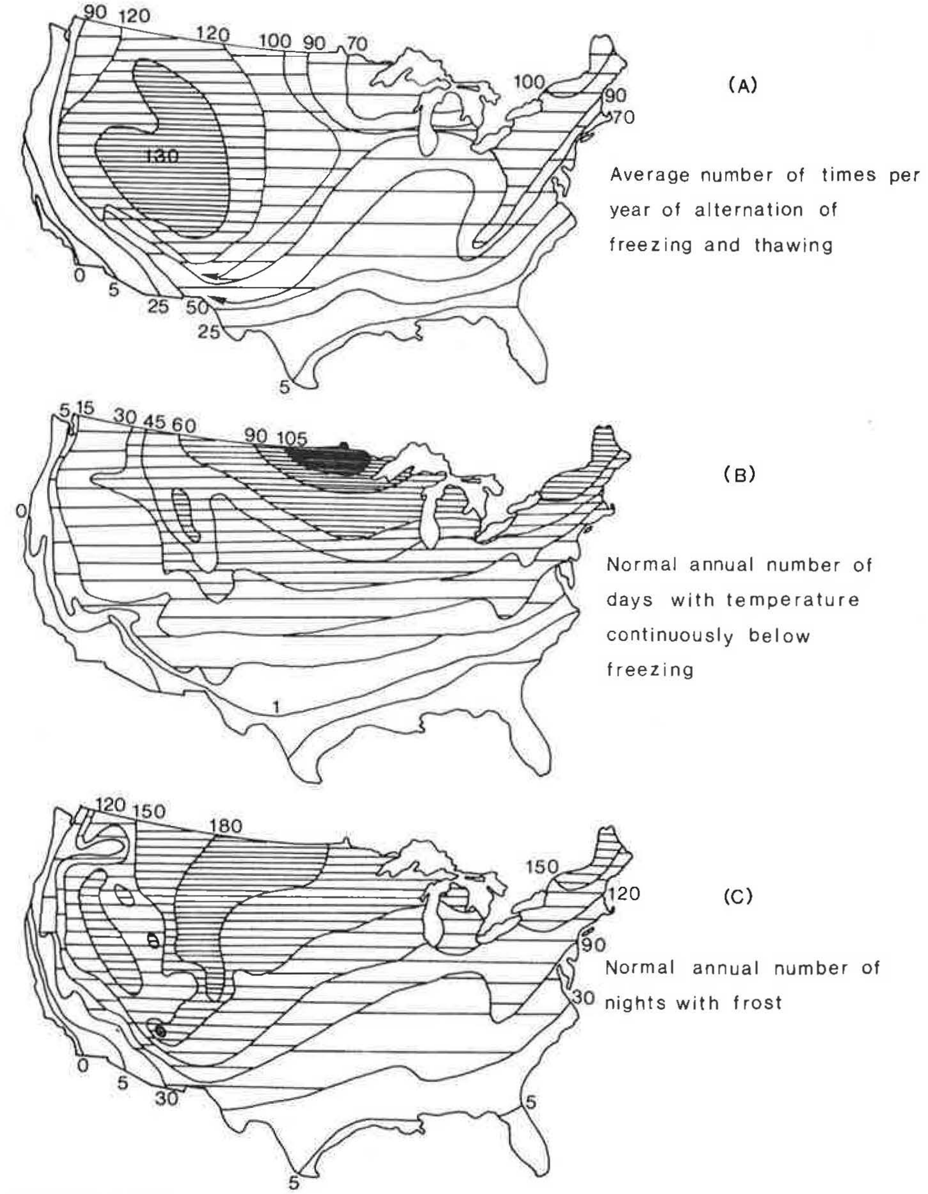

FIGURE 1 Visher maps.

the 130-part Visher scale of the z-axis. Thus, the unit vector on the x-axis becomes (1.1926606, 0, 0) because x/130 = 1/109; the unit vector on the y-axis stretches to (0, 4.0625, 0) because y/130 = 1/32; and the unit vector on the z-axis remains fixed. Then, a climate vector may be associated with each transit authority by multiplying the number of inches of snow for that authority by 1.1926606, and the number of events by 4.0625. Table 1 gives the lengths (norms) of the climate vectors measured from (0, 0, 0) for each transit authority for which both climatic and Section 15 data were available.

Figure 3 employs an azimuthal equidistant projection centered at the national mean of (0, 0, 0) to show, using climate vectors, how much each transit authority lies above or below the average vector of (0, 0, 0). On this projection, distances measured from the center are true. The horizontal line, as a base line in Figure 3, represents a meridian of 65 degrees west longitude to the right of the map center and a meridian of 125 degrees west longitude to the left of the map center. These choices of longitude correspond roughly to the east-west longitudinal extremes in the United States. The meridians that interrupt the projection, at 69 degrees and 118 degrees in the above average zone, and at 75 degrees and 124 degrees in the below average zone, show more precise positions for the transit authorities that are farthest east and west in each of the above and below average zones (i.e., Portland, Maine, and Spokane, Washington, in the above average zone, and Norfolk, Virginia, and Portland, Oregon, in the below average zone). A set of five evenly spaced lines concurrent with the base line at (0, 0, 0) partitions the map into wedges. These radials are assigned values of 75, 85, 95, 105, and 115 to represent longitude, and are followed by a "+" symbol when they lie above the origin and by a "-" symbol when they lie below it. The evenly spaced set of concentric circles, which might generally suggest latitude on a projection of this sort, represents instead the length of the climate vector--the interval measuring the spacing is 10 units of climate vector length. Climate vectors all have positive length measured from the map center. Vector heads associated with triples containing only positive or zero entries

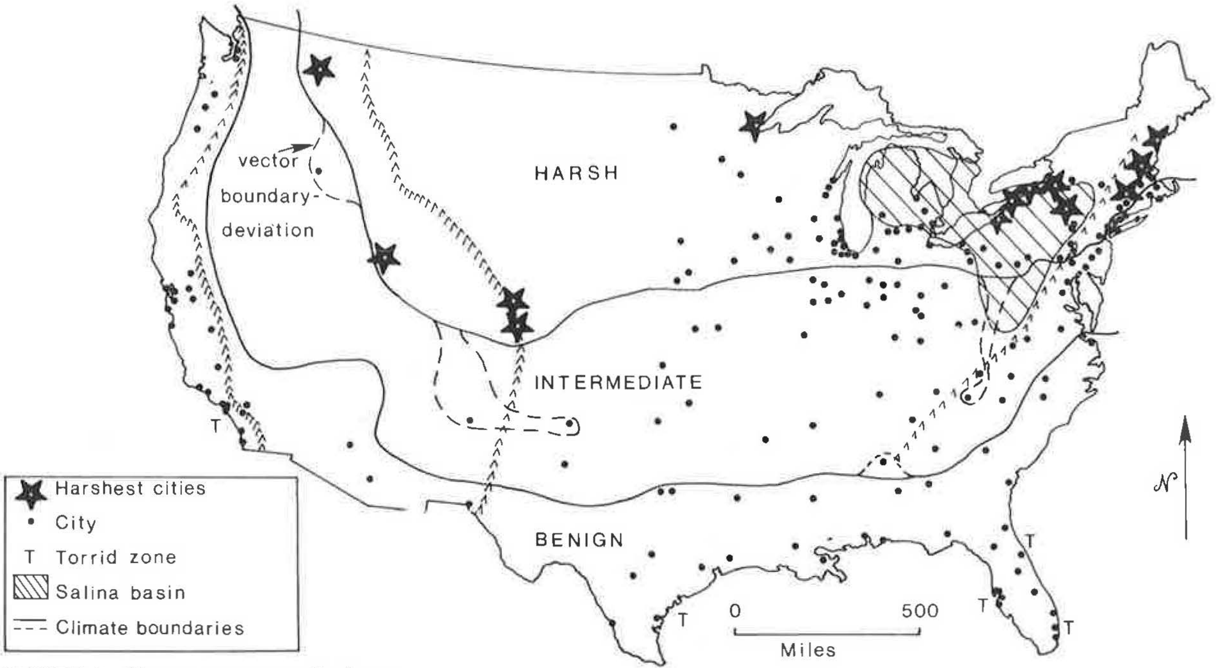

FIGURE 2 Climate peer groups for buses.

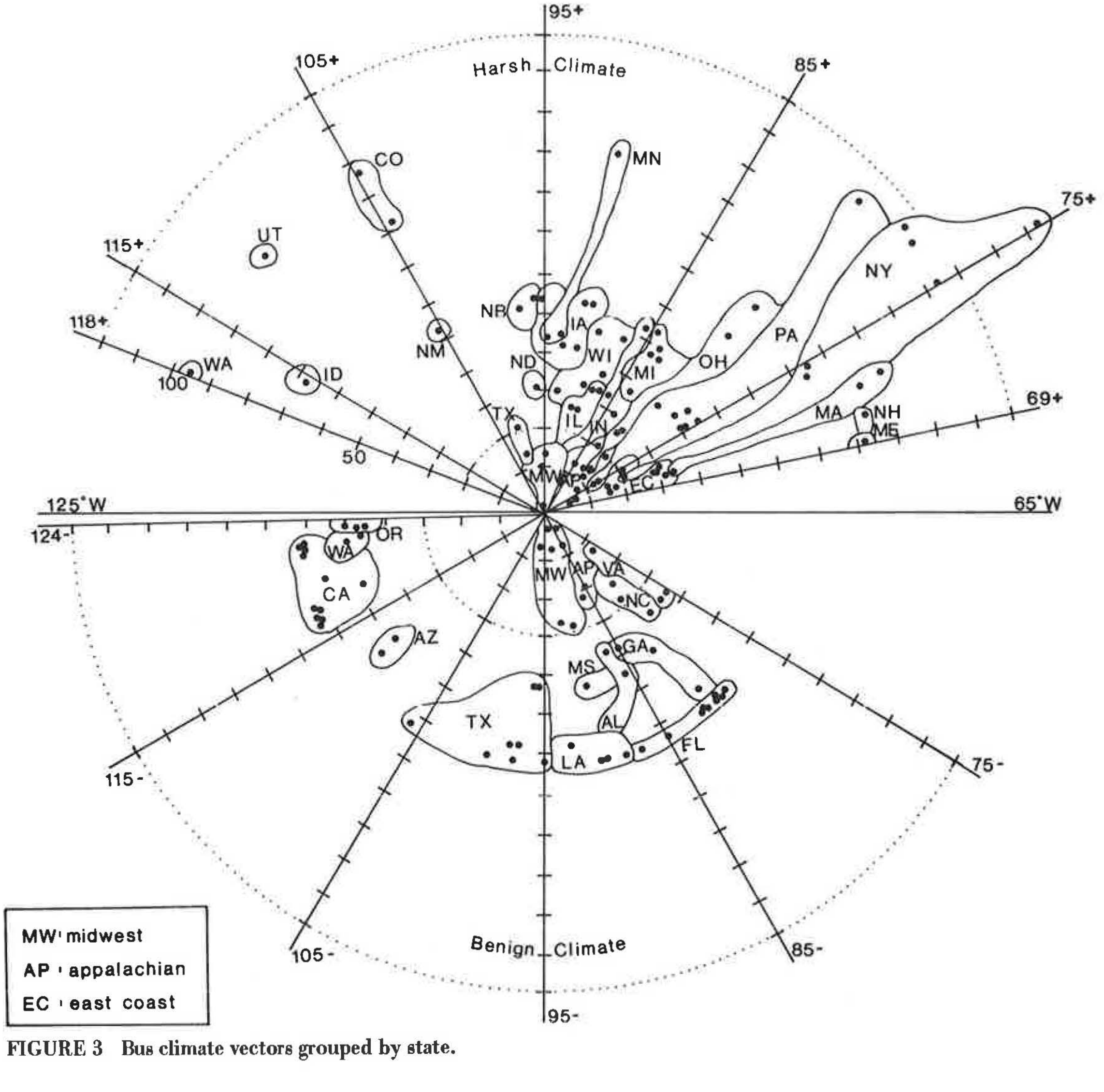

FIGURE 3 Bus climate vectors grouped by state.

TABLE 1 Climate Vector Norms of Cities Arranged by Climate Peer Group[a]

Harsh Climate	Norm	Longitude (degrees and minutes)	Benign Climate	Norm	Longitude (degrees and minutes)	Intermediate Climate	Norm	Longitude (degrees and minutes)
Portland, Maine	82.4	70 16	Norfolk, Va.	37.4	76 15	Philadelphia, Pa.	15.7 ↑	75 13
Haverhill, Mass.	33.6	71 05	Hampton, Va.	37.4	76 21	Wilmington, Del.	9.9 ↑	75 33
Boston, Mass.	33.6	71 07	Raleigh, N.C.	37.4	78 39	Lancaster, Pa.	15.7 ↑	76 20
Lowell, Mass.	33.6	71 18	Fayetteville, N.C.	37.4	78 54	Washington, D.C.	9.9 ↑	77 00
Manchester, N.H.	85.3	71 30	West Palm Beach, Fla.	63.7	80 04	Lynchburg, Va.	13.7 ↑	79 08
Worcester, Mass.	85.1	71 49	Fort Lauderdale, Fla.	63.7	80 09	Columbus, Ohio	15.7 ↑	83 00
Springfield, Mass.	91.9	72 35	Miami, Fla.	63.7	80 11	Knoxville, Tenn.	3.3 ↓	83 55
Hartford, Conn.	31.0	72 40	South Daytona, Fla.	63.7	81 02	Chattanooga, Tenn.	1.9 ↓	85 15
New Haven, Conn.	31.0	72 55	Savannah, Ga.	60.0	81 07	Kansas City, Mo.	14.5 ↑	94 35
White Plains, N.Y.	22.0	73 47	Orlando, Fla.	63.7	81 22	Topeka, Kans.	12.7 ↑	95 41
Albany, N.Y.	74.6	73 50	Jacksonville, Fla.	63.7	81 40	Tulsa, Okla.	0.3 ↓	95 58
Yonkers, N.Y.	22.0	73 54	Augusta, Ga.	46.0	82 00	Wichita, Kans.	7.1 ↓	97 21
Newark, N.J.	22.0	74 10	Gainesville, Fla.	63.7	82 20	Oklahoma City, Okla.	3.3 ↑	97 32
Utica, N.Y.	74.7	75 10	Tampa, Fla.	63.7	82 25	Amarillo, Tex.	23.0 ↑	101 49
Allentown, Pa.	42.9	75 30	Bradenton, Fla.	63.7	82 35	Lubbock, Tex.	16.7 ↑	101 50
Scranton, Pa.	60.0	75 45	Saint Petersburg, Fla.	63.7	82 38	Albuquerque, N.Mex.	50.3 ↑	106 40
Kingston, Pa.	42.9	75 50	Clearwater, Fla.	63.7	82 45	Richmond, Va.	15.5	77 30
Binghamton, N.Y.	113.8	75 55	Tallahassee, Fla.	63.7	84 17	Winston-Salem, N.C.	26.3	80 15
Syracuse, N.Y.	149.9	76 10	Columbus, Ga.	39.5	84 56	Charlotte, N.C.	29.6	80 50
Harrisburg, Pa.	45.0	76 50	Montgomery, Ala.	46.0	86 17	Dayton, Ohio	4.8	84 15
Rochester, N.Y.	114.1	77 35	Pensacola, Fla.	63.7	87 13	Atlanta, Ga.	21.8	84 23
Altoona, Pa.	45.0	78 25	Mobile, Ala.	63.7	88 03	Cincinnati, Ohio	8.3	84 30
Johnstown, Pa.	42.0	78 50	Harahan, La.	63.7	90 00	Newport, Ky.	8.3	84 30
Buffalo, N.Y.	116.5	78 51	Gretna, La.	63.7	90 00	Lexington, Ky.	6.3	84 30
Pittsburgh, Pa.	41.9	80 01	New Orleans, La.	63.7	90 05	Nashville, Tenn.	24.2	86 48
Erie, Pa.	111.9	80 05	Jackson, Miss.	45.3	90 10	Birmingham, Ala.	38.0	86 49
Youngstown, Ohio	64.3	80 40	Baton Rouge, La.	63.7	91 10	Memphis, Tenn.	29.6	90 03
Kent, Ohio	28.1	81 20	Shreveport, La.	60.0	93 46	St. Louis, Mo.	8.3	90 15
Canton, Ohio	28.1	81 25	Houston, Tex.	63.7	95 21	Little Rock, Ark.	28.7	92 16
Akron, Ohio	28.1	81 30	Dallas, Tex.	43.0	96 48	New Bedford, Mass.	17.0	70 55
Cleveland, Ohio	75.3	81 42	San Antonio, Tex.	59.9	97 08	Brockton, Mass.	17.0	71 01
Detroit, Mich.	49.6	83 10	Fort Worth, Tex.	42.3	97 20	Providence, R.I.	17.0	71 23
Toledo, Ohio	31.0	83 35	Corpus Christi, Tex.	63.7	97 24	Flushing, N.Y.	8.3	73 50
Saginaw, Mich.	38.2	83 40	Austin, Tex.	59.3	97 42	Jamaica, N.Y.	8.3	73 50
Ann Arbor, Mich.	49.6	83 45	Laredo, Tex.	63.7	99 29	Jackson Heights, N.Y.	8.3	73 50
Flint, Mich.	51.6	83 45	El Paso, Tex.	63.7	106 27	New York, N.Y.	6.3	73 58
Bay City, Mich.	38.2	83 55	Tucson, Ariz.	56.9	111 00	East Meadow, N.Y.	6.3	73 58
Jackson, Mich.	55.6	84 25	Phoenix, Ariz.	50.7	112 00	Brooklyn, N.Y.	6.3	73 58
Fort Wayne, Ind.	22.7	85 10	San Diego, Calif.	63.7	117 10	West Coxsackie, N.Y.	6.3	73 58
Kalamazoo, Mich.	43.5	85 40	San Bernardino, Calif.	63.7	117 19	Louisville, Ky.	17.0	85 45
South Bend, Ind.	53.4	86 20	Riverside, Calif.	63.7	117 21	Indianapolis, Ind.	6.0	86 08
Gary, Ind.	33.7	87 21	Oceanside, Calif.	63.7	117 22	Urbana, Ill.	1.0	88 15
Chicago, Ill.	33.7	87 37	Garden Grove, Calif.	63.7	117 56	Decatur, Ill.	2.0	88 59
Racine, Wis.	48.8	87 49	Norwalk, Calif.	63.7	118 05	Peoria, Ill.	1.0	89 35
Kenosha, Wis.	48.8	87 50	Montebello, Calif.	63.7	118 06	Springfield, Ill.	2.0	89 37
Waukegan, Ill.	33.7	87 51	Long Beach, Calif.	63.7	118 12	Bridgeport, Conn.	16.5 ↑	73 12
Des Plaines, Ill.	33.7	87 54	Los Angeles, Calif.	63.7	118 15	Stamford, Conn.	16.5 ↑	73 32
Milwaukee, Wis.	48.8	87 55	Santa Monica, Calif.	63.7	118 19	Asheville, N.C.	15.9 ↑	82 35
Joliet, Ill.	33.7	88 05	Gardena, Calif.	63.7	118 19	Charleston, W.Va.	12.8 ↑	81 35
Elgin, Ill.	28.4	88 16	Torrance, Calif.	63.7	118 20	Huntington, W.Va.	12.8 ↑	82 25
Aurora, Ill.	28.4	88 18	Bakersfield, Calif.	59.9	119 00	Baltimore, Md.	15.9 ↑	76 38
Appleton, Wis.	32.0	88 27	Ventura, Calif.	63.7	119 18	Roanoke, Va.	20.3	79 55
Oshkosh, Wis.	32.0	88 35	Santa Barbara, Calif.	63.7	119 43	Boise, Idaho	67.7 ↑	116 12
Rockford, Ill.	28.4	89 07	Fresno, Calif.	59.9	119 47			
Madison, Wis.	48.3	89 23	Stockton, Calif.	63.7	121 16			
Rock Island, Ill.	28.0	90 37	Sacramento, Calif.	50.7	121 30			
Davenport, Iowa	28.0	90 38	Monterey, Calif.	63.7	121 53			
Dubuque, Iowa	54.1	90 43	San Jose, Calif.	63.7	121 54			
La Crosse, Wis.	33.6	91 14	Santa Cruz, Calif.	63.7	122 02			
Cedar Rapids, Iowa	54.1	91 43	Oakland, Calif.	63.7	122 16			
Duluth, Minn.	91.7	92 07	Seattle, Wash.	51.1	122 20			
Waterloo, Iowa	41.9	92 22	San Mateo, Calif.	63.7	122 20			
St. Paul, Minn.	43.5	93 05	San Francisco, Calif.	63.7	122 21			
Des Moines, Iowa	44.8	93 37	Tacoma, Wash.	47.0	122 27			
St. Cloud, Minn.	43.5	94 08	Salem, Oreg.	53.4	123 03			
Sioux City, Iowa	53.7	96 25	Eugene, Oreg.	51.1	123 06			
Lincoln, Nebr.	54.2	96 43	Portland, Oreg.	50.7	123 41			
Fargo, N.Dak.	31.9	96 48						
Omaha, Nebr.	52.3	97 57						
Colorado Springs, Colo.	83.6	104 48						
Denver, Colo.	97.4	104 59						
Salt Lake City, Utah	96.2	111 52						
Spokane, Wash.	95.0	117 25						

[a] Arrows indicate "above" (↑) or "below" (↓) average norm.

were placed at an appropriate distance in the above average zone, and those with only negative or zero entries were located in the below average zone. The distance $\|V\|$ of a vector $V = (p, q, r)$ from the origin $(0, 0, 0)$ is computed as $\|V\| = (p^2 + q^2 + r^2)^{1/2}$ (4). However, vectors with both positive and negative entries could be misplaced using this norm. For example, a high positive Visher value coupled with negative indices far below zero on "frequency of storm" and "total snowfall amount" would represent a city with a norm larger than seems reasonable.

The degree of exaggeration depends directly on

TABLE 2 Vector Rank-Ordering of Transit Authorities Within Climate Peer Groups[a]

Norm	Cities
100+	Binghamton, N.Y.; Syracuse, N.Y.; Rochester, N.Y.; Buffalo, N.Y.; Erie, Pa.
90–99.9	Springfield, Mass.; Duluth, Minn.; Denver, Colo.; Salt Lake City, Utah; Spokane, Wash.
80–89.9	Portland, Maine; Manchester, N.H.; Worcester, Mass.; Colorado Springs, Colo.
70–79.9	Albany, N.Y.; Utica, N.Y.; Cleveland, Ohio
60–69.9	Scranton, Pa.; Youngstown, Ohio; Boise, Idaho
50–59.9	Flint, Mich.; Jackson, Mich.; Kalamazoo, Mich.; Dubuque, Iowa; Waterloo, Iowa; Sioux City, Iowa; Lincoln, Nebr.; Omaha, Nebr.; Albuquerque, N.Mex.
40–49.9	Allentown, Pa.; Kingston, Pa.; Altoona, Pa.; Johnstown, Pa.; Pittsburgh, Pa.; Detroit, Mich.; Ann Arbor, Mich.; Milwaukee, Wis.; Madison, Wis.; St. Paul, Minn.; Des Moines, Iowa; St. Cloud, Minn.
30–39.9	Boston, Mass.; Hartford, Conn.; New Haven, Conn.; Toledo, Ohio; Chicago, Ill.; Appleton, Wis.; La Crosse, Wis.; Fargo, N.Dak.
20–29.9	White Plains, N.Y.; Yonkers, N.Y.; Roanoke, Va.; Kent, Ohio; Canton, Ohio; Akron, Ohio; Fort Wayne, Ind.; Rock Island, Ill.; Davenport, Iowa; Amarillo, Tex.
10–19.9	New Bedford, Mass.; Brockton, Mass.; Providence, R.I.; Bridgeport, Conn.; Stamford, Conn.; Philadelphia, Pa.; Lancaster, Pa.; Baltimore, Md.; Lynchburg, Va.; Asheville, N.C.; Charleston, W.Va.; Huntington, W.Va.; Columbus, Ohio; Louisville, Ky.; Topeka, Kans.; Kansas City, Mo.; Lubbock, Tex.
0–9.9	New York City and suburbs; Wilmington, Del.; Washington, D.C.; Oklahoma City, Okla.
(–10)–(–0.1)	Knoxville, Tenn.; Cincinnati, Ohio; Newport, R.I.; Lexington, Ky.; Dayton, Ohio; Chattanooga, Tenn.; Indianapolis, Ind.; Urbana, Ill.; Decatur, Ill.; Peoria, Ill.; Springfield, Ill.; St. Louis, Mo.; Tulsa, Okla.; Wichita, Kans.
(–20)–(–10.1)	Richmond, Va.
(–30)–(–20.1)	Winston-Salem, N.C.; Charlotte, N.C.; Atlanta, Ga.; Nashville, Tenn.; Memphis, Tenn.; Little Rock, Ark.
(–40)–(–30.1)	Norfolk, Va.; Hampton, Va.; Raleigh, N.C.; Fayetteville, N.C.; Birmingham, Ala.; Columbus, Ga.
(–50)–(–40.1)	Augusta, Ga.; Montgomery, Ala.; Jackson, Miss.; Dallas, Tex.; Fort Worth, Tex.; Tacoma, Wash.
(–60)–(–50.1)	Savannah, Ga.; Shreveport, La.; San Antonio, Tex.; Austin, Tex.; Tucson, Ariz.; Phoenix, Ariz.; Bakersfield, Calif.; Fresno, Calif.; Sacramento, Calif.; Seattle, Wash.; Salem, Oreg.; Eugene, Oreg.; Portland, Oreg.
below (–60)	All of Florida; New Orleans, La.; Baton Rouge, La.; Houston, Tex.; Corpus Christi, Tex.; Laredo, Tex.; El Paso, Tex.; Los Angeles, Calif. and suburbs; San Francisco, Calif. and suburbs

[a] Transit authorities are listed by semicircular bands from Figure 3 and ordered from east to west within a semicircular band.

the size of the spread between positive and negative values; frequent freezing and thawing may be irrelevant if there is no snow, and will be if there is no rain. To overcome this, we computed the distance from the origin $\|w\|$ of a vector $w = (-s, -t, u)$, $s, t, u > 0$, as $\|w\| = |(s^2 + t^2)^{1/2} - (u^2)^{1/2}|$; this procedure reduced the distortion in the norm of "mixed" vectors by preserving the difference in sign between entries of opposite sign. Corresponding calculations were used for $w = (-s, t, -u)$, $w = (s, t, -u)$, and for all of the other possibilities. The vector head of a mixed vector was placed in the above average zone of Figure 3 if the difference inside the absolute value sign was positive, and in the below average zone if that difference was negative. Entries in Table 1 that are followed by arrows suggesting "above" or "below" in the column displaying climate vector length, represent positions for "mixed" vectors that are not classified in the natural manner.

Thus, Figure 3 shows the entries in Table 1 positioned by longitude and by climate vector norm. Grouping these vector heads by state produces a political subdivision of the United States based on climate and longitude. In this map, distortion of the state boundaries away from the standard subdivision, based on latitude and longitude, is due entirely to climatic effects. For example, Washington is fragmented into two parts: coastal Washington, with a mild climate, lying between 115- and 125 degrees west in the below average zone, and mountainous Washington, with a harsh climate, lying between 115+ and 125 degrees west in the above average zone. In a similar manner, cities in Ohio south of Columbus lie below the center between 75- and 85-, and lie in the region labeled MW in Figure 3, while those in northern Ohio fall above the center between 75+ and 85+. The elongation away from the map center between 75+ and 85+ represents the presence of lake effect snow in Cleveland and Youngstown. Indiana is fragmented in the same way as Ohio, with Indianapolis, Muncie, and others south of the map center, Fort Wayne above the map center, and elongation away from the center out to South Bend. Further, southern Pennsylvania cities near the coast (e.g., Philadelphia and Lancaster) have vector heads lying just above the map center although those in mountainous Pennsylvania lie away from it. Again, this boundary stretches out from the center to pick up lake effect snows in Erie. Finally, New York exhibits the most extreme form of this sort of climatic distortion; a coastal section above, but close to, the map center includes New York City and suburbs, and an upstate section, which contains a number of lake effect cities, exhibits climatic indices for buses that are in the harshest climates in the nation.

What this suggests, of course, is that a transit manager in a given city should not necessarily look to another in his own state for a climatic peer; Erie is better advised to examine the climatic problems of Buffalo or Rochester than those of Philadelphia. Thus, the semicircular bands in the above the below average zones of Figure 3 suggest rank ordering for transit authorities within climate peer groups (Table 2). Extremes in the longitudinal spacing within such bands show nearest and remotest peer, and it is on account of this that entries in Tables 1 and 2 are ordered by longitude.

Based on this more technically precise vector approach, Figure 3 and Tables 1 and 2 were used to generate vector boundaries separating harsh, intermediate, and benign climate peer groups. To find these boundaries, note that in Figure 3, cities that are close to the center (whether above or below the center) have a climate vector length close to the national mean. Consequently, the transit authorities associated with these vectors lie in an intermediate climate. One place to separate the intermediate positions from the harsh positions in the above average zone, that appeared to be reasonable in terms of the climatic data, was along the semicircle 20 units from the center. In the below average zone, the semicircle 30 units below the center appeared to be a natural choice. When these vector boundaries were superimposed on the map in Figure 2, they were coincident with the simple boundaries, determined in the first part of this paper, in all but five locations.

In particular, Boise, Roanoke, Albuquerque, and Amarillo belonged in the intermediate climate peer group according to the simple partition, but shifted to the harsh climate peer group in the vector partition. At the other extreme, Birmingham was classified as intermediate initially but as benign in the vector approach (Figure 2). The content of the climate vectors suggests reasons for these transit authorities to be climatic "boundary dwellers" (5). In all cases, the Visher index had by far the greatest numerical value, often because of the presence of mountains, suggesting that in a rain- or snowstorm, the frequent freezing and thawing might cause difficulties for buses. Thus, in mild winters, these cities might be classified in the more benign of the two peer groups because there would be little need for salt (although in severe winters, the more frequent use of salt would push them into the harsher of the two peer groups). Cities in this position certainly appear to have the potential for a significant problem that may arise only every few years. The indices associated with Birmingham show it to have the slightest such potential and those linked to Boise indicate that it has the greatest. Other than these boundary dwellers, the harsh, intermediate, and benign climate peer groups that were formed using the simple procedure correspond identically to those generated by the vector approach. Thus, the vector approach serves not only to pinpoint nearest climate peers but also to verify the more broadly based scheme displayed in Figure 2, within which the next consideration is of other factors such as age profiles and performance.

AGE STRUCTURE BY CLIMATE PEER GROUP OF THE U.S. BUS POPULATION

The application of these climate peer groups to the Section 15 indicator, "Age Distribution of Revenue Vehicle Inventory," produces evidence to support the hypothesis that harsh climates speed bus deterioration. The "Stratification Charts by Climate Peer Group" of Figure 4 show the expected, versus the actual, annual and aggregate age stratification of the bus population by climate peer group. For example, in 1978-1979, 35.8 percent of all buses were in transit authorities in a harsh environment; thus, one would expect that 35.8 percent of 0- to 5-year-old buses, 35.8 percent of 6- to 10-year-old buses, 35.8 percent of 11- to 15-year-old buses, and so forth, would lie in the harsh class in 1978-1979. The position of the horizontal line in Figure 4A represents this expected value. In fact, however, this harsh class contained 38.7 percent of 0-5 year olds, 34.7 percent of 6-10 year olds, 36.8 percent of the 11-15 year olds, 29.8 percent of the 16-20 year olds, 23.0 percent of the 21-25 year olds, and 21.3 percent of the 25+ group (Figure 4A.i). The remaining frames in Figure 4 display similar breakdowns of data on bus age across climate peer groups; frames ii, iii, and iv (Figure 4) show age stratification in the harsh class for the remaining 3 years while frame 4A.v displays the aggregate of frames

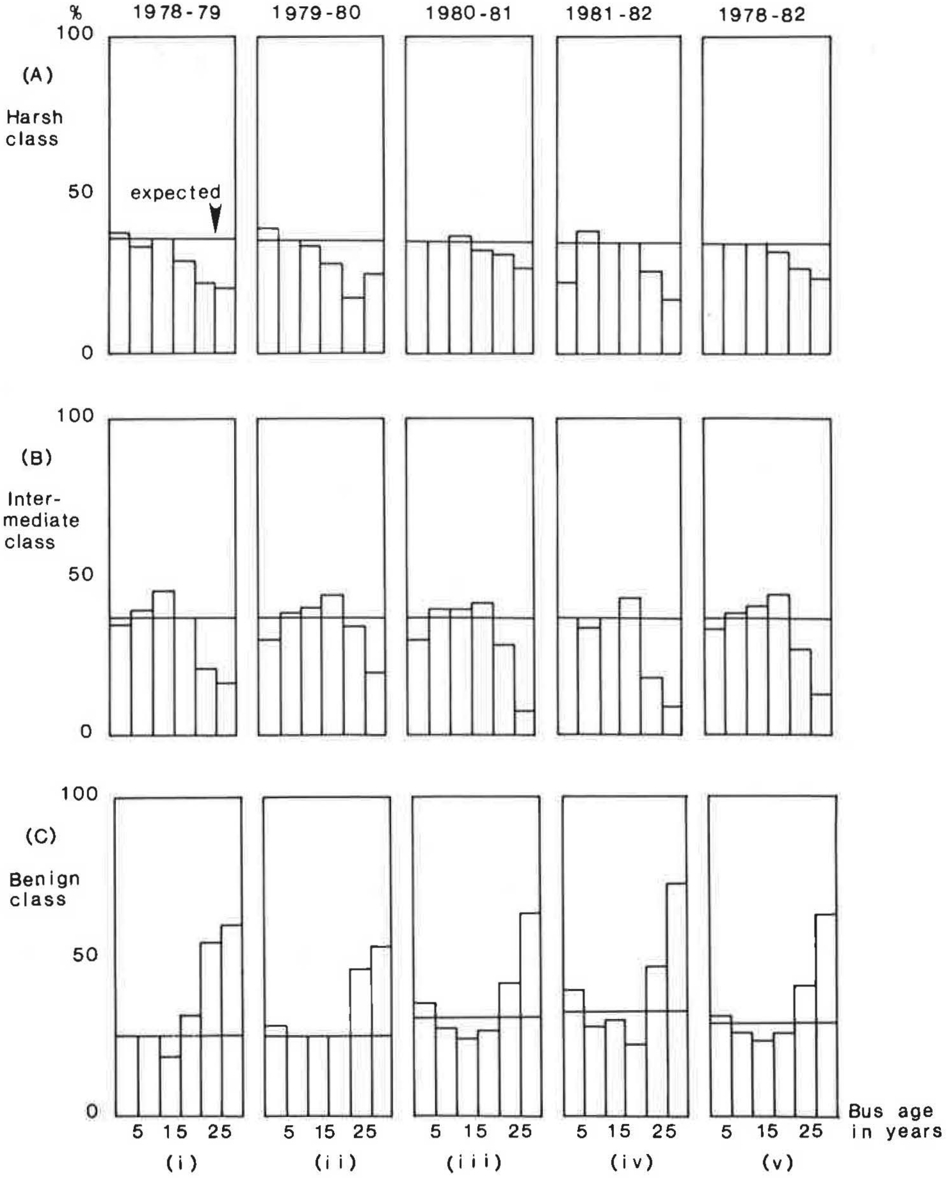

FIGURE 4 Time-series and aggregate stratification charts by climate peer group.

i-iv. Figure 4B shows five frames depicting, in chronological sequence, the annual and aggregate age stratification of the bus population in the intermediate climate peer groups and Figure 4C represents the same sequence for the benign climate peer group.

Of particular note is the distribution of the oldest buses across these peer groups. The harsh group has 23.8 percent of the oldest buses, rather than the expected 34.8 percent (Figure 4A.v); the intermediate group has 12.4 percent rather than the expected 38.1 percent (Figure 4B.v); and the benign group has 63.8 percent rather than the expected 28.9 percent (Figure 4C.v). The fact that the intermediate peer group has a smaller percentage of old buses than does even the harsh peer group, might suggest the (a) lack of expenditure in maintaining intermediate-climate buses, or (b) small size of many transit authorities in this peer group 20 to 30 years ago. The benign climates have far more than their share of old buses; the authors suspect that the graphic distinctions already evident in Figure 3 might become even more apparent if buses could be identified and eliminated subject to airborne salt in warm, humid climates. Figure 4C also shows bus fleets growing through time in sun-belt cities through the rise in the left-hand (0-5) column across the series of figures. As these recently enlarged fleets age, it will be significant, in evaluating climatic effects on bus durability, to see if the trend continues toward high percentages of old buses in benign climates.

MAINTENANCE INDICATORS IN CLIMATE PEER GROUPS

Figure 4 serves to show differences in age profiles between climate peer groups; reasons for these differences might be related to climate, but might be related to other factors as well, such as tightness of maintenance budget. In establishing climate peer groups, size of transit authority was deemed unimportant; general climatic patterns are not a function of number of buses, and climate, unlike maintenance budgets, varies continuously across the map. Thus with maintenance data, economies of scale and increased labor costs in large cities forced partitioning of maintenance indicators by size within each climate peer group. We looked at the maintenance indicators, "vehicle miles per road call" and "total vehicle miles per dollar spent on maintenance." The former indicator appeared less reliable than the latter, on an annual basis, because any single transit authority might have a cluster of road calls toward the end of one year followed by few in the next year. Many entries were missing, especially in the first year, but were filled in, where possible, for "distance between road calls," using data from "total vehicle miles" divided by "total road calls," and for "miles per maintenance dollar" by dividing "total vehicle miles" by the product of "total operating expenses" and "percent of operating budget spent on maintenance." Two outliers were removed, and only entries reporting data in all categories for more than 2 years were included. The total sample for these indicators ranged in size from 138 to 178 authorities.

Table 3 gives distances between road calls over the entire 4-year span for the national bus population and for the bus population in the three climate peer groups. The breakdown into size peer group uses boundaries that appear, from hand-sorting of the data, to record positions of sharp change in indicator values and to separate data along boundaries already present in the tabular data. Table 4 gives miles per maintenance dollar on an annual basis for the bus population by size peer group within each climate peer group. All three climate peer groups show declining mileage per maintenance dollar from 1978-1979 to 1981-1982 (Table 4), suggesting that inflation has eaten into the mileage figures as a result of higher labor and parts costs.

Various interpretations of the patterns in the data in Tables 3 and 4 are available. This is a first effort to analyze the relationship between maintenance and climate; thus, a significant function of these data is to suggest directions in which this climatic partition might aid in controlling for other factors. For example, in both tables, the climate groupings suggest that the poorest performance rests in the intermediate climate class. Is this borne out by actual maintenance practices, by tightness of maintenance budget in these regions, or by the general economic environment in most transit authorities in the intermediate climate peer group? Further, both tables indicate that despite general climatic adversity, the large cities in the harsh climate peer group of transit authorities do relatively well on these indicators. Perhaps these transit authorities are more sensitive to maintenance, and to transit problems in general, than are a number of their counterparts in the more automobile-oriented cities in the benign climate group. Finally, Table 4 gives an improvement in vehicle miles per maintenance dollar as one moves from the small transit authorities in the north to those in the south. This effect might be due in part to climate, or it might be a function of how the indicator itself was constructed (e.g., low wage rates in small southern fleets might make aggregate vehicle miles per main-

TABLE 3 Distance Between Road Calls by Size and Climate Peer Groups

Number of Buses per Transit Authority	Year of Section 15 Report					Number of Entries			
	1981-1982	1980-1981	1979-1980	1978-1979	1978-1982	1982	1981	1980	1979
Harsh	2,665.2	2,487.1	2,547.7	2,993.0	2,652.1	64	64	62	50
Large (500+)	2,789.4	2,688.1	2,829.9	2,991.9	2,818.2	9	9	9	9
Midsize (100-499)	2,066.2	1,876.6	1,896.6	3,439.9	2,119.9	15	15	13	13
Small (25-99)	3,008.9	2,548.7	2,233.4	2,558.1	2,559.9	40	40	40	28
Intermediate	1,104.3	929.5	953.1	1,872.6	1,118.2	52	52	51	48
Large (500+)	981.6	756.9	796.9	2,059.3	979.2	7	6	6	6
Midsize (100-499)	1,398.2	1,423.9	1,418.3	1,427.7	1,417.2	21	22	19	19
Small (25-99)	1,824.9	2,208.6	2,229.6	2,427.8	2,153.8	24	24	26	23
Benign	1,596.8	1,445.8	1,551.1	2,072.4	1,621.7	62	62	57	49
Large (500+)	1,396.4	1,250.2	1,259.6	2,525.1	1,464.1	12	12	8	6
Midsize (100-499)	2,305.2	2,006.7	2,374.3	1,245.6	1,902.6	14	14	16	18
Small (25-99)	2,488.9	2,514.5	2,269.0	2,567.9	2,448.5	36	36	33	25
National	1,618.1	1,403.0	1,457.3	2,230.0	1,611.9	178	178	170	147
Large (500+)	1,503.5	1,250.9	1,293.8	2,490.2	1,509.2	28	27	23	21
Midsize (100-499)	1,791.6	1,685.2	1,822.6	1,564.6	1,716.6	50	51	48	50
Small (25-99)	2,446.2	2,443.9	2,245.6	2,521.2	2,404.6	100	100	99	76

TABLE 4 Vehicle Miles per Maintenance Dollar by Climate and Size Peer Groups[a]

Number of Buses per Transit Authority	Year of Section 15 Report					Number of Entries			
	1981-1982	1980-1981	1979-1980	1978-1979	1978-1982	1982	1981	1980	1979
Harsh	1.57	1.71	1.92	2.61	1.84	63	64	58	49
Large (500+)	1.44	1.55	1.74	2.45	1.69	9	9	9	8
Midsize (100-499)	2.00	2.25	2.72	3.36	2.41	15	15	13	11
Small (25-99)	2.21	2.36	2.62	3.22	2.52	39	40	36	30
Intermediate	1.17	1.32	1.50	1.64	1.39	48	48	46	44
Large (500+)	1.01*	1.11*	1.28*	1.41*	1.18	7	6	6	6
Midsize (100-499)	1.70	2.00	2.18	1.40	2.03	19	20	17	17
Small (25-99)	2.55	2.73	3.35	3.66	3.00	22	22	23	21
Benign	1.65	1.81	2.29	2.80	1.99	61	62	55	45
Large (500+)	1.46	1.56	2.05	2.59	1.73	12	12	8	4
Midsize (100-499)	2.09	2.58	2.44	2.90	2.50	14	14	16	17
Small (25-99)	2.90	3.08	3.99	3.98	3.33	35	36	31	24
National	1.34	1.59	1.85	2.19	1.71	172	174	159	138
Large (500+)	1.29	1.39	1.62	1.94	1.50	28	27	23	18
Midsize (100-499)	1.91	2.21	2.41	2.76	2.28	48	49	46	45
Small (25-99)	2.53	2.70	3.26	3.55	2.91	96	98	90	75

[a] Entries marked with an asterisk include data from New York City; without it, they become: 1.41, 1.65, 1.84, and 2.21.

tenance dollar appear higher if they constitute a relatively small percentage of the total benign maintenance budget). Thus, Tables 3 and 4 provide yet another means of identifying different subclasses within the Section 15 data.

CONCLUSION

The primary contribution of this paper is to classify transit authorities according to climate. The typology has two layers. First, it sorts transit authorities into the three general categories of harsh, intermediate, and benign climates. Second, it pinpoints the nearest climatic peers of transit authorities within each of the broader categories.

In addition, an indication was given as to how these climate peer groups might be used to increase understanding of other factors, such as age profiles and performance. Beyond these, the broad categories might be employed in, for example, a regression analysis context involving several factors related to vehicle performance, while the nearest neighbor map (Figure 3) might be used to run corresponding studies on more narrowly defined climate subgroupings. Ultimately, however, the utility of these peer groups will likely be judged in conjunction with other factors, as they do, or do not, permit distinctions to be made among variables that are significant in the implementation of transit policy.

ACKNOWLEDGMENT

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Exploring the Multiple Factor Concept for Bus Maintenance Using Simulation

GEORGE LIST, MYSORE SATISH, and MARK LOWEN

ABSTRACT

The transit industry has clearly shifted to an emphasis on fleet maintenance, with operators trying to improve their control of this activity by using tools such as maintenance management information systems. One advantage of these systems is their ability to put within reach a wide range of scheduling rules or algorithms. Explored in this paper are the benefits of a scheduling rule that relies on more than one independent variable or factor. It is based on a premise that the failure distributions of vehicle components are functions of different factors. Alternatively, the components are sensitive to different measures of use. The benefits are clear. For systems where buses accumulate use at widely varying rates, one factor to another, or where the services are in a state of flux, multiple factor control provides much lower in-service failure rates than does single factor control. Moreover, sensitivity analyses indicate that the extent of these benefits is dependent on whether on-condition or planned replacement is employed and whether the component failure distributions are normal or exponential.

The transit industry has clearly shifted to an emphasis on fleet maintenance as a result of the recent federal austerity and state and local government belt tightening. Moreover, it appears that many operators are striving to improve their maintenance practices as well, as evidenced by the popularity of recent bus maintenance workshops.

Operators are searching for better maintenance procedures, up-to-date training aids, solutions to specific problems, and better ways to manage the overall maintenance process--especially ways that take advantage of computerized tools such as maintenance management information systems (MMISs). One advantage of an MMIS is its ability to put within reach a great number of maintenance activity scheduling rules or algorithms.

Although maintenance managers have previously had to rely typically on just one factor for practicality, an MMIS allows them to specify more sophisticated algorithms based on several factors, such as oil analysis results, hours, and stops, in addition to miles. But this raises the question as to whether such sophistication has significant value and, if so, when. This question is examined in this paper by analyzing the value of multiple factor control in situations where it is likely to prove useful, such as systems whose routes are different from one another (e.g., in terms of average speed or stopping frequency) or systems whose routes are in a state of flux (e.g., expanding or contracting).

THE MULTIPLE FACTOR CONCEPT

The multiple factor concept states that the failure distributions of the vehicle's components may be functions of different independent variables or factors. Alternatively, its components are sensitive to different measures of use. For example, lights and other electrical equipment may be sensitive to hours of use, air conditioners may be sensitive to equivalent full-load hours, and brakes may be sensitive to the number of stops made. Hence, the vehicle's overall reliability is a function of a vector of factors, not just one. The concept also states that these factors may themselves be functions of other factors (e.g., engine wear may be a function of both miles and hours).

Under these conditions, a maintenance program based strictly on one factor will have significant shortcomings compared to one that uses a vector of factors unless the buses "age" at proportional rates for all factors in the vector. If, for example, the buses accumulate mileage at rates that vary widely from one bus to another, even though they all operate the same number of hours per day, then it will be important to include bus-hours along with bus-miles in the vector of factors.

EVIDENCE OF THE USE OF MULTIPLE FACTORS

The concept of using multiple factors was, at one time, quite popular and it is under consideration again today (1). Evidence of attempts to use the multiple factors concept can be found in the recent Bus Maintenance Workshop Proceedings (2):

- In Syracuse, New York, an inspection program is used that combines mileage and hourly factors;
- In Los Angeles, California, it is predicted that on-board electronics will necessitate better monitoring of bus hours;
- In San Antonio, Texas, it is preferable to schedule engine maintenance based on hours although there is a lack of confidence in hour meters; consequently, mileage is used;
- In Cleveland, Ohio, hours are used (instead of miles) to schedule the city's preventive maintenance.

Moreover, a recent TRB-sponsored study found that some bus property authorities think fuel consumption

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Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, N.Y. 12180.

could be useful as a basis for specifying engine, and perhaps other, component maintenance (3).

ANALYSIS OPTIONS

Clearly, empirical data should be used for analyses whenever possible because actual situations tend to have features that model builders cannot, or fail to, account for, a criticism that can be lodged against the work presented here as well. But researchers have discovered that cross-sectional or time-series maintenance data are difficult to obtain. It seems the industry simply has not computerized its maintenance data and is only now making progress in that direction, which is due, in part, to the microcomputer (4). That bus maintenance data can be used to investigate specific issues has been illustrated by Maze, Dutta, and Kutsal, who sought to determine whether a technological fix to a transmission problem produced any quantifiable improvement in reliability (5).

Section 15 data seem to be of some use, but Fielding, Babitsky, and Brenner clearly showed that many maintenance-related data items have either missing or ambiguous entries (6). In their study, road calls had to be dropped from the analysis because the variable's definition led to inconsistent entries, active vehicle count-related entries had to be deleted because they were ambiguous, and fuel had to be dropped because there was no obvious way to combine the data for the four different types of fuel in use. In a separate Section 15-based study, Foerster, Miller, Kosinski, and Rueda could not obtain a coefficient of determination (R^2) greater than 0.04 in their maintenance-oriented regression analyses (7).

Under these conditions, simulations can often be used to generate synthetic data. For example, Dutta (8) developed a simulation model, including resource allocation suboptimization routines, that allows for experimentation with radically different bus maintenance strategies. Maze, Dutta, and Kutsal (9) illustrated the potential problem of maintenance demand peaking that can occur when all new buses are purchased. Muthukumaran, Miller, and Foerster (10) used MASSTRAM (11) to study optimal maintenance planning, and Sinha and Guenther (12) combined a maintenance planning model with an operations model using a dependability factor to study the impacts of maintenance strategies on service reliability.

For purposes of this analysis, however, although each of these studies approaches the maintenance planning problem with a different methodological framework, they have one significant aspect in common: they use just one variable, mileage, to determine when a vehicle is going to fail and when it should be scheduled for maintenance. Hence, it was necessary to develop a simulation model that incorporated this feature.

THE MULTIFACTOR MODEL

The multifactor bus maintenance model (13) provides a simple representation of a transit system's operation, moving buses from one stage to another in a four-stage system as shown in Figure 1. The stages are as follows:

- In storage, which is either overnight or as a service spare;
- In service, which is differentiated by type (e.g., urban, suburban, or express);
- Awaiting maintenance, which can be repair (high priority) or inspection (low priority);
- In the shop (in the repair facility).

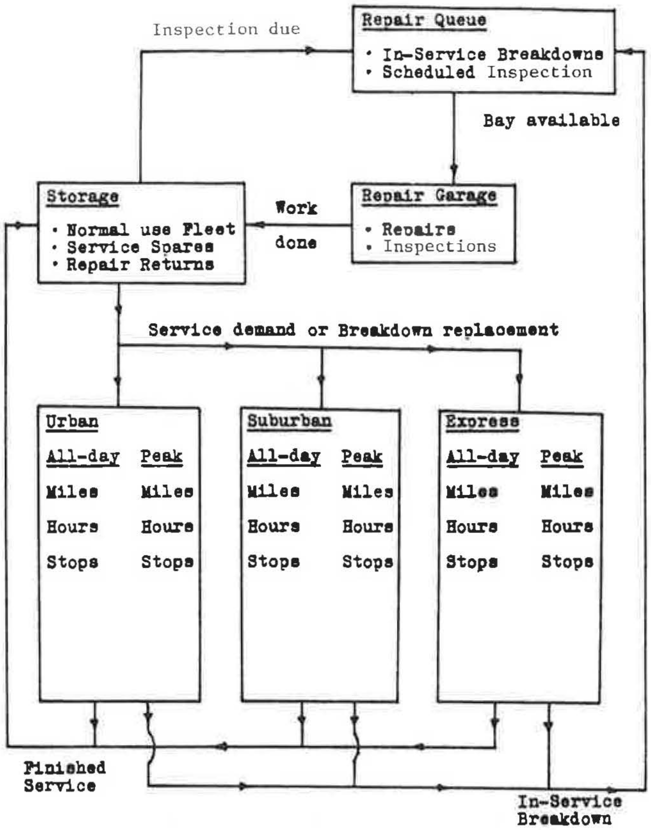

FIGURE 1 Structure of the simulation model.

INITIALIZATION

At the beginning of simulation, each bus is placed In Storage. Its components are assigned "times" to failure (e.g., miles, hours, or stops) by drawing values from failure distributions that use the appropriate causal factors as the independent variable. For example, if component X is sensitive to miles, it samples a distribution relating the probability of failure to the number of miles traveled.

MOVEMENT BETWEEN STAGES

On each day of simulation, buses In Storage are placed In Service by filling route assignments on a random basis. After this process is complete, any buses still In Storage are left In Storage as spares for future assignment.

Routes can be of various types (e.g., urban, suburban, or express) and can have different durations (e.g., peak or all day). Moreover, each one (e.g., an all-day urban route) has a set of probability density functions for the causal factors (e.g., distributions for bus miles, hours, and stops per day). Hence, when a bus is assigned to a given route, these distributions are sampled to obtain a "use" vector for the day (e.g., the day's incremental miles, hours, and stops).

If the day's use vector will push one of the components past its point of failure, the bus will have a breakdown while In Service. The bus accumulates a percentage of the use vector proportional to the component's point of failure, leaves the assigned route, records the failure as being peak or off-peak depending on when it occurred, and goes to the Awaiting Maintenance stage.

Replacement buses are dispatched from In Storage to fill vacancies created by the in-service failures. Each one accumulates the remainder of the failed bus's use vector plus an increment to reflect travel (e.g., miles, hours, and stops) to the point where its service starts. If no replacement bus is available, the model records the lost hours of service, peak or off-peak.

At the end of each day, buses In Service return to storage except when they are due for inspection, in which case, they go to the Awaiting Maintenance stage. Buses Awaiting Maintenance sit in queue until it is their turn to occupy a bay in the repair facility. A bus needing repair has priority over one scheduled for inspection, and within each of these categories, buses are sequenced according to the time when they joined the queue.

Once a bus is In The Shop, it is either repaired or inspected as appropriate. If it is to be fixed, a repair time distribution is sampled for the component being replaced to determine how long it will be In The Shop. Once this time has elapsed, the bus leaves the shop, releases the facility capacity it had employed, and returns to storage, to await its next service assignment.

If the bus is In The Shop for a component inspection, a test is performed to see whether the component is still serviceable or needs replacement. Ideally, this test would be based on the probability that the component shows significant wear given its present age plus a conditional probability that the inspecting mechanic will decide to replace the component given this information. As a simple approximation, the model assumes that at a given point in time, expressed as a percent of the component's time to failure (e.g., 85 percent of its life, measured on the basis of the factor that dictates failure), it will be obvious that the component needs to be replaced. Hence, if the component's percent of time to failure is beyond this point (e.g., less than 15 percent of its life remaining), the bus will be shopped (i.e., put in the Awaiting Maintenance queue) so that the component can be replaced; otherwise, it will be returned to the In Storage stage to await its next service assignment.

THE BENEFITS OF USING MULTIPLE FACTORS

To investigate the benefits of multiple factor control, a hypothetical transit system was developed that was assumed to have the following characteristics.

Its buses have three components, the first of which has a failure distribution dependent on miles; the second, hours; and the third, stops. Corresponding mean times to failure are 50,000 mi, 3,000 hr, and 200,000 stops, and the failure distributions are normal with a standard deviation equal to 20 percent of the mean (see later text for sensitivity analyses regarding these assumptions). The numbers are intended to represent engine-transmission combinations, air conditioners, and brake systems, but there is no claim that the numbers are representative of any specific system. [Note that Foerster et al. (7) did develop such statistics for several components based on miles, and the statistics used here are loosely related to these.]

It is also assumed that three types of routes are being operated: urban, suburban, and express. The urban routes have 10 stops per mile and an average speed (V_{avg}) of 10 mph; the suburban, 1 stop per mile and V_{avg} = 20 mph; and the express, one stop every 10 mi and V_{avg} = 30 mph. Fifty percent of the routes are urban, 30 percent are suburban, and 20 percent are express. For all three types of routes, one-third of the assignments are all-day (16 hr) and the remaining two-thirds are peak (3 hr in the morning and 3 hr in the evening).

The maintenance schedule is based on planned replacement, with an assumed MMIS being used to schedule buses for component change-outs at mileages predicated on the last change-out. For example, the change-out interval for the hours-sensitive component might be set to 40,000 mi. Every time the component fails or is changed-out, the mileage counter is reset, so that the next change-out will be scheduled for precisely 40,000 mi after the preceding one. Figure 2 shows that this minimizes the number of component replacements required while still meeting a given in-service failure rate goal.

The main question is whether a multifactor strategy would offer significant advantages over the present strategy. Consider the situation where service cutbacks are planned in the near future because of fiscal constraints. Assume one of two scenarios is most probable. Either the suburban and urban services will be retained (Scenario A) or only the urban service will be kept (Scenario B), as shown in Table 1.

The maintenance problem under both scenarios is to keep the in-service failure rate under control (e.g., below 20 percent) in spite of the drastic changes in service. This goal is difficult to achieve because in both scenarios buses will be

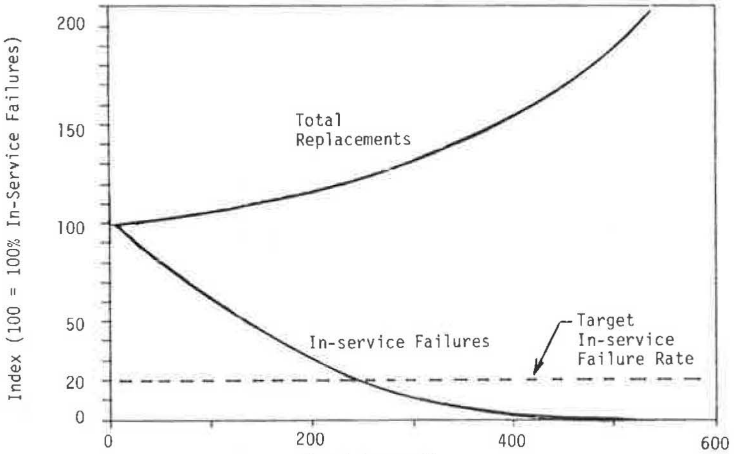

FIGURE 2 In-service failures and total replacements versus total inspections.

TABLE 1 Operating Environment by Scenario

Characteristic	Base Case	Scenario A	Scenario B
Average speed (mph)	17	13	10
Distribution of routes (%)			
Urban[a,b]	50	70	100
Suburban[c,b]	30	30	-
Express[d,b]	20	-	-
Hours of service			
Peak periods	6	6	6
All day	16	16	16

[a] 10 mph average speed, 10 stops per mile.
[b] Two-thirds peak hour buses, one third all day.
[c] 20 mph average speed, one stop per mile.
[d] 30 mph average speed, one stop every 10 miles.

accumulating hours and stops at faster rates per bus-mile than they are presently. Figure 3 shows that while the in-service failure rate in the base case is 20 percent for the hours-sensitive component (using a 40,000-mi change-out interval), it is 70 percent in Scenario A and 90 percent in Scenario B.

One potential solution is to identify a new change-out interval for each scenario. To stay at 20 percent in-service failures, Figure 3 shows that the interval should be set to 32,000 mi for Scenario A and 25,000 mi for Scenario B. But the problem is that this means a different change-out interval for each scenario, and new change-out intervals if other scenarios unfold.

However, multifactor control produces much better results. As Figure 4 shows, a change-out interval of 2,400 hr yields failure rates under 20 percent for all three scenarios, meaning the mix of services can change constantly and yet the in-service failure rate will remain under control.

SENSITIVITY ANALYSES

A number of key questions can be asked about how sensitive the findings are to the underlying assumptions. Most important, the questions deal with the failure distribution (e.g., type mean and variance) and the relative merits of planned change-outs versus on-condition replacements [see Etschmaier (14) for a discussion of the relative merits of these two strategies]. The critical thing to focus on is the relationship between the maintenance interval

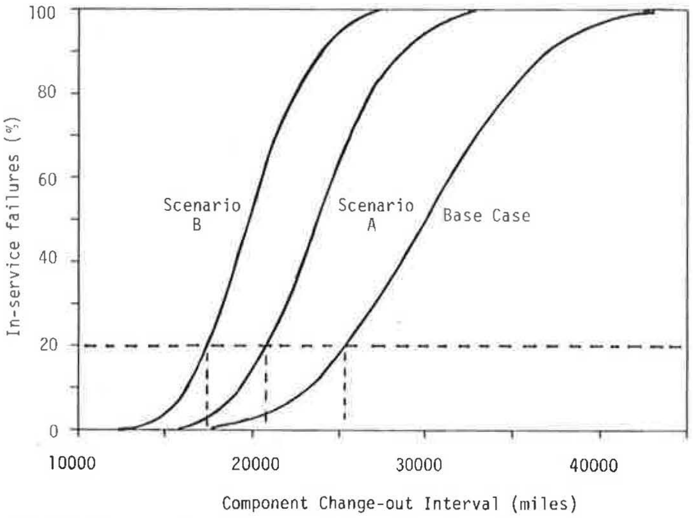

FIGURE 3 In-service failure trends for mileage-based component change-outs and time-dependent, normally distributed failure intervals.

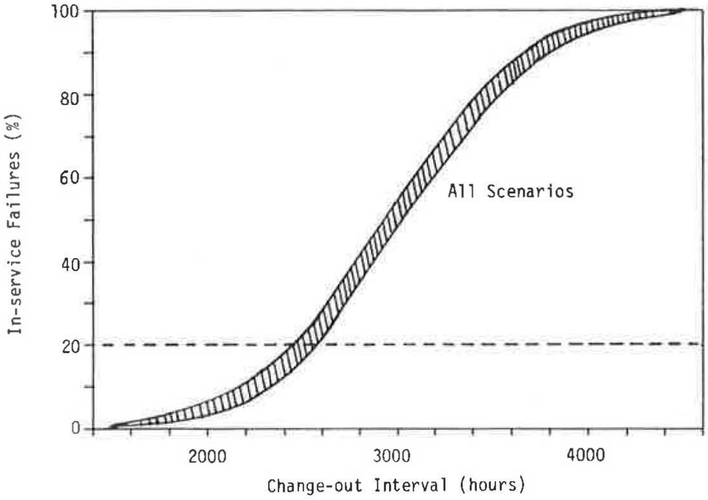

FIGURE 4 In-service failure trends for hours-based component change-outs and time-dependent, normally distributed failure intervals.

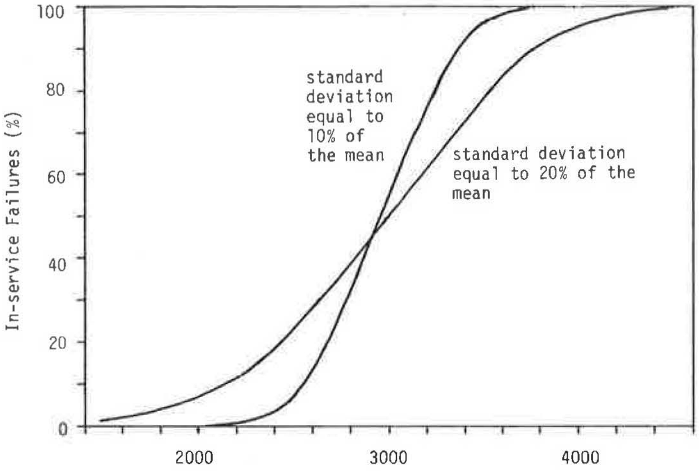

FIGURE 5 Changes in the in-service failure trends due to a change in the standard deviation of the failure interval distribution—time-dependent, normal distribution.

(planned replacement or inspection) and the in-service failure rate. As Figures 3 and 4 show, the key attributes are (a) the shape of the relationship and (b) the range of maintenance intervals over which the in-service failure rate undergoes significant change. Using Figure 4 as an example, the in-service failure rate increases monotonically as the maintenance interval widens, and the failure rate undergoes its significant change as the maintenance interval rises from 1,000 to 4,000 hr.

SENSITIVITY ANALYSES USING A NORMAL-BASED FAILURE DISTRIBUTION FUNCTION

When the times to failure follow a normal distribution, the effects of changes in mean and variance are clear. If the mean increases, the midpoint of the effective range of maintenance intervals increases but the range remains constant. For example, if, in Figure 4, the mean shifts to 4,000 hr, the curve shifts to center on 4,000 hr, but the range of effective intervals remains plus or minus 1,500 hr. If the variance increases, as shown in Figure 5, the midpoint of the range remains fixed, but the width of the range increases, proportional to the change in the standard deviation.

Understanding the effects of a shift to on-condition replacement is more complex. Remember that the model assumes there is a small window of time before failure (the near-failure window) when the component indicates replacement is required (e.g., within 15 percent of the end of its life). For the on-condition replacement strategy to be effective, the component must be inspected during this near-failure window.

Figure 6 shows that the shift in strategy yields a complex relationship between the inspection interval and the in-service failure rate. Most important, the timing of the inspections is critical. When the inspection interval is short, there is a high probability that an inspection will occur during the near-failure window and a low in-service failure rate results. As the interval widens, however, the in-service failure rate rises sharply because the last inspection before failure increasingly comes too early to be useful. In fact, at slightly below two inspections per expected lifetime, the failure rate reaches a local maximum because the synchronization between inspections and

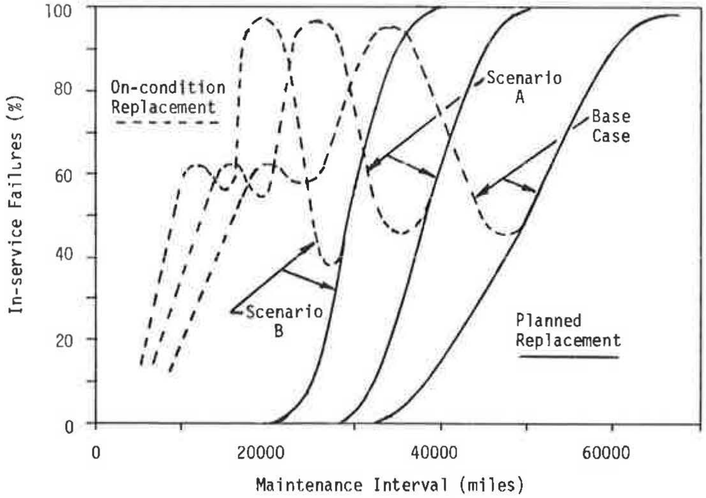

FIGURE 6 On-condition versus planned replacement (change-outs), time-dependent, normally distributed failure intervals.

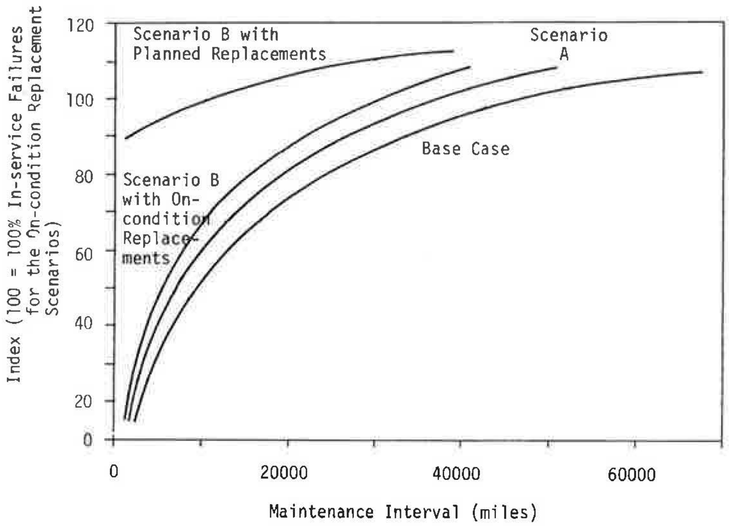

FIGURE 7 In-service trends for on-condition and planned replacement; time-dependent, exponentially distributed failure intervals.

failures is poor. After decreasing slightly at one-half the expected lifetime, the in-service failure rate rises sharply again reaching a rate as high as that encountered when no inspections are conducted because the timing problem is most acute. At first, the problem is severe because there is a low probability that any inspection will occur during the near-failure window. However, as the inspection interval widens still further, approaching the length of the expected lifetime, the in-service failure rate drops markedly because an increasing percentage of the inspections are occurring during the near-failure window. In fact, at intervals slightly smaller than the expected lifetime, there is a local minimum because the number of inspections during the near-term failure window reaches a local maximum. Once past this maximum, the length of the expected lifetime, on-condition replacement appears to be the same as planned change-out with a monotonically increasing in-service failure rate.

SENSITIVITY ANALYSES USING AN EXPONENTIAL-BASED FAILURE DISTRIBUTION FUNCTION

When the times to failure follow an exponential distribution, the effects of planned change-out and on-condition replacement are reversed. A planned change-out strategy keeps the in-service failure rate high no matter what change-out interval is selected (with similarly large total replacements) while on-condition replacement produces small in-service failure rates, provided the inspection interval is kept short relative to the expected lifetime.

As Figure 7 shows, dropping the planned change-out interval from 4,000 hr down to 125 produces only an 8 percent drop in the in-service failure rate. Moreover, although not shown in the figure, the total replacements increase almost ninefold! Switching to an on-condition replacement strategy over the same range drops the in-service failure rate from 100 percent to 13 percent. Moreover, although it is not shown in the figure, total replacements do not increase at all. The figure does show, however, that under these conditions shifts in the service characteristics of the bus system are not as critical because a short inspection interval must be used to keep the in-service failures under control in any event.

IMPLICATIONS FOR FUTURE RESEARCH

There are many implications from this research, but four seem most important. First, the industry should try to determine whether, and to what extent, factors other than mileage are critical in the failure distributions of various components. Second, when gathering historical maintenance data, analysts should strive to measure such things as bus-hours, fuel consumption, and stops, in addition to bus-miles so that these causal relationships can be identified. Third, analysts should also attempt to determine the precise nature of the failure distributions because this paper indicates that they are critical to the selection of an appropriate maintenance strategy. Finally, there is a need to explore further the issue of on-condition versus planned replacement using models such as the one that has been presented here.

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Effectiveness of Improved Repair Scheduling in the Performance of Bus Transit Maintenance

UTPAL DUTTA, T. H. MAZE, and ALLEN R. COOK

ABSTRACT

Described in this paper is a computer simulation model that is used to investigate the efficiency improvements that are possible through the scheduling of bus maintenance repairs through a maintenance shop. The scheduling rules that are investigated rank repair jobs in priority order according to the length of time the bus has been waiting for repair and the length of time the job will take. It is found that scheduling, as opposed to not scheduling, can make dramatic improvements in the maintenance system's efficiency. Further, once scheduling policies are identified that result in superior performance, it is found that these same policies are superior under a variety of system conditions. The conditions varied include the number of spare buses carried, the fleet size, the failure distribution parameters, mechanic labor availability, and the maximum length of time a bus can wait for a repair.

The general financial dilemma faced by transit operators is well documented in the literature (1-3). This condition is a result of escalating operating costs and efforts by the federal government to reduce federal operating subsidies. This financial pinch is placing pressure on members of the transit industry to strive to operate as economically as possible. Many have argued that cost efficiency gains are possible if transit agencies institute more effective fleet management principles (4-6).

The purpose of this paper is to present computer simulation experiments used to determine the potential for efficiency gains from improved fleet management policies. The policies investigated deal with the effective use of maintenance activity scheduling. The scheduling rules rank in priority order the making of corrective repairs. For example, one simple rule would be to schedule for repair first those jobs that require the fewest mechanic-hours to complete. Improved repair scheduling rules have been shown to result in better system performance for a fixed level of resources (labor, spare units, and repair facility resources) in other industries (7).

EXPERIMENTAL APPROACH

To determine if similar efficiency gains are possible in transit bus maintenance as a result of improvements to repair scheduling, simulation experiments are conducted. Simulation allows the analyst to build a symbolic model of a system on the com-

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U. Dutta, Goodell-Grivas, Incorporated, 17320 West Eight Mile Road, Southfield, Mich. 48075. T.H. Maze, Oklahoma Highway and Transportation Engineering Center, The University of Oklahoma, Norman, Okla. 73019. A.R. Cook, School of Civil Engineering and Environmental Science, The University of Oklahoma, Norman, Okla. 73019.

puter. Once constructed, the model can be used to experiment with system changes without disrupting the real operational system. Besides not disrupting the actual system with an experiment, the simulation model has two other important advantages. First, the results are obtained quickly, perhaps within a few minutes. The same experiment with the actual system might take years before the result would be known. Second, because all of the system variables in the model are controlled, the analyst knows that the results from the experimentation were produced by the variable(s) that were manipulated. In other words, results obtained from an experiment with a real system may be affected by uncontrollable variables that change during the course of the experiment, such as the weather or a new union contract. These factors can be held constant in the computer model. Thus, a computer-based simulation model can be less disruptive, faster, and more accurate than a real-life experiment in the analysis of a complex system.

Despite simulation's many positive attributes, the user of a simulation experiment's results must recognize that most complex systems include a larger number of variables than what can be practically considered in one simulation model. Therefore, to make it economical to conduct a simulation, the analyst must limit the number of parameters used and the variables included to just those that are considered important or representative of the entire system, or both. For example, in a study of maintenance practices at the Chicago Transit Authority, Haenisch and Miller estimated that bus mechanics regularly perform 1,800 different jobs (8). If an analyst were attempting to simulate this maintenance system, it would clearly be uneconomical to model the distribution of each and every event and enter the distribution parameters into a computer simulation. However, simulation studies that use only a fraction of the system's elements in the analysis are more than sufficient for policy studies where the primary emphasis is to determine the existence of relationships and to gain inferences of their strength.

Reducing the complexity of systems down to a manageable problem leaves the results of the simulation analysis vulnerable to those who question the model's relevance because of its lack of specific details. However, the model's results should be judged with respect to whether any of the missing details would affect the validity of the relationships discovered. If the missing details do not impact the validity of the relationships, then their inclusion is not necessary at the policy analysis stage.

The first step in the experimentation is to prove that systematic scheduling of repairs, as opposed to nonsystematic repair scheduling (random scheduling), can improve the productivity of the maintenance system. The experimentations show that the efficiency gains that result from systematically scheduling repairs are quite striking. Once scheduling is proven as a robust means for improving the efficiency of the maintenance system, the next step is to search for the most effective repair policies. Eight scheduling rules are developed and tested to determine which is the most efficient on the basis of a series of performance measures. The last step in the experimentation is to investigate whether the same policies remain superior under a variety of conditions. This is done by measuring the sensitivity of the system's performance to changes in fleet size, component failure distribution patterns, number of spare buses (spare factor), and the amount of labor resources available for conducting repairs.

In this paper, only a brief description of the computer simulation model is provided. The interested reader will find a thorough description of the model elsewhere (9).

MAINTENANCE SYSTEM CHARACTERIZATION

The simulation model is structured to represent a 2-tiered maintenance system. The two-tiered system is one in which there are two levels of maintenance performed (10). Light maintenance (e.g., preventive inspection, brake overhauls, and tire maintenance) is performed at storage garages. Heavy maintenance (major corrective component overhauls) is performed at a central maintenance facility. Further, the model is restricted to experimentation with only the work flow at the central maintenance facility.

From the perspective of a storage facility (the first tier), a bus's operating status may be classified into one of several categories. For example, if a bus is due shortly for a preventive inspection, the manager can wait for a convenient time to perform the inspection without taking the bus out of service by assigning the bus to single-trip, peak-period commuting runs (tripper runs) while the maintenance manager waits for an opportunity to schedule the bus for an inspection between tripper runs. Alternatively, the bus could be taken out of service and held while it waits for an inspection, or the inspection could be deferred while the bus is scheduled for regular service. There are other possible categories of status, thus making the classification of a bus's status (from the perspective of the storage garage) a complex problem to model.

From the perspective of the central maintenance facility, categorizing status is less difficult. Because buses are generally only brought to the central facility when they require a major unit overhaul, buses within the system may be classified into one of only three categories: (a) active buses that are operative and scheduled for service, (b) spare buses that are operative but not in service, and (c) failed buses that are out of service and inoperative because of a mechanical failure. Over time, each bus will cycle among the three categories of status.

For purposes of the simulation and in relation to the central facility, the day-to-day events occurring to buses are assumed to be limited to the following scenarios:

1. An "active" bus is assigned to daily service.
2. If a bus fails while in service, it is replaced by a spare bus, if one is available.
3. A failed bus is inspected to determine the cause of the failure and, if the cause is a failure of a major component or part, then the bus is driven or towed to the central maintenance facility.
4. At the end of the day, the central maintenance shop schedules repair work for the next day on the basis of the number of failed buses, mechanic labor, and parts required as well as the availability of parts and labor.
5. The buses that are not scheduled to be repaired the next day wait in the bad order parking lot of the central maintenance facility until they can be scheduled for repair.
6. After being repaired, the bus joins either the pool of active buses or the pool of spare buses depending on the number of buses required to meet scheduled service and the number of operable buses.

Repair Scheduling Policies

The purposes of the simulation experiments are to determine: (a) whether systematic scheduling im-

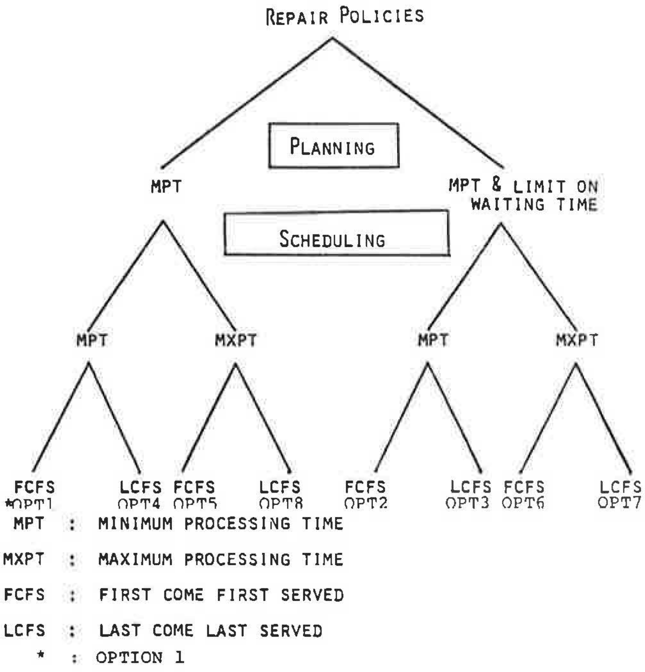

FIGURE 1 Repair tree.

proves the performance of the maintenance system, (b) which repair scheduling policies are the most effective if performance is improved, and (c) how the superiority of scheduling policies is affected by changes in the system's condition. The first step in conducting these experiments is to create scheduling rules and policies. Later, these policies will be modified to represent systems without systematic repair scheduling. A repair policy tree is shown in Figure 1. There are two steps in the repair process. These are

1. Planning. Selection of the number of repairs to be made by component type (e.g., remove and replace transmission or remove and replace air conditioning compressor) is made during the planning step. The selection process is conducted by using an optimization technique. The optimization seeks to maximize the number of repairs made with the available resources (labor and facilities). In planning, it is assumed that the length of time required to make repairs is deterministic (constant).
2. Scheduling. This step determines the execution of the planned repair work. The time required to fix a component is considered to be stochastic (variable). In other words, the time required to conduct each repair is a random variable that follows some typical distribution. Depending on the difference between the stochastic times (assumed in the scheduling step) and the deterministic times (assumed in the planning step), all planned repair activities may or may not be scheduled for repair on a particular day. If repair resources are exhausted before the completion of planned repair work, then the remaining planned repair work is cancelled. If repair resources are available after the completion of planned repair work, then additional repair work is scheduled.

Planning is the first step of the repair process and it follows one of the following two rules. These rules are identified by the upper two branches of the repair tree in Figure 1. The rules are

I. Optimization techniques are used to select the number of repairs to be conducted by repair type. The objective is to maximize the number of repairs by effectively utilizing available resources.

II. Repair those failed buses that have been waiting for a repair more than a certain number of days and utilize Rule I to allocate the remaining resources.

Once planning is completed, the next task is scheduling. The first step in the scheduling process is to determine which type of job waiting for repair (e.g., the buses waiting to have their transmissions removed and replaced) is to be scheduled for repair first. The selection of which waiting line (failed bus queue) to process first is based on either the minimum or maximum time required to complete each type of repair (processing time). In Figure 1, this is represented by the four branches of the repair tree at the scheduling level. The second and final step of scheduling is the selection of the specific bus to be repaired from the selected failed bus queue. Selection of the bus to be repaired from the queue is either first-come-first-served (FCFS) or last-come-first-served (LCFS). This is shown in the last eight branches of the repair policy tree, which defines the final eight repair policies. The repair policies are labeled as Options 1 through 8. For example, if the leftmost branches are followed through the repair tree, planning is based on minimum processing time (MPT), scheduling is based on MPT, and buses are selected from the failed bus queue based on FCFS. This combination of branches is Option 1 (OPT1).

The measures of system performance selected for determining the effectiveness of the scheduling policies are:

1. Average time spent by each bus waiting to be repaired plus the time required for the repair (time in the system = TSTS).
2. Average daily number of vehicles failed and tied-up in maintenance (total number of failed buses = TQUEUE).
3. Average number of buses in all the repair queues (WQUEUE).
4. Average mechanic overtime required per day (OTIME).

BASE CASE STUDY

The development of a simulation model requires that the model be constructed such that it depicts the characteristics of an actual system. This requires that certain assumptions be made regarding system operational procedures and parameters developed that identify the relationships between the various elements of the simulated system. Further, there may be too many possible events in real systems to economically simulate all possibilities. However, it is generally possible to include only the major events in the simulation and assume that the entire system of all possibilities would perform similarly under the same circumstances.

In the simulation's characterization, only 16 types of component or part failures are considered. These components were selected by staff members of the Detroit Department of Transportation (DDOT) as those that are the most common repairs made at their heavy-repair facility. Other assumptions made were that

- Maintenance workers are interchangeable and can perform all repairs made at the central maintenance facility.
- Repair times and miles until failure are stochastic.

- All repairs are corrective.
- Maintenance equipment and tools are always available.
- All buses are the same model.

Model Parameters

The parameters for the base case are

1. Total active fleet. In this study, the active fleet consists of 500 vehicles. This means that at the beginning of the simulation run, 500 entities are created to represent the number of buses in service. Five hundred is also a large enough number so that the sample size is great enough for any statistical test.
2. Spare factor. This is the ratio of spare buses to active buses. For the base case, the factor is assumed to be 10 percent, which is a figure reported as a level that the industry desires to achieve (11,12).
3. Available labor hours. This is the total labor hours available for daily repair. The quantity of labor hours required per day is time-dependent. In other words, the number of labor hours required to repair enough buses to meet service requirements will depend on the number and types of corrective maintenance activities required by the buses in the failed queue, which varies with the age of the buses. Early in the life of the buses, most components will be relatively reliable and, as they age, components will become less reliable and more prone to failure. In the maintenance shop, based on the composition of the failed queue, the amount of labor resources should be varied. When relatively stable (long-term) increases in failure rates occur, labor resources will be increased; similarly, they will be reduced when failure rates are low. It is found in the simulation experiments that as buses age, higher levels of failure occurrence take place after an initial break-in period [see Maze et al., for illustrations of this phenomenon (13)]. Therefore, in practice, adjustments in labor needs would not necessitate abrupt changes in the number of mechanics in the labor pool. Similarly, gradual changes in the labor pool could be obtained in an actual maintenance system through normal mechanic attrition and new hires. In this study, a simple rule is established to specify the available labor resources. When the failure rate is high, it is assumed that the available resources (in man-hours per day) is equal to a factor multiplied by the number of active buses. For example, for the base case, a factor of 0.40 is used and, because there are 500 active vehicles, 200 man-hours are available per day. During periods when failure rates are uniform, the total resource available is assumed to be 75 percent of the peak. These rules may not replicate normal staffing requirements for an actual system; however, the simulation only considers a fraction of the actual activities conducted by a maintenance facility.
4. Overtime. When the number of failed vehicles is so great that the system's ability to meet service demands is jeopardized, then overtime labor resources are used to repair failed vehicles. The use of overtime is also limited by the two following rules: (a) if the total number of failed buses exceeds the number of spare vehicles then, and only then, overtime is permitted; and (b) once overtime is permitted, it is limited to 30 percent of the regular hours if the number of failed buses is more than 15 percent of the total fleet (critical conditions); otherwise, it is limited to 25 percent of the regular hours.
5. Failure patterns. The failure patterns of 16 different bus components are identified from maintenance records of several transit agencies, including the Detroit Department of Transportation (DDOT), the Central Oklahoma Transportation and Parking Authority (COTPA), the Dallas Transit System (DTS), and the Austin Transit System (ATS).
6. Repair time distributions. Repair time distributions of the components considered are determined using repair times recorded by DDOT.

Tables 1, 2, and 3 give the model parameters for the base case study. Table 1 presents the specification of total active fleet, spare factor, repair labor resources, and overtime for the base case. Parameters of the failure distributions of the 16 components considered are given in Table 2. The failure distribution of the components follows two distinct patterns: (a) the Weibull distribution, and (b) the exponential distribution.

Table 3 gives the repair time distribution param-

TABLE 1 Model Parameters

Parameter	Value
Total active fleet	500 buses
Spare factor	10 percent
Repair resource	200 hr (peak) 150 hr (off-peak)
Overtime	30 percent

TABLE 2 Failure Distribution Parameter

Component	Distribution	Minimum Life (mi)	Parameter 1[a]	Parameter 2[a]
Gear train	Weibull	3,051.9	2.751	113,504.0
Control arm	Weibull	8,634.6	1.364	98,489.0
Blower motor	Weibull	22,323.6	1.431	85,776.0
King pin	Weibull	11,056.5	1.507	84,100.0
Bell crank	Weibull	16,263.0	1.397	83,602.0
Fan torous	Weibull	8,649.9	1.165	76,250.0
Destination sign	Weibull	20,439.9	2.049	82,994.0
Power steering	Weibull	3,448.8	1.263	83,823.0
Condenser core	Weibull	6,507.9	1.446	58,183.0
Engine	Weibull	80,302.5	2.173	167,373.0
Dome light	Weibull	14,223.0	2.930	32,726.0
Transmission	Weibull	3,487.0	1.518	55,107.0
A.C. compressor	Weibull	19,983.5	2.107	123,592.0
Starter motor	Exponential	10,300.0	-	27,666.0
Door engine	Exponential	264.0	-	42,187.0
12-V charger	Exponential	127.0	-	27,497.0

[a] For the Weibull distribution, Parameter 1 is the shape parameter and Parameter 2 is the scale parameter. For the exponential distribution, Parameter 2 is the mean mileage.

TABLE 3 Repair Time Distribution Parameter

Component	Mean (hr)	Standard Deviations (hr)
Gear train	65.00	5.000
Control arm	9.75	2.024
Blower motor	4.27	2.036
King pin	14.00	0.250
Bell crank	2.33	1.780
Fan torous	15.29	1.090
Destination sign	1.31	.637
Power steering	5.00	1.000
Condenser core	4.66	1.895
Engine	80.00	5.000
Dome light	1.21	1.110
Transmission	37.97	5.500
A. C. compressor	10.07	.902
Starter motor	2.68	1.880
Door engine	6.00	0.250
12-V charger	1.73	.680

Note: The distribution for all the components is normal.

eters for all 16 components. In this study, repair times are assumed to be normally distributed. The normal distribution is assumed because (a) of limited data, which makes it difficult to ascertain the validity of other distributions, and (b) several distributions have been used to represent repair time distributions. Sinha and Bhandari (14) used the Gamma distribution, Kelly and Ho (15) found that repair times followed the log-normal distribution, and Conway et al. (16) identified repair times to be normally distributed. Because there does not appear to be a consensus, the normal distribution was selected because of its ease of use and familiarity with its properties.

Now that the model parameters have been presented, the next step is to present the results of the simulation experiments. The results are presented in three steps: (a) the running of experiments that schedule repairs randomly (without systematically ordering the priority of repairs) followed by a comparison of these results with the results of the simulation model when comparable systematic repair rules and policies are used; (b) the running of experiments with the systematic scheduling policies and the selection of the superior systematic scheduling policy; and (c) the determination of the sensitivity of the superiority of scheduling policies to changes in system parameters.

RANDOM SCHEDULING

It has been observed that at several transit systems, buses are not scheduled for repair using specific scheduling rules that take into account the expected work content (processing time) involved in repairing the vehicle. Examples of scheduling without regard to the work content would include ordering bus repairs according to the order in which they arrived at the maintenance facility or even with regard to the preferences of mechanics to conduct certain types of repairs. To model a system that does not schedule repairs with regard to job processing time, the experiments assume that repairs are scheduled randomly using the following procedures:

1. Option 1. In this option, the job that arrives in the failed queue at the earliest date will be selected for repair first (FCFS).
2. Option 2. In this option, the failed vehicle queues are separated by type of failed component or part into separate failed vehicle queues. Then, a failed vehicle queue is randomly selected and a bus is scheduled for repair from the queue based on FCFS, unless a bus in the selected queue has been waiting longer than 2 days, and then is it repaired first.
3. Option 3. In this option, if any job in the randomly selected failed vehicle queue has waited longer than 2 days, then selection is made among these jobs using LCFS. If no failed buses have been waiting longer than 2 days, failed buses are selected for repair using LCFS.
4. Option 4. In this option, all jobs are selected according to LCFS without a waiting-time limit.

All four of the random scheduling repair policies are similar to the systematic repair policy with the options numbered identically (see Figure 1 for systematic repair scheduling policies). The difference in each case is that the random policies do not schedule jobs according to minimum processing time.

Four runs of the simulation model are made using the four random scheduling policies. In all cases, the seed value for the random number generator is kept constant. By keeping the seed value constant, the same stream of random numbers is used in all runs. Hence, the same sequence of random samples will be generated for each run of the model. The system performance indicators of these runs are presented in Table 4 along with the performance indicators for the comparable systematic repair policies.

TABLE 4 System Performance of Two Repair Processes

Repair Policy Options	TSYS	OTIME	TQUEUE	WQUEUE
1				
Random	4.279	29.48	68.73	53.19
Systematic	3.384	26.74	58.71	42.73
2				
Random	3.931	22.81	62.84	47.06
Systematic	2.975	18.41	49.48	33.68
3				
Random	4.639	27.55	76.06	60.10
Systematic	2.345	23.79	54.31	38.28
4				
Random	3.345	29.02	71.91	56.35
Systematic	1.721	24.43	54.96	39.10

Comparison of the Two Repair Processes

In Table 4, TSYS for randomly scheduled repair options varies from 2.541 days (Option 4) to 3.424 days (Option 1). For the systematic repair options, TSYS (the average time spent by buses in the maintenance system) varies from 1.721 days (Option 4) to 3.384 days (Option 1). From this experimentation, it is observed that TSYS for each systematically scheduled repair option is always lower than that of the comparable randomly scheduled repair option. Other performance indicators also prove the superiority of systematically scheduling repairs. A t-test is conducted to compare the performance indicators of the two repair processes for similar options and, for all options, they are statistically different at the 95 percent confidence level.

This comparison demonstrates that the system performance for systematically scheduled repairs is superior to that of randomly scheduled repairs. For example, while using systematic scheduling rules, the time that buses are tied up in the maintenance system (TSYS) under the best conditions (Option 4) for both processes (random and systematic) is roughly one half the time required under random scheduling. In the next section, systematically scheduled repair options are compared.

SYSTEMATICALLY SCHEDULED REPAIR POLICIES

Table 5 gives the performance indicators for all eight systematically scheduled repair options. In Table 5, it should be noted that the Option 4 (minimum processing time and LCFS) performance for TSYS is significantly better than the other options. More specifically, the application of Option 4 results in buses being tied up for maintenance a shorter average time than any other repair scheduling policy.

In Option 4, failed vehicles are scheduled for repair based on processing and arrival times. The vehicle that joins the queue at the last moment and needs the minimum time to be repaired is given the highest priority. This causes the repaired vehicles to spend the minimum average time in the maintenance system. It is important to note that other performance indicators are not at their least value for

TABLE 5 System Performance (base case) Systematically Scheduled Repair

Repair Policy Options	TSYS	OTIME	TQUEUE	WQUEUE
1	3.384	26.74	58.71	42.73
2	2.975	18.41	49.48	33.68
3	2.345	23.79	54.31	38.28
4	1.721	24.43	54.96	39.10
5	3.208	15.50	49.31	33.13
6	3.015	14.94	47.22	30.91
7	2.565	16.65	49.71	33.47
8	2.412	14.99	48.49	32.37

Option 4. This trait has also been observed by researchers who have studied scheduling in other industries (16-18). According to Conway et al., under the minimum processing time rule, the mean time spent in the system is small but some individuals' jobs (those requiring long processing time) will be intolerably delayed (19). Thus, although some jobs will take short times to flow through the system, a few will require inordinate lengths of time to be processed through the system. Because of the variability in the time spent in the system, other performance indicators are not at their minimum for Option 4.

The performance indicators, OTIME, TQUEUE, and WQUEUE, are at their lowest values for Option 6. In Option 6, failed buses are scheduled for repair by using maximum processing time (MXPT) and a maximum waiting time constraint. The Option 6 waiting time constraint places vehicles that have waited longer than 2 days first in line for repairs on the next day. Later, waiting-time limits will be explored to determine if 2 days is the most efficient limit and, if not, how many days the limit should be.

The values of OTIME, TQUEUE, and WQUEUE are close for Options 2 and 6. The only difference between Options 2 and 6 is that in Option 2, the repair work is scheduled using minimum processing time (MPT) and FCFS rules. The waiting time constraint is common to both options. A t-test is conducted to compare the performance indicators of these two options. It is found that, at the 95 percent confidence level, there is no statistically significant difference between the performance indicators of Options 2 and 6.

In all the policies tested, it is observed that the system is operating at capacity almost all of the time. In other words, the utilization of available resources is approximately the same under all policies. The main objective of scheduling is to maximize the number of repairs using available resources. Therefore, all the policies utilize repair resources equally.

Another important observation is that the total number of failed vehicles waiting for repairs (performance indicator TQUEUE) attributed to Options 1, 4, 5, and 8 is significantly greater than that of Options 2, 3, 6, and 7, respectively. However, the only difference between the two sets of repair options is that Options 2, 3, 6, and 7 have waiting time constraints. This difference permits the measurement of the waiting time constraint's impact on system performance.

SENSITIVITY ANALYSIS

This phase of the experimentation is designed to determine the extent to which the performance of the simulated system is affected by changes in model parameters. The model parameters considered in the sensitivity analyses are as follows:

1. The failure distribution parameters of components,
2. The spare bus factor,
3. The fleet size,
4. The man-hours (repair resources) available, and
5. The maximum waiting time limits for Options 2, 3, 6, and 7.

The impacts on the superiority of the various options as the parameters are changed are examined in the following sections.

Failure Distribution Parameters

The distribution of component failures with respect to wear varies with environment, duty cycle, terrain, and so forth. In this part of the sensitivity analysis, the failure distribution parameters of bus components are modified and two different sets of simulation runs are made. The outputs of the two sets of runs are compared with the base case. The two sets of runs have two distinct features:

1. In Case I, the Weibull distribution has three parameters: (a) shape, (b) scale, and (c) minimum life. The components whose failure distribution shape parameters are close to 2 and above are considered to have age-dependent and predictable failure rates (20). Those with shape parameters close to 1 or lower are considered to have random failure patterns. Those components with failure distribution shape parameters close to 1 have their shape parameter changed to 2. By doing this, the failure distributions are all age-dependent. One run is made for each of the eight scheduling options using the age-dependent parameters and the results are given in Table 6.
2. In Case II, the component failure distribution parameters are changed from age-dependent to

TABLE 6 Distribution Parameter and System Performance

Repair Policy Options	TSYS	OTIME	TQUEUE	WQUEUE
1				
Case I	6.056	36.29	107.03	91.48
Case II	6.110	36.24	108.20	91.96
Base case	3.384	26.74	58.71	42.73
2				
Case I	4.834	33.92	83.14	65.87
Case II	4.914	35.35	85.10	67.77
Base case	2.975	18.41	49.48	33.68
3				
Case I	5.490	35.30	95.03	78.21
Case II	5.830	35.60	101.40	84.73
Base case	2.345	23.79	54.31	38.28
4				
Case I	3.149	36.29	108.30	92.00
Case II	2.906	36.29	113.90	97.56
Base case	1.721	24.43	54.96	39.10
5				
Case I	5.161	36.19	87.14	70.23
Case II	5.393	35.99	90.27	73.42
Base case	3.208	15.50	49.31	33.13
6				
Case I	4.841	33.23	82.73	65.54
Case II	4.749	33.34	81.41	64.12
Base case	3.015	14.94	47.22	30.91
7				
Case I	5.181	33.19	86.17	69.20
Case II	5.330	33.19	89.40	72.52
Base case	2.565	16.65	49.71	33.47
8				
Case I	3.176	36.19	85.52	68.44
Case II	3.593	36.20	92.56	75.64
Base case	2.412	14.99	48.49	32.37

random. Similar to Case I, eight runs of the model are made and the results are also given in Table 6.

The system performance indicators for the base case and Cases I and II are given in Table 6. The average time spent by buses being repaired reaches a minimum under Option 4 for all three cases. For both Cases I and II, the repair policy, which resulted in the minimum value of OTIME, TQUEUE, and WQUEUE, is Option 6. It should be noted that there is no statistically significant difference between the performance indicators of Options 2 and 6.

For Cases I and II, as well as the base case, the same repair policy is superior. From this observation, it can be concluded that the superiority of scheduling policies is not sensitive to the values of the failure distribution parameters. This means that if one policy is superior in one environment, it will be the superior policy in another.

Spare Factor

Sinha and Bhandari found that the number of spare buses has a significant influence on the reliability of transit service (14). To analyze the impact of the spare factor on the simulated system's performance and the superiority of scheduling policies, the spare factor (i.e., spare buses/active buses) is varied from the base case value.

The base case spare factor is 10 percent. The modified spare factors chosen are 8 and 12 percent. Sixteen different runs are made using the eight repair scheduling options and the two new spare factors. The observed performance indicators are given in Table 7.

Performance indicators for the base case and modified spare factors are tabulated in Table 7. In all cases, the minimum value for time in the system (TSYS) is observed for Option 4. The values for OTIME, TQUEUE, and WQUEUE are at their minimum in Option 6. The superior repair policy remains unchanged under all spare factors.

TABLE 7 Spare Factor and System Performance

Repair Policy Options	TSYS	OTIME	TQUEUE	WQUEUE
1				
Spare factor (8%)	2.942	29.54	52.11	35.80
Base case (10%)	3.384	26.74	58.71	42.73
Spare factor (12%)	3.546	22.44	61.29	45.49
2				
Spare factor (8%)	2.599	21.52	44.27	27.60
Base case (10%)	2.975	18.41	49.48	33.68
Spare factor (12%)	3.492	15.52	57.72	41.80
3				
Spare factor (8%)	2.849	27.03	52.84	36.44
Base case (10%)	2.345	23.79	54.31	38.28
Spare factor (12%)	2.005	23.88	64.58	48.53
4				
Spare factor (8%)	2.086	29.94	55.11	38.78
Base case (10%)	1.721	24.43	54.96	39.10
Spare factor (12%)	1.678	23.49	63.97	48.10
5				
Spare factor (8%)	2.897	21.77	45.08	28.47
Base case (10%)	3.208	15.50	49.31	33.13
Spare factor (12%)	3.707	13.89	57.16	41.10
6				
Spare factor (8%)	2.661	18.27	42.77	25.97
Base case (10%)	3.015	14.94	47.22	30.91
Spare factor (12%)	3.527	13.48	55.49	39.31
7				
Spare factor (8%)	2.826	20.59	44.44	27.52
Base case (10%)	2.565	16.65	49.71	33.47
Spare factor (12%)	2.355	15.03	58.10	41.90
8				
Spare factor (8%) 1	2.547	20.88	44.18	27.18
Base case (10%)	2.412	14.99	48.49	32.37
Spare factor (12%)	2.487	14.89	58.86	42.75

In Table 7, note that all system performance indicators except OTIME are higher for the spare factor of 0.12 relative to 0.08. While modeling, it is assumed that if the number of failed vehicles exceeds the number of spare vehicles, then, and only then, will overtime be permitted. Through time and by-random-chance failures will occur in surges. How well the system can absorb these surges depends on the number of spares that is available to replace the failed vehicle. Therefore, the simulation experiments demonstrate that there is a relationship between the spare factor and the labor hours required (both overtime and regular time), which indicates the relationship between transit system operating costs and capital costs. In other words, there is a definite trade-off between the capital costs invested in spare vehicles and the operating expenditures on mechanic labor.

This finding has serious transit industry policy implications. The Urban Mass Transportation Administration (UMTA) is currently evaluating its policy on permissible spare ratios (12). Presumably the emphasis in UMTA's spare ratio policy will be to place a reasonable cap on the number of spare buses that a transit system may carry. If spare ratios are reduced, it will come at the cost of additional operating costs. Because the portion of operating costs of U.S. public transit systems subsidized by the federal government is less than the portion of capital costs that is federally subsidized, capping spare ratios will have the impact of pushing more of the total costs of transit service back on the transit systems that currently have spare ratios that are higher than the cap. However, the trade-off between maintenance labor hours and spare buses has not been quantified and, without this information, policy makers placing a cap on spares (in the name of cost savings) may select an inefficient cap. An inefficient limit may ultimately increase the total cost of transit service (operating plus capital cost) for those systems that are forced to reduce the number of spares they carry.

Fleet Size

The fleet size varies with the transit system and depends on the quantity and quality of transit services provided. In this experiment, the fleet size is changed from 500 to 600 vehicles. Although the fleet size is changed, the spare factor is kept at 10 percent. The system performance indicators for all eight options and fleet sizes of 500 and 600 buses are given in Table 8.

When the fleet size is 600 buses, the minimum value of TSYS is 1.971 days for Option 4. It is 1.721 days for a fleet of 500 buses. When the fleet size is 600, more buses are put in service resulting in more failures than with 500 buses. This creates a higher level of competition among the failed entities to be selected for repair. Because maintenance resources are held constant for both fleet sizes, the failed entities spend more time in the maintenance system waiting to be scheduled for repair. This causes a higher value of TSYS for the 600-bus fleet. The other performance indicators also have higher values for the 600-bus fleet.

With the exception of TSYS, the performance indicators are at their minimum for either Option 2 or Option 6 for the 600-bus fleet. Further, no statistically significant difference is found between the performance indicators for Options 2 and 6. Because the same result occurs when the fleet size is 500 buses, it can be concluded that scheduling policy superiority is insensitive to fleet size.

TABLE 8 System Performance for Various Fleet Size

Repair Policy Options	TSYS	OTIME	TQUEUE	WQUEUE
1				
600-bus fleet	6.890	36.16	128.51	114.50
500-bus fleet	3.384	26.74	58.71	42.73
2				
600-bus fleet	5.027	33.32	92.44	74.19
500-bus fleet	2.975	18.41	49.98	33.68
3				
600-bus fleet	3.101	36.16	133.50	116.20
500-bus fleet	2.345	23.79	54.31	38.28
4				
600-bus fleet	1.971	36.16	136.50	119.40
500-bus fleet	1.721	24.43	54.31	38.28
5				
600-bus fleet	5.833	36.16	103.90	86.09
500-bus fleet	3.208	15.15	49.31	33.13
6				
600-bus fleet	5.122	33.82	93.31	75.06
500-bus fleet	3.015	14.94	47.22	30.91
7				
600-bus fleet	3.852	35.82	97.60	79.53
500-bus fleet	2.565	16.65	49.71	33.47
8				
600-bus fleet	2.752	36.00	111.80	94.06
500-bus fleet	2.412	14.99	48.49	32.37

Labor Availability

Labor availability is the most important element of maintenance activities. It controls the number of failed vehicles not scheduled for repair on a particular day. In this part of the analysis, the sensitivity of repair scheduling policy superiority to labor availability is tested. For the purpose of the simulation, the following equation is used to specify the level of available labor hours:

$$\begin{array}{l}\text{Labor hours}\\ \text{available} \\ \text{per day}\end{array} = (\text{Number of buses}) \times (\text{a Factor}) \qquad (1)$$

Then, the factor is given a variety of values, including 0.20, 0.35, 0.40, 0.425, 0.45, and 0.50. In the base case, the labor available per day was 200 hr [(Number of buses) x 0.40)]. Forty-eight runs of the simulation model are made using all combinations of the varied number of labor hours available and the eight scheduling policy options. Plots of the values of TSYS, OTIME, TQUEUE, and WQUEUE for all the combinations are shown in Figures 2-5, respectively.

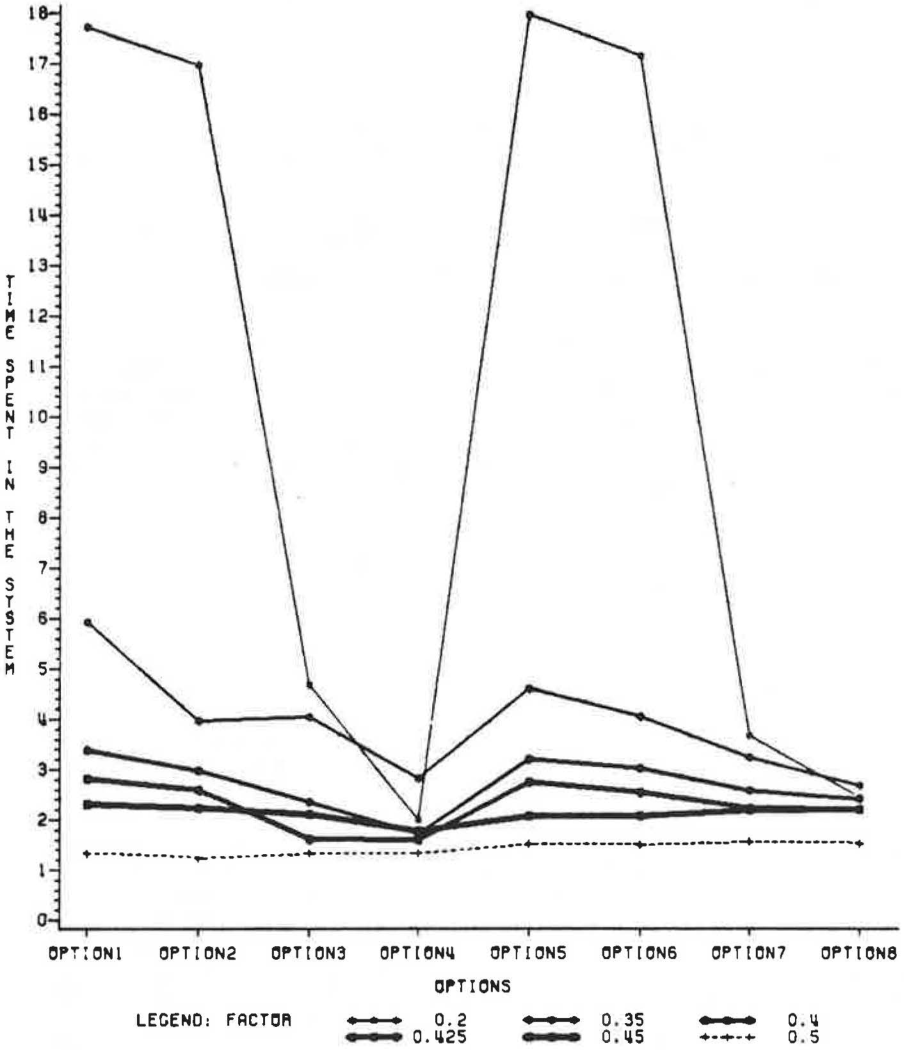

FIGURE 2 System performance (TSYS) of different repair policies.

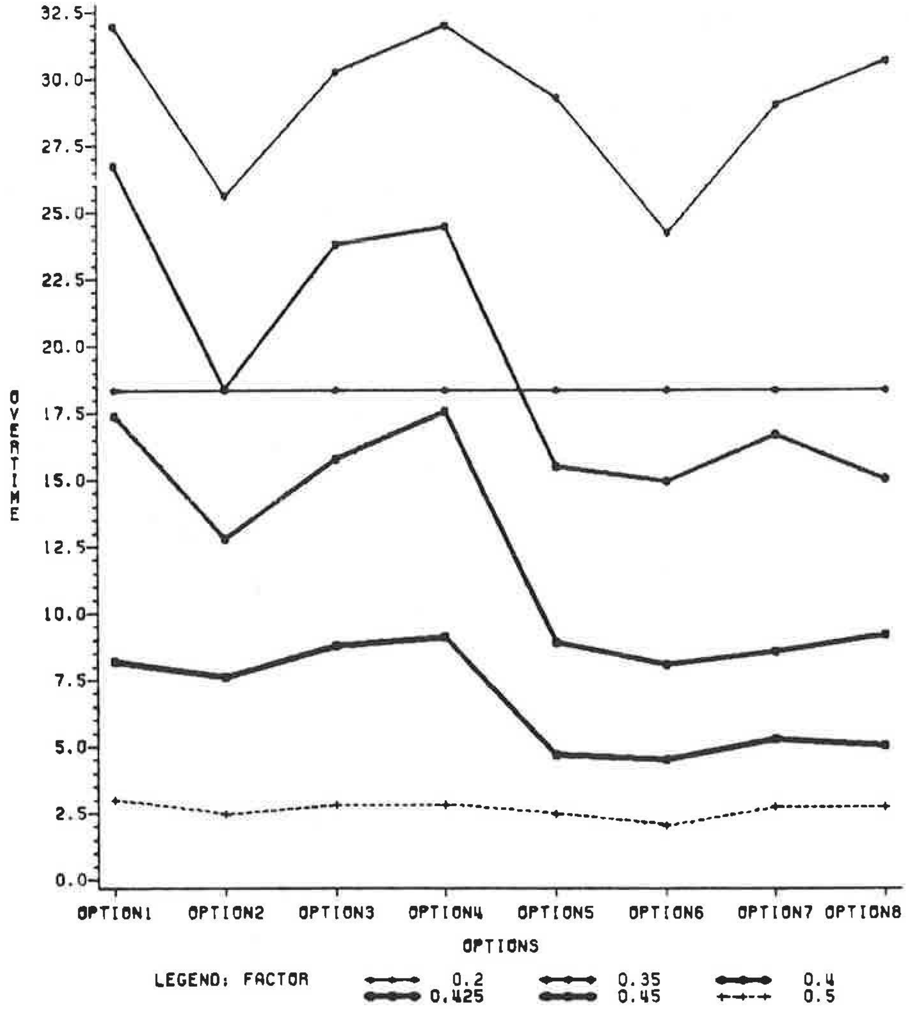

FIGURE 3 System performance (OTIME) of different repair policies.

As shown in Figure 2, it is evident that for values of the factor up to 0.425, the same repair policy is superior (i.e., Option 4). For other indicators, Option 6 is superior up to a factor of 0.425. After 0.425, repair resources move toward saturation. This means that when the value of the factor is more than 0.425, there is no competition among the failed entities for repair resources because there are more than enough available. As a result, when the system is saturated with available labor, the system performance for all options becomes approximately the same because efficient scheduling no longer matters. This means that when labor availability is excessive, there is no need for scheduling. Spinner, while researching the importance of scheduling, found that the same is true in other industrial applications of scheduling (18).

Waiting Time

For the simulation runs made with the base case parameters, Options 2 and 6 provided nearly the same level of performance. The important feature of both options is the limit on the maximum number of days a bus could wait before being scheduled for repair work. In this experiment, the sensitivity of system performance to the length of the waiting time constraint is analyzed.

The analysis is performed using Option 2 and varying the waiting time limit. The maximum waiting time limits considered in the experiments include 2, 3, 4, 5, and 10 days. The observed performance indicators for the various waiting times are given in Table 9. It is observed that the average time spent in the system (TSYS) increases with increased waiting time constraints. On the other hand, based on the value of TQUEUE and WQUEUE, the 4-day waiting time constraint seems to be better in comparison to the other waiting time limits. This result points out the importance of a proper waiting time limit on the system performance.

CONCLUSIONS

Presented in this paper were the results of a series of simulation experiments. The experiments were conducted to determine superior repair policies and test the sensitivity of repair policies with varied system conditions. From this study, it is concluded that

1. The performance of transit maintenance can be dramatically improved with the use of systematic repair scheduling rules.
2. The performance of transit maintenance varies widely with different repair scheduling policies.
3. Specific repair policies for scheduling are almost always superior regardless of the values of the system parameters.
4. The importance of efficient scheduling is increased when labor resources are constrained.

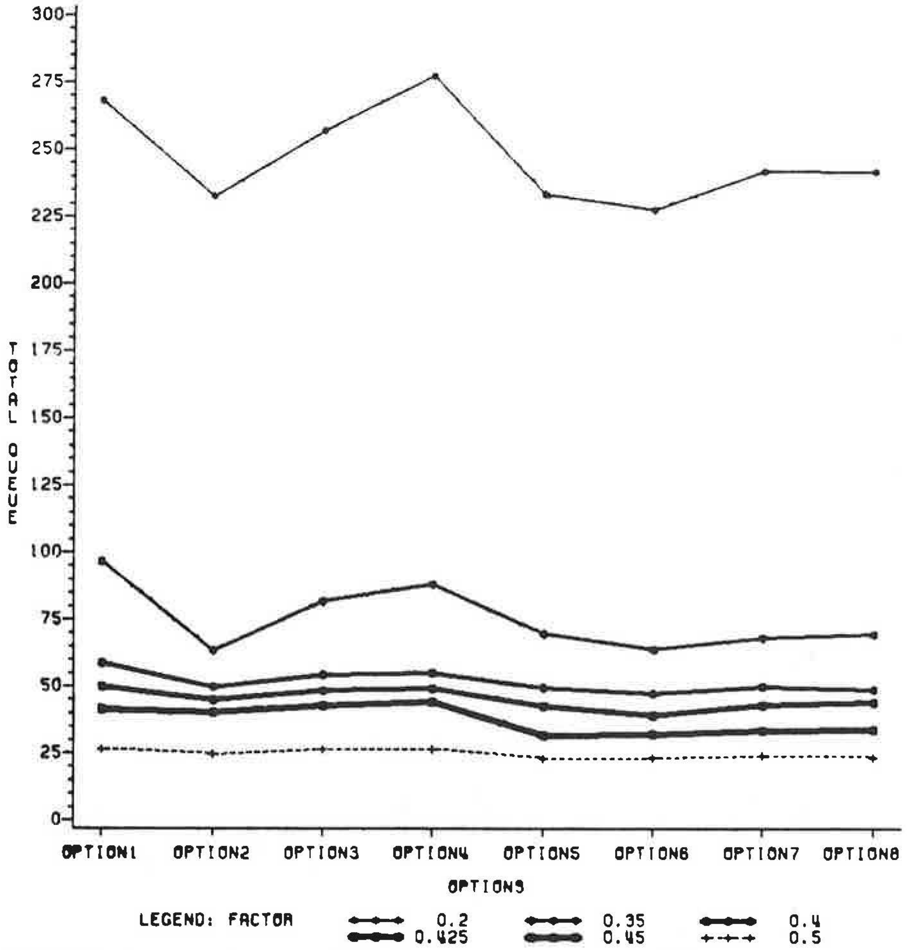

FIGURE 4 System performance (TQUEUE) of different repair policies.

5. Capital cost savings through reduction in spare buses can be accomplished at the expense of increased maintenance labor costs.
6. By assigning a higher priority to those failed buses that have waited for repairs more than the maximum waiting time, the system performance can be significantly improved.

RECOMMENDATIONS

Recommendations were derived for two subjects. The first involves transit industry policy designed to regulate the management of bus fleets (e.g., spare factor limits, maintenance standards, and age requirements for vehicle replacement). The second level deals with the future use of simulation analysis to study bus fleet management issues.

Policy Recommendations

In 1981 UMTA attempted to develop standard policy guidelines for transit maintenance (21). However, this effort was finally abandoned because of a lack of agreement on universally acceptable standards. The important point that UMTA's experience illustrates is the inability to prescribe specific sets of blanket minimum standards that are applicable and acceptable under all circumstances.

Experiments conducted in this study found that the superiority of specific scheduling policies is universal to all conditions. This finding is another demonstration that tested management methods (e.g., scheduling policies and other techniques) are universally applicable. This suggests that, if some assurance of proper maintenance is required, transit agencies should be advised by UMTA to institute proven management methods (e.g., repair scheduling techniques and other management techniques) instead of adopting blanket standards (e.g., minimum spare ratio requirements). Through the use of proven fleet management methods, the transit system's management has the flexibility to efficiently adjust their maintenance procedures to fit their own circumstances (e.g., fleet age, vehicle mix, duty cycle, labor wage rates, and terrain). On the other hand, blanket minimum requirements leave no room for flexibility.

Methodology Issues

As outlined earlier in the paper, the simulation methodology utilized in this study has the drawback of including only a limited number of events. This is an inherent problem in any simulation model that utilizes probability distributions to generate event occurrences. There are simply too many events to be able to economically derive probability distributions for each one. This necessitates using a limited subset of the possible events in the model. Simulation studies that use only a fraction of the system's activities in the analysis are generally appropriate for policy studies, but such simulations are of limited value to the study of operational is-

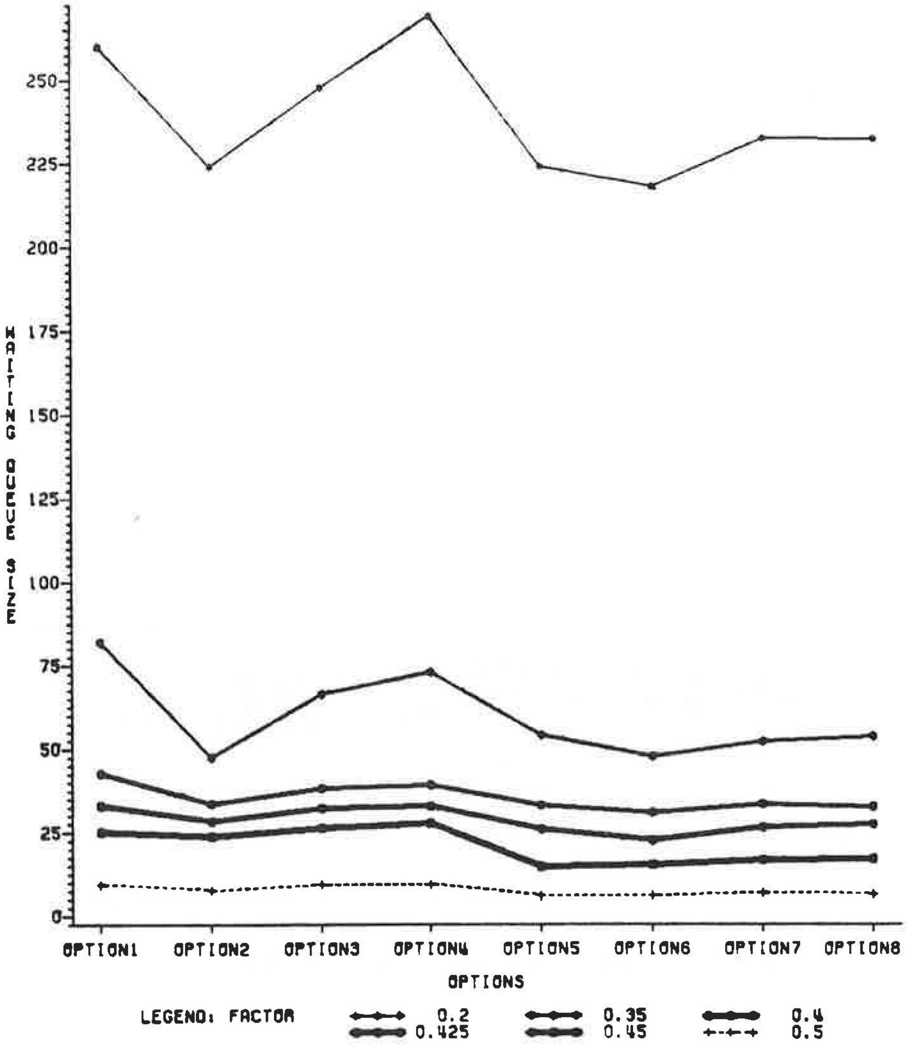

FIGURE 5 System performance (WQUEUE) of different repair policies.

TABLE 9 System Performance for Waiting Time Limit

Waiting Time (days)	TSYS	OTIME	TQUEUE	WQUEUE
2	16.96	18.32	232.2	223.8
3	17.29	18.32	226.7	217.3
4	17.27	18.32	224.7	215.1
5	19.91	18.32	232.2	222.9
10	18.45	18.32	229.8	220.3

Note: The total resource for this run during peak was 100 hr per day and the total resource for this run during offpeak was 75 hr per day.

sues. Operational issues require that the analysis provide information on the strengths of relationships with a high degree of confidence in the results.

A possible alternative to the use of a probability distribution-driven simulation model is the use of a trace-driven simulation model (22). A trace-driven model does not generate a stream of events from distributions. It uses a stream of historical events to drive the simulation. In other words, a simulated bus fleet assumes events in the same order that they were experienced by an operational fleet of buses. Therefore, all events that occurred in the period during which the data were collected are included in the simulated stream of events. Through the use of a trace-driven simulation, detailed analysis could be conducted of specific operational issues. However, whether future researchers use trace-driven simulation or some other approach, and before any detailed analysis can be conducted, richer and more complete data sets than those currently in existence must be made available to researchers.

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Discussion

Peter Wood*

Early last year, as in prior years, I had the opportunity to review two papers that were submitted for presentation at the Transportation Research Board's Annual Meeting. Both related to simulations of maintenance strategies. As usual, both papers were well written, scientifically sound, and included extensive bibliographies.

Some quotes from these papers follow. In the paper "Effectiveness of Improved Repair Scheduling in the Performance of Bus Transit Maintenance," the authors wrote "Maintenance workers are interchangeable and can perform all the repairs made at the central facility . . . all buses are the same model . . . maintenance equipment and tools are always available." In the paper "Exploring the Multiple Factor Concept for Bus Maintenance Using Simulation" (elsewhere in this Record), the authors wrote "The fleet is brand new . . . the maintenance manager must promulgate different PM interval guidelines for each of the garages."

Simplistic assumptions and unrealistic procedures such as these characterize virtually all the papers on this subject that I have reviewed over the past few years. This is unfortunate, because many of them contain useful ideas that, if implemented, could lead to some improvements in efficiency. However, when a paper based on artificial restraints, hypothetical data, and broad assumptions states that: "From this study it is concluded that the performance of transit maintenance can be dramatically improved . . ." it is not surprising that the transit industry dismisses it as yet another paper produced by an academic with no knowledge of the real world.

What can be done to make this work more useful, more usable, and, most important, more acceptable? First, let me state some assumptions of my own:

1. Data are, and always will be, inaccurate, incomplete, and out of date,
2. We should concentrate more on decision support tools and less on optimization under steady-state conditions, and
3. Any program, however good, that increases the workload of the maintenance manager, is likely to be ignored.

I will examine each of the assumptions in turn. First, I will consider data. Typical of the comments that appear in papers are: "Data are not presently available . . . not viewed as particularly meaningful . . . if reliable data could be collected the

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*The MITRE Corporation, 1820 Dolley Madison Boulevard, McLean, Virginia 22101.

concept would have significant merit . . . the results were misleading because the data were inconsistent." Similar statements have been made.

And yet, one model calls for "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 of and times for replacement, average costs of replacement, average cost of an accident, and bus preparation costs." Even if these data were provided, would anyone be prepared to guarantee their accuracy? In the remarks of British economist Sir Josiah Stamp (1880-1941), "The government is very keen on amassing statistics. They collect them, add them, raise them to the nth power, take the cube root and prepare wonderful diagrams. But you must never forget that every one of these figures comes in the first instance from the village watchman, who puts down what he damn well pleases."

It should not be believed that a 10 or even a 1 percent improvement in efficiency can be achieved if this is dependent on the generous availability of accurate data. Models should be designed using industry averages, modified where appropriate by local estimates, and refined whenever possible by validated data. These are the first steps toward utility.

Now to the second point. Most work on maintenance modeling today is based on maximizing efficiency in a steady-state environment. We have a given number of buses, a certain number of miles operated, component failures occurring at statistically established intervals, preventative maintenance performed at specified times, and so forth. A common objective is to minimize the maintenance cost per vehicle mile. If a more sophisticated model is being dealt with, an element will be included that relates to road calls (it is undesirable to run buses until they break down) and spares ratio (it is undesirable to concentrate on simple repairs only).

But how should the situation be handled where, for example, an attempt is being made to service and repair all the air conditioning equipment before the start of the summer? Or where a new fleet of buses is being introduced and several of the key mechanics are placed at the manufacturer's plant? What about the staff to handle the inevitable high level of initial failures? Because these are warranty repairs, they do not affect costs, but they certainly affect labor availability. The situation is even worse when a new bus design is introduced. And yet, these are real-world problems that a maintenance manager has to face. They are precisely the kind of problems that could usefully be handled through a simulation.

There is a class of software systems now being introduced under the general heading of "decision support systems." These are not intended to replace the manager, but to provide him with information on which he can make informed decisions by providing a range of acceptable alternatives, together with the advantages and disadvantages of each. In contrast to management information systems, which report the results of previous actions, decision support systems attempt to predict the results of future ones. They allow the manager to say "What if . . .?" and look at the results.

A simulation that, for example, aids in resource allocation (such as labor) is based on the data that are regularly available, takes into considera- tion the constraints that exist within a specific system, and allows the user to choose from a range of alternatives, is precisely the type of mainte- nance simulation that would be useful.

Such a system would satisfy my third assumption: It should be configured to minimize the demands on the user--for example, through the use of graphics and menus, and by requiring inputs to be of the simple "yes/no" variety--and to provide an explanation facility so that the user understands why a particular answer has been given.

Such a simulation could provide answers to questions such as "Which buses should be worked on so that the maximum number will be available for a special event?" "How should the work be scheduled during the period when two of my key employees will be at the manufacturer's plant inspecting the new bus order?" and "The level of service is being reduced by 10 percent; by how much can my maintenance costs be reduced?" Note that all of these are dynamic conditions, not the static conditions that have been assumed for most simulations.

How can such a simulation be worked toward? By concentrating on researching how a maintenance department is managed, rather than on how it is operated. An essential first step would be to establish the decisions that are being made by the maintenance manager in his day-to-day operational role. What are the steps that he takes in reaching these decisions? What information does he need? What information would make the decision-making process easier? Based on this information, the requirements of the simulation that would answer the maintenance manager's needs could then be examined. I have no doubt that such a simulation would be both useful and accepted, for at least four reasons:

1. Most decision making could be improved if more time were available to analyze the alternatives. An effective simulation would present a greater range of alternatives to the manager, together with an analysis of the impact of each.
2. The simulation capability would provide for improved decision making at abnormal times (e.g., if a type of bus developed a defect that required that all buses of that type be removed from service).
3. The manager could spend less time planning and more time managing, and
4. The simulation would be a valuable training tool, allowing a new or potential manager to assess the impact of various decisions "off line."

I have tried to provide some suggestions about how the many valuable ideas that these papers (on bus PM systems) contain can actually be "reduced to practice." I believe that this can be achieved easily by concentrating less on scientific abstractions, and dealing more with practical realities.

Authors' Closure

Although it is apparent that Wood's comments are directed at a number of papers and not just the authors' paper (Effectiveness of Improved Repair Scheduling in the Performance of Bus Transit Maintenance), it is perhaps fitting that the authors should respond to Wood's comments. In past years, the authors have written many of the papers to which Wood is referring.

From Wood's comments, two responses come to mind. First, Wood has articulately outlined responses the authors have received from many practitioners regarding their work. Indeed, practitioners have tended to view the authors' work as "yet another paper produced by an academic with no knowledge of the real world." However, the authors believe that Wood and other practitioners should not summarily dismiss academic studies solely because they are constrained by simplifying assumptions that fail to entirely duplicate real-world situations. Academics may be in an "ivory tower," but, from this perspective, they can perhaps "see the forest" while practitioners get distracted by the "trees" of assumptions.

Second, Wood's recommendation regarding the development of dynamic computer modeling tools that can be directly applied to day-to-day maintenance problems is sound. In fact, in two previous papers, the authors reached the same conclusion and suggested approaches for the development and use of such systems (1,2). However, there are many reasons why such models have not been developed and, on closer inspection of the state of the practice of bus maintenance management, the authors believe that such models may not even be warranted.

MAINTENANCE MANAGEMENT DECISION SUPPORT SIMULATIONS

Wood is correct in asserting that the lack of quality data is a common scapegoat for the lack of computerized simulations of maintenance management decisions. However, lack of data is not the only problem. It has been the authors' impression that transit maintenance managers do not value these tools or recognize the need for the research needed to develop them. All too often, this is because transit maintenance managers attained their positions because of their experience and knowledge of maintenance, not because of their formal (or informal) training in management.

Transit maintenance managers, like all other managers, should be managers first. Only when maintenance management is raised to the same level of professionalism as other transportation system managers (e.g., transportation engineers, planners, and accountants) will the need for better management support systems be recognized. Because there is no perceived need, there is no pressure for the development of more sophisticated tools. Without such pressure, there will be little funding for the development of maintenance management decision support tools. Without dramatically increased levels of funding, it is unlikely that useful decision support systems will be developed.

It seems realistic, however, to believe that the modest funding that may be available could support the research required to develop static management principles to direct decision making under a number of significant "real-world" situations. To illustrate the value of applying sound management principles to maintenance management, consider the San Juan Metropolitan Bus Authority, which, 10 years ago, was troubled by having too many of its buses tied up in the maintenance shop. Even though they had a spare ratio of almost 50 percent, some runs were missed because of the unavailability of buses (3). Management asked an academic industrial engineer, who was not a bus maintenance expert, how to increase the vehicle flow through the maintenance shop. He drew on scheduling-sequencing theory, which has proved that the flow through a simple system is maximized when the backlogged jobs that require the shortest time are done first (4). Therefore, he advised that when the shop supervisor assigns a job to a mechanic from the maintenance backlog, the job that appears to require the least time to repair should always be selected. The shop supervisors of the San Juan Metropolitan Bus Authority followed this simple management principle and within 3 months, bus unavailability was decreased by nearly 50 percent.

Given that conditions in a bus maintenance system are subject to dynamic change, maintenance management is probably better equipped if they have simple management principles for instant application to day-to-day decisions rather than a cumbersome, data-intensive computer simulation model.

THE "IVORY TOWER" SYNDROME

At the 1986 Annual Meeting of the Transportation Research Board, two bus maintenance simulation papers were presented that were apparently reviewed by Wood. One paper, by List, Satish, and Lowen (elsewhere in this Record), sought to show that it is important to use other variables besides mileage (e.g., hours of bus use and the duty cycle) to trigger the need to conduct preventive maintenance. The other paper was the authors', which sought to show that is is important to rationally sequence the order of processing maintenance work through a maintenance facility. Both papers resulted in findings that seem obvious: (a) maintenance managers should consider service attributes other than the mileage traveled when deciding on preventive maintenance intervals, and (b) they can improve the flow of bus repairs through the maintenance facility if they sequence repairs with regard to the length of time required to make a repair.

The significance of these papers is that they confirmed their findings through the use of computer simulations that are dramatically less expensive and time consuming than experiments with an actual maintenance system. During the simulation experiments, the researchers made simplifying assumptions to allow the work to fit within the meager resources allotted to them (both studies originated through the modeling work of a graduate student completing a thesis). Both made assumptions which, as Wood noted, do not reflect actual bus maintenance operations. However, both papers had useful findings that can be converted to sound maintenance management principles. It would be unfortunate if practitioners ignored these principles only because they were based on work that made simplifying assumptions. They would then fail to see the forest because of overconcern with suspect details (the "trees").

CONCLUSIONS

Wood's and the authors' arguments may be moot, however. Given the current austere conditions for funding of academic research on transit maintenance management issues, it is likely that there will be little research to create any sort of simulation of bus maintenance systems. However, the authors believe that if there is any funding available in the area of bus maintenance research, it would be more fruitful to examine the relationship between management actions and system performance. From such examinations, the researchers could recommend management principles that appear to improve performance.

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