doubt until actual operational experience is obtained. Since our paper was written, further information (1) has come to our attention. This information indicates that snow removal can be achieved for elevated guideways by a satisfactory mechanical means. The open grill would not be contemplated in cases in which dripping of oil or other debris might be hazardous; its primary use might be in cases in which the guideway is inaccessible to the public and airborne noise is not a problem.

The second problem clearly illustrates the need for recognition of guideway constraints in vehicle design as well as the more usual converse. A subway vehicle operating in tunnel provides essentially no opportunity for access to vehicle components. Thus, in the event of failure, the other vehicles of the train provide a self-rescue capability. There are only two cases for the Toronto Transit Commission subway in which there is a need for access underneath the vehicle: if the operator needs to free a tripped emergency brake and to free a suicide victim from the vehicle undercarriage. The LRT line for which this guideway is designed would operate multicar trains; therefore, the need for operator intervention is reduced since it is preferred policy for a faulty vehicle to be towed out of service rather than for the operator to attempt to repair it. If there are some functions the operator must reset after a fault, it should be a straightforward matter to modify the vehicles with reset mechanisms that are accessible from the walkway, if not from the vehicle interior. In this study, it is preferred to modify the vehicles rather than the guideway on the line because it is expected that the initial existing LRV operating on the line will ultimately be replaced by a vehicle designed for exclusive right-of-way operation. Thus, the guideway concept is designed to reflect ultimate rather than immediate needs.

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Publication of this paper sponsored by Committee on Rail Systems Planning and Development.

Model for Cost-Effective Maintenance of Rail Transit Vehicles in Urban Mass Transit Systems

Stephen R. Rosenthal, Jerome D. Herniter, and U. Peter Welam, School of Management, Boston University

A new computer-based model to assist rail transit management in determining maintenance schedules for rail transit vehicles is presented. The model evaluates the aggregate cost and service implications of conducting prescheduled inspections and preventive maintenance activities for the various components of a transit vehicle. The model also consolidates information on size of vehicle fleet, cost of maintenance and repair of vehicle parts, relations between maintenance frequency and subsystem failures, and historical patterns of the different types of in-service breakdowns. On this basis, the model determines relations among preventive maintenance alternatives, average number of transit cars available for peak service, expected number of in-service car failures, and the total cost of maintenance and repair. The model was originally developed for use by the Massachusetts Bay Transportation Authority in Boston. Preliminary findings in the initial application of the model to generate and evaluate alternative maintenance schedules for the authority's Red Line suggest that use of the model could result in noticeable, though probably not dramatic, savings for this particular line. The authority intends to refine the data used in these analyses and to extend the use of this model to its other lines. The model is a conversational FORTRAN program. It can be adopted for use in any rail transit system that has the required data on vehicle maintenance and repair activities.

Transit vehicles, like most complex pieces of equipment, are prone to unforeseeable failure. Although preventive maintenance programs may keep the frequency and nature of nonscheduled repairs within acceptable bounds, the notion of acceptability is subjective from the rail transit management's point of view. In-service breakdowns will disrupt the scheduled flow of cars along the line and directly inconvenience or even endanger the passengers. Up to a point, a transit system manager will naturally desire to keep the cars in working order through a regular program of preventive maintenance. Maintenance, however, is a non-revenue-producing activity and must be kept within reasonable bounds. If service reliability is satisfactory and accidents are rare, then transit managers are unlikely to expand their preventive maintenance programs. The costs and impacts of vehicle inspection and repair activities must be identified before a sense of the economic trade-offs between preventive and remedial work can be gained.

To aid transit managers in appreciating these trade-offs and to help them in evaluating alternative vehicle maintenance schedules, we have developed the Maintenance Analysis and Scheduling System for Transit Management (MASSTRAM), which is a computer-based model. MASSTRAM analyzes the cost and service implications of alternative preventive maintenance strategies for various subsystems of the vehicle and displays tabular and graphical data that identify various trade-offs between costs and service loss. MASSTRAM is programmed in FORTRAN and is designed for conversational interaction with the user.

This paper describes the vehicle maintenance problem and the basic concepts and capabilities of MASSTRAM. Preliminary findings are presented for the initial application of the model by the Massachusetts Bay Transportation Authority (MBTA) to a rapid transit line in the Boston area. The application efforts described include plans for the implementation of a controlled experiment in which the effect of alternative preventive maintenance intervals is estimated. The paper concludes with some observations on the possible implementation of MASSTRAM elsewhere.

VEHICLE MAINTENANCE PROBLEM

The essential contribution of a preventive maintenance program is the support it provides for the delivery of high-quality transit service. At one level, the dependencies of transit service on vehicle maintenance are largely intuitive. Transit service is measured in a variety of ways such as convenience, speed, safety, and comfort. Convenience and speed depend in part on the establishment of reasonably short headways (the time interval between consecutive trains on the same line). The feasibility of meeting headways clearly depends on the size of the fleet, the percentage of the fleet that is in running condition, the physical layout of the line, and the operating speed of the vehicles. Perhaps another less obvious condition is the type and frequency of in-service breakdowns that also affect the achievement of target headways, since these breakdowns disrupt the planned flow of vehicles. By influencing the effective size of fleet and controlling the likely breakdown rate, the vehicle maintenance policy partially determines the convenience and speed of the transit service. Passenger safety and comfort, both important measures of transit service, are also affected by maintenance policy.

The requirements for preventive maintenance are determined by many factors such as the design of the transit vehicle, the physical layout and condition of the line, and the age of the fleet. One other crucial factor that deserves special mention is the number of spare vehicles. At any time, one may calculate how many spare vehicles exist by subtracting the number of vehicles needed for use in peak-period service from the total number available for use. By this definition, the number of spare vehicles will vary daily because some vehicles are brought in for inspections or repairs and others that were in the repair shop are returned to the pool of available cars. Thus, spare vehicles reduce the impact of failures by providing a backup supply.

If the number of vehicles in the total fleet barely exceeds the established peak-hour requirement, it is likely that the number of spares will always be low and the pressure to keep all vehicles in good working condition constant. Multiple breakdowns in a single day can eliminate the stock of spare vehicles for the next peak period, thus making it impossible to meet the desired headways. In such a situation, a carefully designed, comprehensive, preventive maintenance program is crucial since routine inspections, timely minor repairs, and adjustments are needed to guard against frequent major breakdowns. Paradoxically, when the repair needs of the fleet are small, it is difficult to implement intensive and frequent preventive maintenance. Thus, this procedure requires that a number of different cars be taken out of service each day for routine inspections, thereby reducing the number of spare vehicles available for service that day. However, it is possible to schedule preventive maintenance activities during the night shift, as is done in Philadelphia. Short of purchasing more vehicles to supplement the existing fleet, this reduction in spare vehicles can only be countered by an increase in the planned headways, an increase that is large enough to provide for an adequate number of spare vehicles that could be properly maintained and used as a cushion against emergencies. Thus, when a few spare vehicles are available, the strategic decision regarding the optimal frequency of preventive maintenance may center on a trade-off between achieving the planned headway or experiencing an increased variability in headway to account for unplanned, in-service breakdowns. (Current practice in the transit industry seems to stress a marketing strategy for meeting publicized headways.) Thus, it seems unlikely that a decision would be made to increase the existing headways on a regular basis for accommodating the more extensive or frequent preventive maintenance of vehicles. It is more likely that this trade-off would be explicitly determined and acted on in cases such as designing and scheduling new transit systems or new fleets of vehicles on existing lines.

In contrast, a different kind of situation may arise when a large number of spare vehicles are available. For example, the costs for the preventive maintenance program might be cut, if vehicles that break down can be replaced from a large number of spare vehicles. However, this strategy is short term, and the fleet will gradually deplete because deferred maintenance results in serious vehicle failures that necessitate major overhauls before these vehicles can be returned to active duty. Eventually, the original surplus will no longer exist and the resultant failures will have incurred other costs because of service disruptions and adverse passenger reactions. Despite these long-term dangers, transit managers are often faced with severe budgetary pressures and they often view the cutback of preventive maintenance activities as an easy short-term saving.

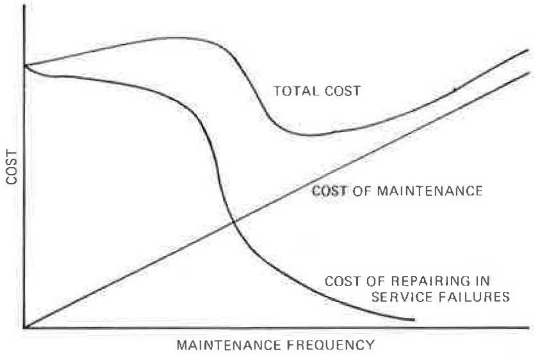
Each transit system needs to define a vehicle maintenance program with capacities and capabilities that best meet its own special performance requirements. Viewed from this system perspective, a vehicle maintenance program is undoubtedly a crucial component of a viable transit service policy. But how much maintenance is appropriate? And, at what frequencies should maintenance be performed? These are the questions that demand a careful cost-benefit analysis. MASSTRAM, a conversational FORTRAN program, has been designed and developed to aid transit managers in performing this task.

COST-EFFECTIVE CONSIDERATIONS

Preventive maintenance involves the repair of items or the restoration of certain components to their initial operating condition (e.g., lubricating, wheel trueing, filling brake cylinders and hoses with appropriate liquids and gases, cleaning out motors with compressed air). For any particular fleet of transit cars, a preventive maintenance program attempts to find a cost-effective balance between two opposing forces. Not enough preventive maintenance leads to costly service-disrupting vehicle failures, and too much preventive maintenance incurs unnecessary expenses and unjustifiably reduces the number of in-service cars. More specifically, the two types of costs that must be balanced are (a) the cost of scheduled inspections for regular adjustments, repairs, and replacement of components that might not last until the next scheduled inspection; and (b) the cost of repairing and replacing a component that failed while the train was operating and carrying passengers. Thus, the overall goal of any analytic effort to establish or review a preventive vehicle maintenance policy is to aid management in identifying the desirable balance among these opposing forces.

The curve shown in Figure 1 for cost of repairing in-service failures indicates that, the more frequent preventive maintenance is, the greater the reduction in failure rates and repair costs associated with such failures will be. This will be the case for vehicle components that fail because of wear and tear (e.g., brake shoes) or age (e.g., rubber hoses). Since a transit car

Figure 1. Cost functions for maintenance and repair.



has many components with these characteristics, a more active preventive maintenance program will generally result in fewer expected failures over a period of time. Naturally, in any particular situation there are uncontrollable factors such as a major snowstorm that can lead to component failures despite the existing level of preventive maintenance.

Another dimension of the maintenance-failure relation is service reliability. Certain serious breakdowns will render a vehicle unusable; thus the passengers will have to be discharged and the transit line will be delayed until the crippled vehicle is cleared away. The ultimate costs of such incidents are hard to determine since crucial considerations such as loss of patronage and public confidence are not easily converted to dollars and cents. Nevertheless, some indication of the trade-off between hard dollars spent on maintenance and repair and soft dollars attributed to in-service failures should be made available to transit management.

MASSTRAM was developed to satisfy this need in two stages. First, as shown in Figure 1, total tangible costs are minimized by establishing an economic balance between the costs of scheduled inspections and the costs of repairing and replacing components that fail while the train is operating and carrying passengers. The maintenance schedule leading to this cost minimum is evaluated in terms of in-service failures or the expected number of cars available for peak service.

Second, with these trade-off estimates, management can proceed to select the most desirable alternative that is based on an implicit valuation of service considerations. Thus, MASSTRAM assists management in selecting a maintenance schedule that will be cost-effective over the course of the existing planning horizon. Since MASSTRAM is designed to reflect aggregate performance over a period of time, it does not attempt to predict the probability of different patterns of occurrences within a single planning period.

DEVELOPMENT OF MASSTRAM

MASSTRAM is a flexible planning tool that can be readily applied by transit managers to the type of complex assessment just described. Therefore, in the development of this model, it was especially important to include certain generalized capabilities that would allow different users to tailor the model to their own needs. Several important considerations were represented that included levels of maintenance, level of aggregation for planning horizon, and rail vehicle representation.

Levels of Maintenance

There are three benchmark levels of maintenance for a fleet of transit cars: (a) daily inspection, (b) regular periodic maintenance at 6400 to 19 200-km (4000 to 12 000-mile) intervals, and (c) overhauls at 320 000-km (200 000-mile) intervals. The daily inspection usually amounts to no more than a quick visual check of certain key components before a transit train is brought into service. In contrast, overhauls can vary in terms of scope and intensity that range from putting on a new coat of paint to completely disassembling a transit car or replacing and repairing a number of major components. Thus, a vehicle may undergo only one or two major overhauls during its useful economic life, whereas regular periodic maintenance is done several times a year.

The regular periodic maintenance typically involves an average of 20 to 25 person-h of work/transit car. It is roughly analogous to the periodic tune-ups and inspections that a conscientious automobile owner performs to ensure that his or her car is running safely and properly. In many transit systems, the regular periodic maintenance is actually a program of different maintenance tasks to be carried out at different intervals. For example, the Green Line streetcars of the MBTA in Boston are given an A-inspection every 6400 km (4000 miles) and a more thorough and comprehensive B-inspection every 12 800 km (8000 miles). The maintenance shops for the Bay Area Rapid Transit (BART) in San Francisco schedule a more comprehensive maintenance activity every third inspection interval, rather than trying to do the same work at each of the monthly checkups. The maintenance shop for the Port Authority Transit Corporation (PATCO) in Philadelphia schedules increasingly comprehensive maintenance at 4800, 19 200, 57 600, 115 200, and 384 000-km (3000, 12 000, 36 000, 72 000, and 240 000-mile) intervals. The Red Line of the MBTA used an A-inspection every 6400 km (4000 miles) and a B-inspection every 12 800 km (8000 miles) until 1971. At that time, a new inspection and maintenance procedure was instituted to be performed every 8000 km (5000 miles).

MASSTRAM is primarily designed for evaluating long-term policies that are relative to regular periodic maintenance. It is not designed to generate daily maintenance schedules, give details regarding the specific cars to be inspected on a given day, or designate specific work crew assignments. Though MASSTRAM is not currently designed to include the vehicle overhaul activity, it can easily be extended to evaluating the overhaul schedules in situations in which the same set of maintenance facilities are used for both periodic maintenance and overhauls. For example, the PATCO system in Philadelphia has one maintenance facility at the end of the line. For such a transit system, an overhaul can be treated as an extensive maintenance operation. This situation is in contrast to a system such as BART that has three maintenance facilities; two facilities concentrate on periodic maintenance and a third facility does both periodic maintenance and major overhauls. It is possible to use MASSTRAM for analyzing the overhaul schedules in this situation; however, this procedure is more complicated. At MBTA, overhaul and periodic maintenance are performed in geographically distinct locations, and the heavy maintenance shop caters not only to rapid transit cars but also to streetcars and buses. In this type of situation, MASSTRAM is primarily applicable to establishing policies for regular periodic maintenance (e.g., generation and evaluation of the intervals at which the different components of the cars in the fleet should be maintained).

Level of Aggregation for Planning Horizon

Budgetary cycles of 1 year are standard for most transit authorities. Since budget preparation and control are one important area of application for MASSTRAM, its standard planning horizon is also 1 year. However, the planning horizon can be changed to any length desired. For example, in negotiating a labor contract, management can use MASSTRAM to evaluate the impact of new hourly rates on maintenance costs and to determine whether the new rates would make a shift in the maintenance schedule desirable. In such a situation, a planning horizon equal to the contract period may be more meaningful than the standard 1-year horizon. Similarly, in planning for a completely new fleet of vehicles, a planning horizon equal to the warranty period of the most important components might be desirable.

Rail Vehicle Representation

As a strategic planning model, MASSTRAM does not explicitly recognize particular rail transit cars. Instead, it functions in terms of an average transit car. (Equivalently, MASSTRAM can use an entire fleet of vehicles as its basic unit of analysis, since, in concept, the characteristics of the total fleet and associated maintenance criteria can be represented by the characteristics of the average car in the fleet multiplied by the number of vehicles in the fleet.) However, vehicle maintenance policy alternatives are not identified in terms of an entire train; individual cars; or the several major systems of a rail vehicle such as the control system, truck, or car body. Indeed, a key contribution of a model such as MASSTRAM is to identify the tradeoff possibilities among alternative maintenance options for the many different subsystems of the vehicle. (MASSTRAM incorporates decision rules for constructing cost-effective maintenance cycles.) The extent to which a transit car should be represented by systems and the extent to which these systems should be separated into subsystems are important technical decisions that have managerial ramifications. When the particular set of subsystems to be included in MASSTRAM are specified, unnecessary detail must be traded off against oversimplified aggregations.

In the initial application of MASSTRAM to the Red Line of the MBTA, a transit car is represented as a collection of 26 subsystems. These subsystems are as follows.

System and Code	Subsystem
Control	
co01	Motor generator
co02	Compressor
co03	Compressor motor
co04	Compressor switch
co05	Heat and fan
co06	d-bar cable and button banks
co07	Cineston
co08	Relays and switches
co09	Grids and connections
Trucks	
tr01	Truck frame
tr02	Wheels
tr03	Contact shoes
tr04	Emergency trips
tr05	Hand brake and cable
tr06	Drawbar
tr07	Brake shoes
tr08	Suspension
tr09	Operating unit
Air brakes	
ab01	Cineston and d-man control
ab02	Batteries
Motors	
mo01	Traction motors
mo02	Brushes
Car body	
cb01	General condition
cb02	Window glass
cb03	Destination signs
cb04	Door, light, and crew signal equipment

By using this set of categories, the level of detail through which different systems are represented intentionally varies. What one abstractly represents as a subsystem in MASSTRAM may physically correspond to a very specific item (e.g., the compressor switch) or to a large group of individual items (e.g., relays and switches). The grouping of items into subsystems is primarily guided by physical proximity, functional similarity, and similarity with respect to the type of tasks performed during an inspection.

APPLICATION OF MASSTRAM

MASSTRAM can aid management in setting cost-effective maintenance schedules by (a) evaluating any specified schedule, (b) determining an optimum schedule subject to conditions imposed by the management, and (c) providing curves that show the trade-off between maintenance costs and number of failures.

As an introduction to MASSTRAM, a sample set of model output is presented below. Although realistic, these outputs are only illustrative. A comparison between the standard schedule in which all subsystems are maintained at 8000 km (5000 miles) and a modified schedule in which some subsystems are maintained at 6400 and 12 800-km (4000 and 8000-mile) intervals is given below.

Item	Standard	Modified
Estimated hours for maintenance		
Straight	17 110	17 110
Overtime	6 844	4 572
Total	23 954	21 682
Inspection	5 967	5 112
Emergency	17 987	16 570
Vehicle status		
Vehicles in service per day	105	109
Vehicle-hours out of service	197 771	181 538
Vehicle failures	3 444	3 185
Maintenance costs, $		
Regular	222 000	222 000
Overtime	102 000	68 000
Total	324 000	290 000

The modified schedule is the least costly schedule under the condition that the schedule contains, at the most, two different maintenance intervals. In this comparison, the modified case shows an expected annual net saving of 2272 h (about 10 percent) for maintenance labor. The modified case requires fewer hours per year for scheduled inspections (855 or 14 percent) and fewer hours for emergency repairs (1917 or 8 percent). In this illustrative comparison, the expected net annual savings of $34 000 (about 10 percent) is due entirely to a reduction of overtime costs. The costs for parts that were ignored in these sample runs would tend to make maintenance more frequent. The modified maintenance schedule not only costs less but should also result in better service since fewer (259 or 8 percent) in-service vehicle failures are expected during the year and the annual vehicle-hours lost are reduced by 16 233 h. On the average, this results in having four more vehicles available for service on this line.

Table 1 gives the detailed subsystem evaluations for the modified schedule. Subsystem evaluations are listed in terms of the expected person-hours required for regular inspections (i.e., preventive maintenance) and emergency repairs, the estimated number of failures per year, and the associated annual vehicle-hours out of service. Note that the subsystems are maintained at 6400 and 12 800-km (4000 and 8000-mile) intervals.

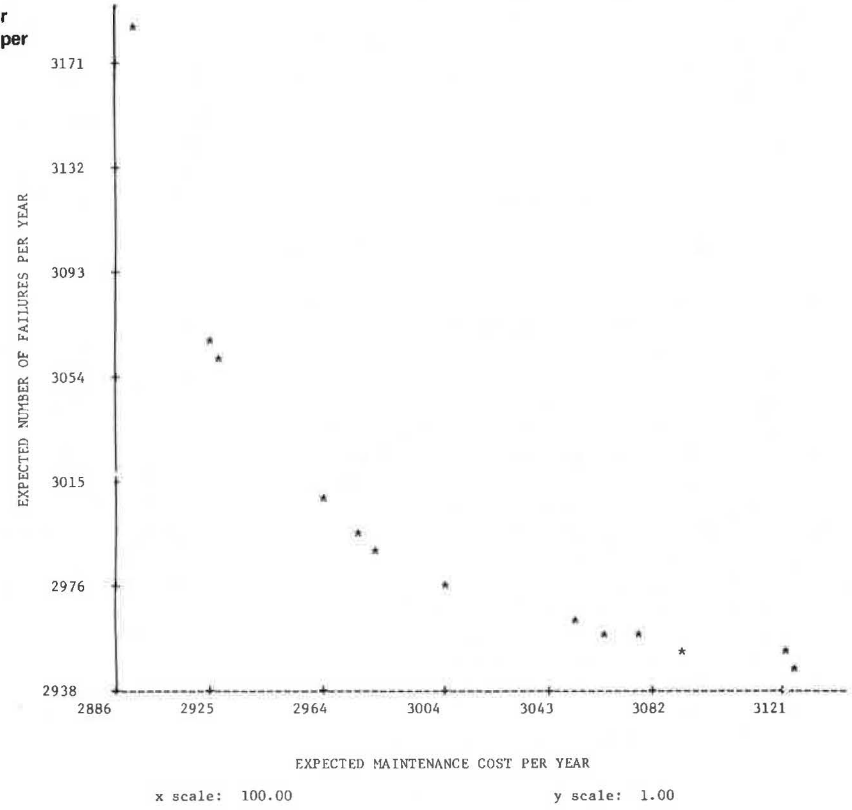
If Table 1 were compared with a table for the standard program of 8000-km (5000-mile) intervals, it would show the expected net changes required for preventive maintenance and nonscheduled repairs. For each subsystem that has been shifted to a 6400-km (4000-mile) inspection interval, the number of failures will decrease since the preventive maintenance effort is increased. The opposite occurs for those subsystems that have been

Table 1. Sample output of MASSTRAM for subsystem evaluation.

Code	Subsystem	Maintenance Interval (km)	Expected Person-Hours Required for Maintenance			Out-of-Service Vehicle-Hours per Year	Vehicle Failures per Year
			Regular	Emergency	Total		
ab01	Cineston and d-man control	12 800	83	73	157	122	5
ab02	Batteries	12 800	75	160	235	1 523	23
cb01	General condition	6 400	442	680	1122	9 443	227
cb02	Window glass	6 400	233	678	911	2 594	75
cb03	Designation signs	6 400	83	9	93	97	9
cb04	Door, light, and crew signal equipment	6 400	525	2475	3000	27 831	619
co01	Motor generator	12 800	71	53	124	2 520	42
co02	Compressor	12 800	71	206	276	4 263	137
co03	Compressor motor	6 400	0	0	0	0	0
co04	Governor switch	12 800	63	33	95	1 105	33
co05	Heat and fan	6 400	125	1936	2061	3 228	242
co06	d-bar cable and button banks	12 800	112	137	250	1 246	91
co07	Cineston	12 800	79	201	280	2 361	101
co08	Relays and switches	12 800	500	1803	2303	20 193	451
co09	Grids and connections	12 800	75	561	636	3 930	70
mo01	Inspect trac motors	6 400	508	2202	2710	11 512	183
mo02	Motor brushes	6 400	0	0	0	0	0
tr01	Truck frame	6 400	600	1931	2531	14 093	161
tr02	Wheels	12 800	292	572	864	2 551	36
tr03	Contact shoes	6 400	250	2039	2289	23 652	255
tr04	Emergency trips	12 800	150	189	339	1 777	47
tr05	Hand brake and cable	12 800	83	81	164	1 268	40
tr06	Drawbar	12 800	100	6	106	139	4
tr07	Brake shoes	12 800	125	20	145	1 038	20
tr08	Suspension	12 800	192	309	501	5 691	206
tr09	Operating unit	12 800	275	215	490	4 412	108

Note: 1 km = 0.6 mile.

Figure 2. Plot of expected number of failures per year as a function of expected maintenance cost per year.



shifted to a 12 800-km (8000-mile) interval. However, the total annual cost related to any particular subsystem may either increase or decrease depending on the net aggregate change between the preventive and failure-responding efforts. On balance, considering all of the vehicle subsystems together, this modified schedule represents a less intensive preventive maintenance program than the standard 8000-km (5000-mile) inspection program.

MASSTRAM can be used to examine a broad range of trade-offs between increased preventive maintenance and decreased in-service vehicle failures. A set of efficient schedules can easily be determined for which the expected number of failures is reduced with a minimum increase in the associated total cost. A set of results for schedules of 6400 or 12 800-km (4000 or 8000-mile) intervals for vehicle subsystem inspection is given below.

Expected Maintenance Cost per Year ($)	Expected Failures per Year	Expected Maintenance Cost per Year ($)	Expected Failures per Year
289 768	3185	299 799	2985
292 271	3069	303 416	2969
292 637	3062	305 236	2962
296 130	3016	306 024	2960
296 995	3005	307 835	2956
297 899	2997	310 929	2951
298 736	2991	311 841	2950

For each line of the table, MASSTRAM will have determined a complete maintenance schedule such as that shown in Table 1. Figure 2 shows a plot of the frequency for this cost-failure trade-off that can also be generated by MASSTRAM. The cost increases shown in the plot and the table arise when some of the subsystems are rescheduled from 12 800 to 6400-km (8000 to 4000-mile) intervals. The specific sequence of these changes is designed to be the most cost-effective way of achieving a particular reduction in the total number of failures. Thus, management must select the maintenance schedule that will best serve the opposing cost and service objectives of the transit system during the current planning horizon.

Data Requirements

The input data required by MASSTRAM are given below.

1. General operating statistics include (a) total kilometers for all vehicles on the line during a specified time period, (b) total number of serviceable vehicles, (c) number of required vehicles for peak service, and (d) average time for moving an in-service vehicle to the repair shop.
2. Maintenance and repair crew characteristics include (a) average annual working hours for each type of repairman (straight time and overtime), (b) number of available workers and average hourly wage rate for each type of repairman, and (c) overtime pay rate.
3. Maintenance and repair-related activities and events organized by subsystem include (a) number of workers in each category required for maintenance or repair of each subsystem together with the average elapsed time per worker for performing a particular task, (b) direct material cost attributable to maintenance or repair activities, (c) average number of hours for holding a transit car when a subsystem must be repaired because of in-service failure, (d) maintenance interval in number of kilometers between the scheduled inspection of each vehicle subsystem, (e) failure rate (per 16 000 km) that is related to the maintenance interval being used, and (f) probability of a subsystem failing and a vehicle needing repair.

The availability of machine readable input data is a fundamental assumption in the design and construction of MASSTRAM. The effective use of MASSTRAM requires an automated data collection and processing system such as the Maintenance Planning System (MPS) that is currently used in the BART system or the Computerized Maintenance Record System (CMRS) that is soon to be installed for the Red Line of the MBTA. Such preexisting data bases would not be organized to feed MASSTRAM directly with data. Instead, summarized data from these systems would be used.

The current MASSTRAM data base for the Red Line was assembled by using a combination of interviews and previously conducted special purpose studies and sampling the manually kept historical records. Interviews with the car house foremen yielded subjective estimates for much of the required data. In this manner, relations between maintenance intervals and failure frequencies for the different vehicle subsystems were obtained. These estimates were then converted to quantitative form for use by MASSTRAM.

The only true means of verifying the maintenance interval-failure rate relations is to collect actual performance data while the maintenance intervals are being varied. This can be accomplished experimentally by intentionally changing the maintenance interval for selected subsystems on a number of rail vehicles. Experimenting with a shorter maintenance interval involves some additional cost but no added risk. At longer intervals, the subsystem should be closely monitored so that if a failure appears imminent it can be tallied as a failure and repaired at once. In this way, longer maintenance intervals can be tested without increasing in-service failures during the course of the experiment. This experimental procedure is being adopted at the Red Line by the MBTA to provide systematic data for refining the failure rate relations and to encourage a movement toward a more cost-effective maintenance program.

Managerial Prerequisites

Satisfying the input data requirements is only one of the prerequisites for a successful implementation of MASSTRAM. There are three other key organizational requirements: direct operations management involvement, a predictable work environment, and a rational budget-making process. Each of these aspects is briefly discussed below.

Once a maintenance schedule is established, it must be carefully implemented and monitored. Successful use of the model requires not only that cost-effective maintenance schedules be determined, but also that they be achieved. If the maintenance schedules are not achieved, the problem may well be in the area of management and control rather than in the realm of strategic planning for which our model has been developed. If technological or labor-related practices tend to be unstable, generating an unpredictable work environment, then implementation and control actions by management can become especially difficult.

Furthermore, it is important to realize that this evaluation model, like others applied elsewhere, can do no more than aid management in making rational and informed decisions. It is ultimately up to management to interpret the output of the model in light of available options and costs. In the case of rail rapid transit systems, managers of vehicle maintenance must be committed to the installation of a complete planning

Figure 3. Contribution of MASSTRAM to improve transit system management.

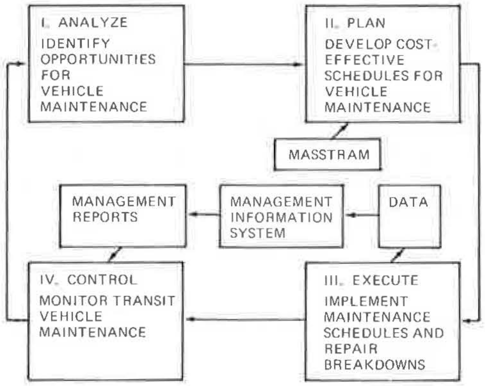
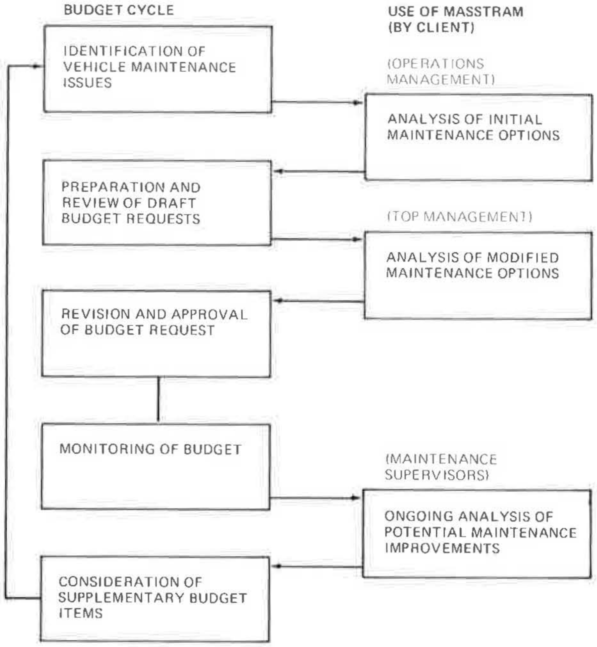


Figure 4. Use of MASSTRAM throughout budgetary cycle.



and programming approach to decision making. The major features of such a managerial approach, as shown in Figure 3, involve a continuing cycle of program planning, execution, control, and analysis.

Within such a planning and control process, MASSTRAM can aid management in the following types of activities:

1. The development of alternative guidelines for vehicle maintenance scheduling within a fixed budget or manpower allotment,
2. The determination of budgeting/manpower implications of changes to the maintenance schedule or intensity,
3. The projection of budgeting/manpower implications of trends in vehicle breakdown (as related to maintenance schedules),
4. The assessment of how potential provisions of new labor contracts could affect cost-effective vehicle maintenance schedules,
5. The assessment of maintenance program expansion necessary to achieve enhanced transit service objectives, and
6. The development of cost-effective maintenance schedules in planning for significant changes in the existing fleet of vehicles.

Even with extensive management involvement, it is possible for MASSTRAM to be less effective than desired because of misconceptions concerning the work environment and capacities of the system. The model makes no explicit judgments regarding the ability of a maintenance shop to conduct the various needed types of vehicle inspections and repairs. In other words, the model is neutral on issues such as the relative skills of existing repairmen or the potential for improved productivity. The model user supplies data that realistically reflect operational aspects of vehicle maintenance; the model calculates the aggregate performance implications resulting from the specified data and associated assumptions. Despite this neutrality, computer-based program evaluation models implicitly assume that the operational activity being modeled is represented within realistic bounds. MASSTRAM will accept any level of the repairman's productivity specified by the manager or planner. It is crucial that there be some productivity level that can confidently be employed for this purpose.

For example, if past levels of the repairman's productivity are used as a basis for determining inputs of the model, there should be a high degree of confidence that productivity levels are likely to remain constant over the current planning horizon. If, however, the model is being run under an assumption of improved productivity levels, then there should be persuasive evidence that such levels are indeed achievable. Variations on this theme would account for and include operational assumptions such as the average skill level of the work force, the reliability of the rail vehicle components, the availability of spare parts, and the extent of cooperation and communication between members of the transportation departments and the maintenance shop departments. Different lines of a single transit system, e.g., the MBTA, could exhibit different maintenance requirements.

A third prerequisite for the successful implementation of MASSTRAM is that transit management as a whole engages in a fairly rational budget-making process. Figure 4 shows how the model can be used within a budgetary cycle. A reliable model, a conducive operational system, and a committed line management are helpful, but, if budget choices do not reflect managerial decisions, such decisions and the tools that support them will not have a considerable impact. In the case of rail vehicle maintenance programs, our model can evaluate the incentives and costs associated with changes in the timing of preventive maintenance. Increased inspections and overhauls may indeed be cost-effective in the long run, but such incentives can only be achieved if annual (and perhaps supplemental) budget reviews offer the opportunity for considering a wide range of managerial choices. For example, if budgetary guidelines deny the possibility of any planned use of overtime work in the maintenance shops, then much of the potential value of analytic model-based findings in this area is lost. Often, when an organization's budgetary guidelines are rigid, it operates either in a business as usual mode, or in difficult times, through reactive cutbacks of men, machines, and service. Models might be of some use at that time, but will be of less use than when the development of a new program strategy is being encouraged.

CONCLUSION

Vehicle maintenance is an essential part of a rail rapid transit system. Many people care about the maintenance of the vehicles. The operators, the car house repairmen, foremen and supervisors, and local agency management work together inside the transit organization to make improved maintenance a planning goal and an everyday reality. Federal officials who sponsor the design, development, and capital improvement of rail transit systems look to transit managers to achieve the service levels that were planned; there is the hope that the elements of transit improvement programs such as the construction of modern car houses and the purchase of new rail vehicles will be well supported by effective operating programs such as preventive maintenance. Other people care about the system simply because they ride it and depend on it. In the spirit of responding to these concerns and hopes, MASSTRAM was developed for use by rail transit management to aid managers of rail vehicle maintenance in their ongoing planning, programming, and budgeting activities.

ACKNOWLEDGMENT

This research was conducted at the Boston University School of Management under contract with the Urban Mass Transportation Administration, U.S. Department of Transportation.

Publication of this paper sponsored by Committee on Maintenance and Operations Systems.