

TRANSIT VEHICLE MAINTENANCE:
A FRAMEWORK FOR THE DEVELOPMENT OF MORE PRODUCTIVE PROGRAMS

by

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ABSTRACT

This thesis examines the role of vehicle maintenance in the transit industry and defines a framework which can be used to develop more productive programs and to subsequently aid in their management.

The importance of the maintenance function to the ability of the transit industry to meet the challenges it faces and will be facing is pointed out. The general goals and objectives of a vehicle maintenance program are discussed and the program components utilized by the industry to meet them are described. The effects of each on the maintenance and transportation departments and the consumer, and the level of effort presently applied to each are discussed. The importance of 'purchasing' to the maintenance function is pointed out.

The potential benefits of performing preventive maintenance on a vehicle system are classified into seven basic types. The cost savings elements associated with each of them are defined. The framework which is then defined utilizes the cost savings of these benefit types in the development of a vehicle maintenance program. A program structure is defined by first programming 'primary' systems, or systems whose parts require the most frequent maintenance. Through the coordination of these systems' programs a 'minimum interval' is defined. The vehicle's systems are then programmed so that scheduled actions may occur only at multiples of this interval. The basic premise, on which program development is based, is that there exists an optimal balance of preventive and non-preventive maintenance for the vehicle and each of its systems, at which the cost of maintenance to the agency is minimized.

A few special ways in which the framework can be applied to maintenance management subsequent to program development are briefly detailed. Finally, some recommendations for subsequent steps to take in improving the vehicle maintenance function of the transit industry are offered.

Thesis Supervisor: Nigel H. M. Wilson
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CHAPTER 1

INTRODUCTION

In this thesis, the planning and management of the transit vehicle maintenance function is examined. The general objectives of a vehicle maintenance program are discussed and the components of today's typical programs are described. The main goal of this thesis however, is the definition of a framework which can be used by maintenance managers to develop productive vehicle maintenance programs for their transit agencies. Although the thesis is oriented toward the transit bus mode, the general theoretical concepts which are employed in the development of the framework can be applied to the development of any vehicle maintenance program.

1.1 The Transit Industry - A Brief Historical Perspective

As we enter the 1980's, the importance of the United States' public transit industry to the nation and its economy is growing rapidly. This growth is in sharp contrast to the industry's precipitous decline which followed World War II and lasted for more than a quarter century. Between 1945 and 1972 transit (revenue) ridership fell an astonishing 72%, from about 19 billion to 5½ billion.¹

Certainly a portion of this decline can be attributed to the initial high level of usage which was encouraged to support the nation's war effort in the early to mid-1940's. However, by 1955 ridership was below that of 1940, and by 1972 was just 50% of it.²

To some extent, the transit industry became a victim of circumstances

¹(24, pg. 24)

²Ibid.

beyond its control. Government highway and road construction and home financing policies were among the important factors which led to what has become known as 'urban sprawl'. The land-use pattern which characterizes this sprawl is an extremely inefficient one for transit to serve and thus ridership, and the importance of the industry, plummeted.³

The decline continued undisturbed until the early 1970's, when there was finally a realization that the health of our urban areas and their residents was being threatened by the congestion and pollution caused by urban auto use. Slowly, the awareness of the potential benefits of transit as an alternative mode of urban transportation increased. However, the problems of our urban areas in dealing with congestion and pollution were just the beginnings of major changes which would soon elevate the transit industry once again to a position of importance to the nation.

Uncertainty over the supply of oil, which when refined is of course a necessity for the operation of today's automobiles, was made clear during the 1973-1974 Arab oil embargo. Although the embargo was quite a shock to many people in the United States, many people also felt that the problem was not of crisis proportion. Thus transit ridership was relatively slow to increase, until it began to become evident that we were indeed treading on soft ground.

Between 1973 and 1977 oil imports more than doubled⁴, until they became the source of nearly half of the oil consumed in the country.⁵ The

³for further information see Meyer, J.R., et al., The Urban Transportation Problem, Harvard University Press, Cambridge, Mass., 1965

⁴(13, pg.28)

⁵Ibid.

level of oil imports has become an issue of great concern, as the stability of the governments of the supplier nations has become more suspect. The instability in Iran led to the gasoline shortage of the summer of 1979. Fear of similar occurrences in other countries which are important sources of oil for the United States, along with steep price increases levied by the oil supplying nations⁶ has led to important shifts in national policy. These shifts limited the level of oil imports and resulted in the gradual decontrol of domestic oil prices in an attempt to spur expansion of domestic oil production.

These developments have of course affected the United States in many different ways. One of the effects, however, was to cause a still accelerating increase in transit ridership. In fact, if ridership continues to increase at the rate that it did in 1979 (6.75%)⁷, it would reach the level of 1950 ridership in only ten years and that of 1945 in about fifteen years.⁸

1.2 The Role of Transit Vehicle Maintenance

The role of transit vehicle maintenance in the ability of the transit industry to meet the challenge of such a rapidly increasing demand is bound to be an important one. In order to meet the rising demand for transit service, the number of vehicle miles traveled will increase, thereby increasing maintenance demands. Increasing the number of vehicle miles traveled during peak hours can only be accomplished by increasing

⁶resulting in the tripling of retail gasoline prices between 1/73 and 12/79, over half of this increase came in 1979 alone; (12, pg. 79; 15, pg. 58).

⁷(17, pg. 1)

⁸(24, pg. 24)

the number of vehicles in service. Thus, maintenance managers will, on a regular basis, be told to increase the proportion of the fleet which is in service.

When peak service demands reach the point where meeting them requires an expansion of the fleet, further pressure to increase vehicle availability results if the lead time involved in the delivery of newly ordered vehicles is underestimated by the transit agency. When the new vehicles do finally arrive, the maintenance department will be faced with the task of maintaining an expanded fleet. Thus the manager will be directing an ever larger operation.

Finally, maintenance managers will often find that the new vehicles, which have been designed to try to meet the public's rising expectations for high quality service, are more complex and more difficult to maintain than were the older vehicles. It is likely, however, that they will be asked to supply at least the same proportion of these vehicles for in-service use, as they were asked to supply when only the older vehicles were being used.

The pressure which is being and will continue to be placed on the maintenance function to increase the supply of vehicles, will be a major shift for many maintenance managers, whose first priority for the last thirty years has been to cut costs. The relative lack of pressure on the maintenance function to supply enough buses to meet service demands during transit's long decline is indicated by the fact that although bus service miles decreased by 31% between 1950 and 1972, the number of buses owned decreased by only 13.6%.⁹ Although other factors play a role in this

⁹(24, pgs. 30, 35)

discrepancy, it's magnitude makes it difficult to deny that the job of the maintenance department was eased by the declining proportion of the bus fleet needed for service.¹⁰

However, with increasing service being offered to meet expanding demand for service, the emphasis on availability is increasing. In fact, while bus service miles increased 24% between 1972 and 1978, the number of buses owned rose only 7.7%.¹¹ Assuming that a significant portion of the increase in bus miles occurred during peak hours, these statistics seem to indicate that the proportion of the fleet which must be made available to meet service needs had increased by 1978. Thus the demands on the maintenance function have resulted in increasing the importance of bus availability, while the pressure to keep costs down has not diminished.

1.3 The Need for and Development of a Framework For Program Development

Due to the increasing maintenance demands discussed in Section 1.2, the need for the maintenance function to be carried out in a well-planned

¹⁰The picture for the rail mode is quite different. Rail vehicle miles and vehicles owned were reduced in much closer proportion between 1950 and 1972; 68.5% and 53.9% respectively. This is probably a result of the greater capital costs (rails, cars, etc.) involved in rail service than in bus service (24, pgs. 30, 35).

¹¹Again the rail mode tells a different story. Vehicle miles decreased by 7.9% in this period, but the number of vehicles owned increased by 1.5%. This may be attributable to the Section 3 U.M.T.A. capital grants policy which would affect the rail mode to a greater extent than bus, due once again to its higher associated capital costs (24, pgs. 30, 35).

systematic manner has never been as great as it is today, and the future, at least in the near term, promises only to increase this need. The wide disparity in the maintenance programs of different agencies, discussed in Chapter 2, is an indication that the industry's programs are presently not being developed in such a manner.

A method or framework can be established which can aid transit vehicle maintenance managers in the program development process. The different environments in which different transit agencies operate, certainly precludes the establishment of a uniform system of vehicle maintenance for the entire industry. These differences, however, are not an obstacle to the definition of a single framework for developing transit vehicle maintenance programs for all agencies. The definition of such a framework is the main goal of this thesis.

The idea that a single framework can be applied to an entire transportation industry is not brand new. In fact, in 1978 the Federal Aviation Administration provided what might be termed a loose framework to be used by air carriers as guidance in developing a vehicle maintenance program. The F.A.A. must also approve the programs which are developed by each airline. These steps were taken following the realization that the existing policy of requiring a uniform program for all carriers was not most efficient.¹²

The framework developed here goes beyond the level of detail of that developed for the airlines, and will of course differ somewhat in approach due to the differences inherent in the operation of an airplane

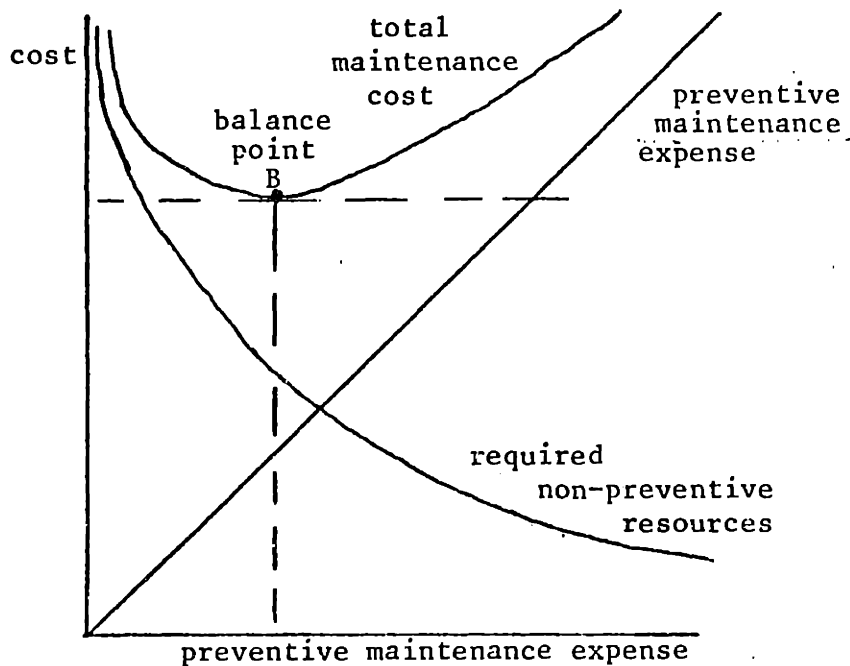
¹²(7, 19)

and a transit vehicle. The emphasis will be on the bus mode although all of the concepts which are developed are applicable to other conventional transit modes.

The framework is based on one important premise. This is that the vehicle maintenance program which best meets its objectives can, under any set of circumstances, be found by striking an optimal balance between preventive and non-preventive maintenance. This notion is illustrated in Figure 1.

Allocating less than the optimal level of resources to preventive maintenance results in a more than proportionate increase in the resources which would be required for non-preventive activities. This is demonstrated by the part of the graph to the left of 'B'. The right-hand side of the graph illustrates that increasing resource allocation to preventive maintenance beyond the 'balance point's' level would result in a less than proportionate return in decreased resources required for non-preventive maintenance.

Figure 1: Balancing Preventive and Non-preventive Maintenance



Thus, when the program involves the practice of less or more preventive maintenance than at this 'balance point (B)', the program will result in a higher than necessary total cost.

Although it is obviously extremely important that the vehicle's maintenance program be executed in a well-coordinated manner, a transit vehicle is composed of different systems, or groups of parts (i.e., bus-steering, brakes, fuel, power plant, etc.), which have varying maintenance needs and thus should be programmed separately.

On the other hand, the independent development of each system's program would cause the task of coordination of the systems' programs into a single desirable vehicle maintenance program to be quite cumbersome. Thus, the systems should be programmed in an order which accommodates such coordination. This can be accomplished by first programming those systems which are expected to require the most frequent maintenance. The structure which emerges following coordination of these systems' independently developed programs would then be used to develop programs for the remaining systems, which would ease coordination into a unified vehicle maintenance program.

The balancing of preventive and non-preventive maintenance is applicable not only to the entire vehicle's program but to that developed for each system as well. In defining the level of preventive maintenance which enables this balance to be achieved by a system's program, the characteristics of that system and the way it functions need to be identified and understood. This will enable the determination of which of the potential benefits of preventive maintenance apply to the system being programmed. It will also aid in the definition of the forms which the

system's maintenance program can take in attempting to achieve the desired balance of the system's preventive and non-preventive maintenance.

Since transit vehicles, particularly transit buses, which are being used by different agencies are extremely similar, it would be most efficient for tasks such as identification of systems, the order in which they should be programmed, and the potential benefits of performing preventive maintenance on each of them, to be executed once by a central authority such as U.M.T.A. This would also have the effect of establishing a common ground for agencies' maintenance programs, enabling easier inter-agency communication and cooperation.

1.4 Contents of Subsequent Chapters

In Chapter 2, the general goals and objectives of the transit vehicle maintenance department are identified and discussed. The general components of a prototypical program, which are used in today's industry to meet these goals and objectives, are defined and classified by whether or not they are scheduled or unscheduled and preventive or non-preventive actions.

Seven basic benefit types of preventive maintenance actions are identified in Chapter 3. The elements of potential cost savings associated with each of these types are defined, and their actual estimation discussed. In addition, the ways in which these cost savings relate to the achievement of the goals and objectives identified in Chapter 2 are discussed.

The framework for developing more productive maintenance programs is presented in Chapter 4. Through application of the costs or cost savings

developed in Chapter 3, this framework can be used to develop the program which meets the maintenance objectives defined in Chapter 2, at minimum cost to the agency. The method by which the program's structure may be developed is described and the procedure and information requirements for programming a vehicle system are detailed.

Chapter 5 describes a few special ways in which the framework, and the concepts developed therein, can be applied in order to aid a maintenance department and the rest of the agency of which it is a part. Finally, Chapter 6 summarizes the thesis, and makes some recommendations concerning the subsequent steps which can be taken by both U.M.T.A. and the transit agencies, to improve the industry's maintenance programs.

CHAPTER 2

THE TRANSIT VEHICLE MAINTENANCE FUNCTION

Before setting out to develop a framework for making maintenance policy decisions, it is necessary to understand the role of the maintenance department as well as what the maintenance task entails. The purpose of this chapter is to develop this basic knowledge.

The general goals and objectives of the maintenance department will first be discussed. The various components of maintenance programs, which have been classified into scheduled and unscheduled maintenance,¹³ will then be described. References to variations in present industry practice will be made where appropriate and the effects of the program components on the user as well as the transportation provider will be noted. The level of resources which are being applied to the different types of maintenance activities in today's industry is discussed. Finally, the important relationship between the maintenance and purchasing departments will be examined.

2.1 Goals and Objectives of the Maintenance Department

The development of a maintenance program is primarily the responsibility of the director (or superintendent) of maintenance. The director, throughout the program development process as well as its implementation, must keep in mind the goals and objectives which the program must satisfy. The primary goal of any vehicle maintenance department can be stated rather

¹³This typology is employed, instead of the more common one of preventive and non-preventive maintenance, in order to stress the importance of the ability to schedule activities. The important differences between preventive and non-preventive actions will be pointed out and discussed within the typology used here.

simply: to supply a fleet of safe and reliable vehicles of sufficient size, to meet the needs of the transportation department at the least possible cost. This goal highlights four major objectives: safety, supply, fleet reliability, and cost minimization.

Providing for the safety of employees of the transit agency and users of the services it supplies must obviously be of the utmost concern to the transit agency and its vehicle maintenance department. Generally, approximately 50% of an agency's staff is drivers and so the maintenance department is entrusted with the responsibility of providing for the safety of a majority of the agency's employees as well as all of the riders of the transit system. Although the safety of those aboard the agency's buses cannot be absolutely guaranteed, every reasonable precaution must be taken by the maintenance department to ensure their safety.

The consistent achievement of the supply objective is a necessary (although not sufficient) condition to the fulfillment of the transportation department's goal of providing adequate service, or more specifically, providing service according to an established schedule. The failure of the maintenance department to satisfy this objective on any single day could easily lead to the transportation department's failure to meet its goal.

Although meeting the peak periods' supply requirements will usually require the greatest attention of the maintenance managers/planners, they must also be aware of the scheduled vehicle needs for the entire day, so that no conflicts arise between vehicles' maintenance assignments and scheduled service vehicle needs. Thus, the supply requirement will often require that vehicle availability be maximized during peak service hours,

and will otherwise have a much lesser influence on maintenance scheduling.

The supply requirement includes not only the number of buses needed to meet scheduled service, but some additional spare buses as well. A spare will be used whenever a replacement bus is necessary for an in-service vehicle which has been 'road called' due to a system's failure. Peak needs will therefore be determined by the schedule and also by the number of expected road calls requiring a replacement bus and its variability.

Thus, if the supply shortfall is not too serious and the transportation department adjusts its plans then, with a bit of luck, the service requirements may be met. For example, if fewer emergency or spare vehicles are made available by maintenance, service requirements may be met if the spares are distributed more efficiently between garages and the number of serious road calls is low.

However, a single department failure may lead to subsequent failures. In such cases, the severity of the failures will have a tendency to increase, due mainly to the fact that increasingly greater performance is required as the department falls further behind. Thus repeated failure to meet the maintenance supply objective will inevitably have a serious effect on the functioning of the transportation department.

When the number of vehicles supplied by the maintenance department is insufficient to cover even scheduled service then there will certainly be missed trips as well as lack of spare vehicles with which to respond to road calls. Service quality would therefore deteriorate rapidly with respect to the variables which are generally thought to be most important in the consumer's mode choice, reliability and safety. At the same time

transit agency costs will increase substantially for reasons which will be discussed in detail later in this paper, but generally because it is more efficient for an agency to input a constant level of resources than to have the level vary widely over time. Thus the consistent achievement of the maintenance department's vehicle supply goal is crucial to the transit agency as a whole.

The need to supply a spare bus fleet is only one effect of the occurrence of failures and road calls which must be taken into account in the development of a maintenance program. In fact, failures and their effects should be considered an important measure of fleet reliability, one of the four major maintenance objectives.

There are a number of different types of system failures however, which have varying impacts on the agency's costs and the level of service which is provided by it. A system failure may or may not result in:

- 1) endangering the safety of those aboard the bus,
- 2) an interruption in service (due mainly to road calls),
- 3) the need for a replacement bus to be dispatched into service, and
- 4) damage to systems or parts not initially involved in the failure.

Thus the fleet reliability objective may actually consist of a series of objectives related to the occurrence of these different types of failures. It may be broken down even further by considering the number of the different types of failures for individual systems.

The importance of the fleet reliability objective then, extends beyond the effects on the level of service offered. It has a significant effect on the ability of the maintenance department to meet its other objectives as well.

Finally, keeping costs down to a reasonable level obviously is an

important objective which must be fulfilled by the maintenance program. As desirable as cost minimization is, it must be realized that a transit agency is not a 'for-profit firm' but an instrument to offer a public service to its users and the entire area which it serves. Further, maintenance is only one function of a transit agency and it is a function whose performance affects that of other agency functions. Thus a program which minimizes the cost to the maintenance department is not necessarily equivalent to one which minimizes transit agency costs. It is therefore necessary, in order to develop a maintenance program which is best for the transit agency, to integrate, or internalize the effects which maintenance has on other agency functions.

Aside from the primary goal of the maintenance department, defined at the beginning of this section, important secondary goals may be set for the maintenance department. The most important, as well as most common secondary goal is to upgrade the public's image of transit through the use of clean, quiet, comfortable and generally attractive vehicles. By cultivating a positive attitude toward transit, ridership may be increased. The implementation of this type of maintenance goal must be preceded by a recognition that a safe and reliable fleet is not equivalent to a comfortable and attractive fleet. Furthermore, it requires the understanding that releasing vehicles into service with such things as broken or missing windows, damaged interiors, or exteriors covered with a layer of dark soot from dust and exhaust, will produce a negative image of transit for both users and non-users. This negative image may result in ridership decreases or a ridership significantly below that which otherwise might be enjoyed. Thus, improving the public image of transit is an important goal for any transit maintenance

department.

Although the goals and objectives of the maintenance program may seem rather simple, their achievement at minimum cost is a difficult task. There are a number of distinct maintenance activities which should receive varying degrees of emphasis depending upon prevailing conditions, though each is vital to the overall maintenance program. The level of commitment to any single activity cannot be adjusted without affecting the quality of the performance of the entire program, unless the level of commitment given to another activity is adjusted to counterbalance the effect.

A maintenance program then, is not something which can simply be turned on or off - the development of a useful and productive program requires careful advance planning coupled with effective execution of those plans. In this respect, the maintenance department's task is no different from that of the transportation, marketing, purchasing or any other department.

2.2 Unscheduled Maintenance Activities

Unscheduled maintenance activities are those which will probably occur but when, where and in what situation they will be needed cannot be determined in advance. These activities may or may not be part of the preventive maintenance program.

2.2.1 Unscheduled Preventive Maintenance

Two unscheduled activities which are also part of a preventive maintenance program are the correction of defects either reported by a driver upon returning the vehicle to the garage at the end of the service day or discovered during the performance of scheduled preventive

maintenance¹⁴. These unscheduled preventive maintenance actions may be completed within the time allotted for daily servicing activities and the scheduled preventive activity respectively, or they may require additional time.

The most significant unscheduled preventive action may be that of unit overhaul (or rebuild). The overhauling of a unit or a part is a major repair process in which a thorough check for needed repairs to the part is conducted, and those repairs and adjustments which are required to restore it to 'good working order' are implemented. The part which emerges following the process should have a significantly longer expected life than that of the part prior to the process. In fact, the expected life of the overhauled part may be the same or sometimes even longer than that expected for a new part.

The overhaul of many parts is often conducted on a schedule (see section 2.3.3). However, for some of these parts an overhaul might also be done as an unscheduled preventive action, prior to and instead of its scheduled overhaul. Such an action would be based either on analysis of data collected during daily servicing (see section 2.3.1) or on scheduled inspections (see section 2.3.2) performed for the express purpose of determining whether or not an overhaul is warranted. For some other parts overhauls are never scheduled and are always performed based on inspection and/or data analysis.

Finally, for some parts it is possible to do the overhaul with the part either on or off the vehicle. In these cases it may be desirable

¹⁴In fact, a maintenance program may be designed such that a relatively minor scheduled task is performed, in order to determine whether or not a more major unscheduled preventive task should be performed. This type of program is often referred to as on-condition maintenance and is discussed in detail in section 4.2.3.

to remove the part to be overhauled and replace it immediately with another new or overhauled part so that the vehicle may be returned to service. The overhaul would then be completed and the part used to replace another part, itself removed for overhaul. The decision to perform the overhaul on or off the vehicle depends on many factors, including the times required to complete the overhaul on the vehicle and off the vehicle, time to remove and replace the part, and the cost of owning the extra part.

2.2.2 Unscheduled Non-preventive Maintenance

An action is classified as unscheduled non-preventive maintenance, if it is carried out in response to a system failure which has occurred. The most important unscheduled maintenance task is that of responding to road calls. A road call occurs when the driver of a bus in scheduled service reports that the bus is inoperable for mechanical and/or safety reasons.

A driver might initiate a road call for a wide variety of reasons ranging from a malfunctioning windshield wiper to a flat tire to a blown engine. The driver of the inoperable bus will call the central dispatcher to report the problem. The dispatcher will then call the garage foreman of either the garage closest to the incident or the one to which the bus is assigned, or will directly radio a service truck in the area.

The mechanic or mechanics assigned to road call duty will usually also have the garage assignment of doing relatively minor jobs which do not require the use of a hoist or pit. In this way, when they are notified of a problem they can leave what they are doing immediately without 'tying up' an important hoist or pit.

As soon as the 'road crew' reaches the disabled bus, the mechanics

attempt to fix it as rapidly as possible by any means which does not jeopardize their (or anyone else's) safety. The crew will attempt to fix the bus so that it can return to passenger service or at least be driven back to the garage. If even this proves to be impossible in a reasonably short time, the mechanics will usually call for a tow truck to tow the bus to a garage for further work.

Concurrently, the central dispatcher informs the transportation department of the road call. He may order that a 'cover man', or a spare driver be assigned to a spare bus and that the bus be driven to the site of the breakdown to replace the disabled bus. This order may be warranted from the driver's description of the problem or may be delayed as long as the road crew takes to determine whether or not the bus can be returned to scheduled service.

In any event, when the spare bus reaches the disabled bus, the two drivers switch positions - that is, the driver of the spare bus is replaced by the regular driver, and the spare driver stays with the disabled bus to be driven or towed back to the garage. The spare bus-regular driver pair may be put into scheduled service either at the point of the breakdown or at or near the point where the bus would have been if it had adhered to its established schedule.

There are a number of points in the preceding general description of a road call response, at which different agencies and different individuals might act in significantly different manners. However, the description does give a good idea of what is involved and the decisions which must be made in responding to a road call.

2.2.3 Effects on Transportation and Maintenance Departments

Unscheduled preventive maintenance activities will have little or no

effect on other departments, including transportation, unless the demand for these activities grows to the point where maintenance cannot supply the vehicles required by transportation - an unusual occurrence.

However, the occurrence of road calls does have a definite impact on transportation. The time between a bus breakdown and its return to passenger service or the arrival of a spare vehicle is unproductive time for which the regular operator is being paid. In addition, road calls require the employment of a number of 'extra' drivers for use only during such emergencies. Finally, the road call may have serious effects on schedule adherence. The trip which the bus was running at the time of its breakdown may not be completed, and the following trip or trips the bus was scheduled to run may be delayed or even eliminated. In addition, the passengers from the disabled bus may cause schedule adherence problems for a number of subsequent trips due to increased passenger loads and resulting longer travel times. Road calls then, not only have a negative financial effect on the transportation department but on its performance with respect to its goal of schedule adherence.

The effect of unscheduled activity on the operation of the maintenance department is also clearly significant. Unscheduled preventive maintenance may obviate the need for more difficult and costly work at a later date. In addition, although the demand for unscheduled preventive maintenance cannot be precisely predicted, thereby precluding their accurate scheduling, it is possible to a certain extent, to plan for their occurrence¹⁵ in order to ease the impact on the maintenance

¹⁵For instance, it is known that any driver-reported defects will occur upon return of the bus to the garage, and that the specific inspections which may result in this type of work are performed at particular times of the day.

department. If such planning has not occurred, or for some reason could not be implemented, then it is much more likely that unscheduled preventive activities will cause problems for the maintenance department.

As a relatively simple but not unusual example, consider an agency which does some of its scheduled preventive maintenance between the morning and evening peaks. If a vehicle is found to have a serious defect which will take a few hours to repair and thereby exceed the down time allotted for inspection (the time it's scheduled to be out of service), then an unsatisfactory choice exists. Either service needs are not met or an unreliable and possibly unsafe vehicle is returned to scheduled service.

As serious as the above scenario may seem, the occurrence of road calls causes problems to the maintenance department which are at least as severe and usually more common. There is an opportunity cost associated with the maintenance work that the 'road crew' would otherwise have done. Further, the road crew's productivity is much lower than it would have been if the mechanics were working in the garage on other activities. This is due mainly to the fact that the time spent driving between the garage and the breakdown site are wholly unproductive, but also because the mechanics may be working in less than optimal conditions in trying to fix the bus on the road and not in the garage.

There are also notable secondary effects which road calls have on maintenance operations. The need for spare buses which are required by transportation, depend to a great extent on the expected number of road calls. Thus in order to meet the needs of the transportation department, the maintenance department must supply a larger operable fleet as the number of expected road calls increases. This may be a

very difficult task due to the increased resources which must be applied to road call response. This problem will be discussed at greater length in the next chapter. Another effect which road calls have is that much of the maintenance supervisory staff's time is spent in a crisis-response mode, reducing the time available to plan the remaining maintenance tasks.

It is evident then that unscheduled maintenance, particularly non-preventive actions, are undesirable for the transit agency as a whole and especially for the maintenance department. In fact many transit agencies use the number of road calls as one of the primary measures of their maintenance program's performance.

2.2.4 The Consumers' View

Beyond the direct effects on the transit agency, it is important to consider the impact of road calls, and the agency's response to them, on the public, which the transit agency is serving.

The people who are obviously most directly affected are those riding on the disabled bus. They are not only inconvenienced by the delay and discomfort which results, but also their safety may have been endangered, either in reality or in their own perception. The memory of the dangerous experience may remain with the users for some time and may strongly affect their subsequent mode choice.

The delay and discomfort imposed upon the riders of the disabled bus and on other people who are less directly affected (i.e. people waiting at stations up the line from the road call site) by the incident, may be reduced through an efficient response on the part of the maintenance and transportation departments. Such a response would basically entail getting these people into another bus and to their destination as quickly as possible. This would certainly ease some of their negative perceptions

of the incident.

Unfortunately though, the more typical occurrence in today's industry is that the people have to wait for the next scheduled bus, or possibly much longer if they can not fit onto it. This is particularly true for those who wanted to ride on the trip which the bus was running at the time of the road call, and sometimes even for those wanting to ride on subsequent trips which the bus was scheduled to have run. As stated earlier, these effects often could have been avoided if the maintenance (and transportation) department(s) had responded efficiently.

Since reliability significantly affects mode choice, an agency which is consistently unreliable due to in-service failures or road calls, will find itself losing ridership as a result. It will also be difficult to attract new riders, particularly when they witness the towing of a disabled bus.

2.3 Scheduled (Preventive) Maintenance

Scheduled maintenance involves activities whose execution can be planned in advance based on knowledge of what will be needed, and when. Scheduled activities are part of the preventive maintenance program, which includes actions planned and executed (but not necessarily scheduled) by the maintenance department in order to reduce the probability of a road call due to vehicle failure, and/or to aid in the achievement of other maintenance objectives defined in section 2.1.

The scheduled maintenance task may be divided into three basic activities; daily servicing, inspection, and preventive parts replacement or repair. Although these activities have distinct meanings, their functions will occasionally overlap. In spite of these occasional similarities, this division most accurately reflects prevailing industry

practice.

2.3.1 Daily Servicing

The set of actions taken daily to ensure that vehicles are in condition for passenger service is called daily servicing. These actions may be scheduled prior to a vehicle's entry into passenger service (pre-run) or following the completion of the vehicle's passenger service runs for the day (post-run). The majority of pre-run servicing would therefore be done in the first shift between midnight and 8 a.m. and post-run servicing would take place in the third shift between 4 p.m. and midnight.¹⁶

Following is a description of the typical procedure for servicing a bus after it leaves passenger service and before it is retired to the parking lot for the night. Variations in the procedure do exist and will be noted where appropriate.

The operator returning the bus to the garage will usually leave the bus adjacent to or on the service island, or parked in the regular overnight storage area. (A relatively small number of agencies have the operator stay with the bus through the entire servicing cycle.) If the bus is parked in overnight storage a maintenance employee must retrieve the bus when it's time to service the bus. If a driver has reported a defect in the bus which cannot be corrected by the servicing personnel then the bus will be taken to a separate area where other maintenance workers can work on it. Otherwise, when the bus arrives in the service lane one employee will start filling the fuel tank by setting the fuel pump

¹⁶The starting and ending times of the shifts vary between agencies but these times are representative.

on automatic flow. While the tank is filling he will do minor mechanical checks on the vehicle and others will clean and vacuum the interior of the bus.

Specific activities carried out in the daily servicing process vary between agencies, as shown in Table 1, which summarizes the results of a 1975 M.I.T.R.E. survey of transit agencies' servicing activities.¹⁷

Table 1
Daily Servicing Activities

<u>Activity</u>	<u>Number of Respondents</u>
Fuel refill	61
Oil check and refill	61
Record fuel, oil consumption	58
Tire check	54
Coolant level check	54
Interior cleaned	51
Lights checked	44
Torque fluid check	38
Farebox removal	37
Automatic bus wash (+ manual)	35 (+6)
Minor maintenance check	34
Brake check	24

The above table demonstrates that although there are activities which are fairly common, there are very few activities performed uniformly

¹⁷(21, pgs. 28, 31), total number of respondents not available.

throughout the industry.

The same M.I.T.R.E. study found that daily servicing generally required a major portion of the maintenance resources. In fact, typically 50% of maintenance labor-hours were found to be spent on daily servicing. It should also be noted that 50% of the maintenance labor hours used in daily servicing were in bus movement and walking between the parked bus and the service island. The average time a bus spent on the service island was 5 to 6 minutes while the average total cycle time required 10 to 12 minutes.¹⁸

The daily servicing activity is an important one for a number of reasons. It not only serves to ready the bus for another day of service, but it can also be an important part of preventive maintenance and/or a useful tool for marketing the transit service. The daily servicing activities including fluid checks and refills, light check, brake check and minor maintenance checks, are themselves preventive maintenance actions. However, another important contribution can be made to preventive maintenance if the data collected concerning fuel and oil consumption is used wisely. Further, additional data recording the condition of parts and fluids checked (i.e. tires, brakes; coolant, torque, air) could be collected and used in the same way. For example, irregularities in fluid consumption might indicate that a problem exists which, if discovered early might be easily rectified, avoiding serious damage or a road call. Unfortunately, many of the industry's maintenance programs do not take full advantage of this potential offered by daily servicing.

A clean bus interior makes a significant contribution to riders'

¹⁸(21, pg. 29)

comfort and their image of the transit service. In addition, a person is more prone to being convinced to enter a bus which looks clean from the outside, than one which is coated with unsanitary black soot accumulated from exhaust fumes and dust.

Finally, all daily servicing activities, including the response of maintenance employees to driver-reported defects, are important to the drivers. A driver's attitude is bound to be more positive when the accessories needed to make driving the bus safe and comfortable are functioning correctly, and also when the bus is clean and attractive. These effects are significant because it has been found that the interaction between the passenger and driver is important to the passenger.¹⁹ It is, after all, the only personal contact that users regularly have with the transit system.

The important role that daily servicing plays in the maintenance program as well as in the rest of the transit agency's functions has been explained in the preceding discussion. No maintenance program can be fully effective without including a good daily servicing program. Unfortunately, many of the industry's maintenance programs do not fully account for the importance of daily servicing activities and therefore its potential as a maintenance tool is often not fully realized.

2.3.2 Inspection

An inspection will be defined as the scheduled checking of and/or minor adjustment of specified systems or parts of a bus. The purpose of scheduled inspections is to correct relatively minor problems before they become more major and costly problems such as breakdowns, road calls and

¹⁹(25)

reduced bus life. Scheduled inspections are generally considered to be the backbone of the transit industry's preventive maintenance programs.

In establishing an inspection schedule, one must determine the type and frequencies of required tasks. In determining one task's frequency, the frequency of other tasks must be taken into account as is clearly illustrated in the following example. It is found that the ideal period between inspections for three different parts is 1900 miles, 2100 miles and 4300 miles. If the bus is inspected on these intervals it would, in its first 5000 miles of service, have to be worked on (and thus be unavailable for service) five times; after 1900, 2100, 3800, 4200 and 4300 miles of service. This is extremely inefficient compared to a compromise program where the bus is inspected only twice - at 2000 and 4000 mile intervals. The tasks whose ideal periods are 1900 and 2100 miles will be included in the 2000 mile inspection, and the 4000 mile inspection will also include the task ideally performed at 4300 miles. Continuing this type of pattern over long periods results in the development of an inspection hierarchy.

Vehicle miles is the unit commonly used in the bus transit industry to establish inspection periods as in this example. Its prevalence appears to be due to the relative ease with which it can be measured as well as to the sizeable portion of bus maintenance needs which are based on the number of miles operated. However, a valid alternative basis for inspection scheduling which is not widely used in the industry is vehicle hours.

There are a number of arguments in favor of the incorporation of vehicle hours into inspection scheduling. The maintenance requirements for many, if not most, bus systems may be more strongly associated with

vehicle hours operated than vehicle miles.

If the number of vehicle miles per vehicle hour were fairly uniform for the entire bus fleet - that is, if all buses in the fleet averaged approximately the same speed - then hours or miles could be used interchangeably as a basis for inspection scheduling. However, there are likely to be significant differences in average operating speed for different services. A bus which is driven all day in a congested downtown area is certain to accumulate less miles than one which operates on suburban or express routes for the same number of hours. In addition, a bus which operates only during peak hours will very likely accumulate less miles per hour than a bus operated during the off-peak as well as peak hours. Thus, different buses may experience widely disparate average speeds over a period of time (i.e. week, month), unless their service assignments are systematically rotated to avoid this occurrence. As a result, the use of miles as a basis for inspection scheduling would not be effective in meeting maintenance demand generated by operating hours.

Finally, the use of vehicle miles as a scheduling basis ignores the effect on maintenance needs of buses being idled when they are out of service. This factor may be significant for agencies located in areas with moderate to cold climates, where it is sometimes necessary to keep buses running all night to ensure that cold-weather starting problems will not keep the buses out of service the next day.

Thus, while there are good reasons for using vehicle miles as a basis for scheduling inspections, there are also important reasons why vehicle hours should be used. Ideally, a formula which may be applied would be developed through testing and would take into account the maintenance needs resulting from a vehicle mile as well as from a vehicle hour of

operation. A simpler approach has been taken by CITRAN in San Antonio where an interval for both vehicle miles and vehicle hours is set and whenever either limit is reached an inspection ensues.

In any case, after reaching a decision concerning the variable on which inspections will be based, the intervals must be determined. This is a very difficult assignment if the schedule is to be most efficient. A great deal of information must be available concerning the rate of decay of the parts involved as well as the rate's variability. The variability is important not only when considering a single bus, but also in considering the bus fleet as a whole. Most agencies own fleets composed of groups of buses from different manufacturers and/or years of production. Maintenance needs for each group of buses may be significantly different and there will probably even be variations within groups of buses. Despite this, it is industry practice to apply a single inspection schedule to the entire bus fleet. There is, however, a rather wide variation in inspection intervals in the industry, despite the fact that the tasks which are performed are rather similar. This is demonstrated in Table 2 which summarizes the results obtained from an informal survey of transit agencies.

The less frequent inspections will obviously require more labor hours to complete than the higher frequency inspections. This may be accomplished either by assigning additional workers, allotting a longer job time or some combination of the two. Some transit agencies' inspection intervals and the corresponding labor and stall hours allotted to them are presented in Table 3.

Table 2

Agencies' Inspection Intervals

<u>Agency/City</u>	<u>Inspection Intervals</u>					
MBTA-Boston ²⁰	2000	4000	12000	24000		
SDTC-San Diego ²¹	2000	4000	8000	24000	36000	72000
Golden Gate Transit ²²	1500	3000	12000	24000	96000	
CTA-Chicago ²³	4000					
GRTC-Richmond	500	6000				
NYCTA-New York ²⁵	3000	6000	24000			
Tri-Met-Portland ²⁶	1500	3000	12000	24000		
GCRTA-Cleveland ²⁷	1500	3000	6000	18000	24000	
RTD-Denver ²⁸	1500	3000	6000			
TTC-Toronto ²⁹	2000	8000	32000			
SCRTD-Los Angeles ³⁰	1000	6000	12000	18000		
NORTRAN-Chicago ³¹	3000	18000				
Seattle Metro ³²	1000	2000	4000	6000	12000	24000

²⁰(10)

²⁶(37)

²¹(18)

²⁷(28)

²²(2, pg. 106)

²⁸(5)

²³(26)

²⁹(36)

²⁴(27)

³⁰(34)

³¹(20)

²⁵(30)

³²(32)

Table 3

Agencies' Maintenance Resources Allocated to Inspections

									Total for <u>72,000 mi.</u>
GORTA ³³	Interval	1500	3000	6000					174
	Labor hours	1½	4	7½					90
	Stall hours	1½	2	2½					
Tri-Met ³⁴	Interval	1500	3000	12000	24000				448
	Labor hours	2/3	1 1/3	64	72				80
	Stall hours	1/3	2/3	8	12				
MBTA ³⁵	Interval	2000	4000	12000					162
	Labor hours	3	5	8					81
	Stall hours	1½	2½	4					
SCRID ³⁶	Interval	1000	6000	12000	18000				96
	Labor hours	2/3	4	4	6				44
	Stall hours	1/3	2	2	2				
Seattle ³⁷	Interval	1000	2000	4000	6000	12000			75
	Labor hours	½	3/4	1	2½	5½			42
	Stall hours	½	3/4	½	1½	1 3/4			
<hr/>									
33 (28)	34 (37)	35 (10)	36 (34)	37 (32)					

There are obviously rather wide variations in both the inspection intervals which are used by different agencies and the level of resources allocated to each inspection and to inspection activity as a whole, There are numerous potential justifiable explanations for these differences. Therefore, their existence alone should not be used to draw any conclusions about interagency efficiency. That is, it may be that an agency's inspection program may not be optimal, but it is difficult to make such a determination through comparison of the data supplied in Tables 2 and 3.

The variations in inspection intervals which are used by different agencies, which is demonstrated in Table 2, implies that variations also exist in the intervals at which specific tasks are performed. This was confirmed in my survey. These differences in task intervals may be justifiable for several reasons. Each agency is operating under a different set of environmental conditions. These include not only the region's climate, but the general condition of the roadways which are used, the degree of congestion of these roads, and even such things as the skill of the agencies' operator labor and the degree to which they are trained to drive to reduce maintenance demands.

The variations in the composition of the agencies' fleets will also cause their maintenance demands to vary. This is becoming an increasingly important factor to consider, not only with respect to fleet age but also in light of the increasing number of different bus models which now characterize the industry's fleet.

Although they are more likely to affect inspection intervals which are used, all of the factors mentioned above may also result in the allocation of different levels of resources to inspections. However, physical

capacity and characteristics of the labor supply are more likely to cause variation in the resources applied to inspections.

The physical capacity of an agency is to a great extent determined by the number of stalls available per bus and the number of different types of stalls per bus (i.e. hoist, pit). An agency with a 'shortage' of stalls is more likely to decrease the stall hours of an inspection, often at the expense of increased labor hours. In addition, the level of sophistication of equipment and tools used for maintenance (i.e. dynamometer) will affect the time required for inspection.

The characteristics of the labor supply which are relevant here include not only the cost of labor, but the level of skill of the mechanic workforce, the general availability of mechanics in the region, and any work rules which restrict managerial policies. This subject could easily be a topic for an entire research project. However, the general effects are rather clear - the more difficult it is to find cheap labor, the greater the inclination will be to substitute capital costs (labor-saving devices) for labor costs.

Tables 2 and 3 obviously leave many questions unanswered concerning the reasons for differences in agency practices. Perhaps the study of the types of differences in maintenance practice would be a rewarding subject for further research. The remainder of this thesis should shed some light on justifiable causes for such variations in industry practice. However, based on my research, I suspect that existing differences are just as likely to be a result of poor program planning and implementation as they are to be a result of differences in operating environment.

The workshift during which inspections are scheduled to be carried out is important, since it determines the procedure for bringing a bus into

the garage for the inspection.

It should be pointed out that a bus is not taken out of service as soon as it reaches its scheduled inspection interval. It may be removed slightly before or slightly after the interval is reached. This 'slack time' allows the maintenance department to plan the inspection of the bus so that the impact of its availability on the transportation department is minimized.

A bus requiring inspection on the second shift, between peaks, would be assigned by the garage foreman to a peak-hour run. The bus can then be driven to the garage for inspection after the morning peak, inspected, and then returned to service for the evening peak. The problem with performing inspections on the second shift, particularly if they are major inspections, is that if defects are found on the bus during the inspection, there may not be enough time to perform the unscheduled work which is necessary to fix them before the bus is needed for evening peak service. Thus either an unreliable bus is placed into service (which may lead to a road call), or the transportation department fails to meet the service schedule. Doing the inspections on the third shift instead would build in a much greater safety margin for the process.³⁸

2.3.3 Preventive Parts Replacement/Repair - P.P.R.

Some transit agencies have made a commitment to scheduled preventive maintenance beyond the common inspection hierarchy by practicing preventive parts replacement/repair. This involves not only a check of bus' systems at certain mileage intervals, as in inspections, but their

³⁸The problems discussed above led to such changes or proposed changes in at least two agencies which I have spoken to - GCRTA and Tri-Met.

replacement or repair prior to in-service failure. This practice is warranted for a number of parts in order to ensure safety and reliability, where costs associated with an in-service failure are high, and to prevent damage to other bus systems or parts which a deteriorated or malfunctioning part might cause.

P.P.R. activities are usually integrated into the inspection hierarchy so that parts are replaced or repaired during a major inspection at specific mileage intervals. The main problem encountered in attempting to implement a P.P.R. program is the accurate prediction of parts' in-service failure rates and their variability. This problem is accentuated by the fact that many parts show little or no sign of deterioration prior to a failure. Thus, in order to determine what parts have failure rates with low enough variability to warrant establishment of a P.P.R. program, a substantial amount of data must be collected on bus parts' failures. Such an approach has apparently been taken in Toronto (T.T.C.), where a data based P.P.R. system is sponsored by the provincial government.³⁹ In addition, Seattle Metro⁴⁰ and Portland Tri-Met⁴¹ are analyzing their available data to establish intervals for the parts most suited to P.P.R. activity.

It appears, however, that in the majority of agencies where P.P.R. is being practiced, either manufacturers' recommendations or judgement and past experience have been used to establish P.P.R. intervals instead of hard data. This approach could easily result in the establishment of sub-optimal intervals and a significantly higher cost than if better information was used to establish intervals.

³⁹(36)

⁴⁰(32)

⁴¹(37)

P.P.R. involves relatively high capital (spare parts) costs as well as the high labor costs of repair or replacement. As a result, in contrast with inspections, overemphasis on P.P.R. with intervals shorter than the mean part life may increase costs more than underemphasizing it with intervals longer than the mean life.

Due to the uncertainty of the benefits of P.P.R. as it is practiced in the industry today, particularly relative to the inspection hierarchy, P.P.R. activities have not yet become common in the transit industry (except where required by the warrantee on the part or bus). In fact, where it is being practiced, it would often be the first activity eliminated if more severe resource constraints were placed on the maintenance departments.

2.3.4 Effects on Transportation and Maintenance Departments

A well planned preventive maintenance program benefits both the transportation and maintenance departments. The maintenance department will have much greater control over its performance. Road calls should be reduced and so maintenance labor time can be used more efficiently. The overall cost of maintenance can be minimized by balancing the cost of preventive and non-preventive maintenance.

However, if preventive scheduled maintenance is either under- or over-emphasized, the overall cost will increase. If it is over-emphasized, scheduled maintenance will be occurring too often and as a result labor costs and spare parts costs will be higher than they should be. Underemphasizing scheduled maintenance will result in increased failures and road calls which would increase costs, possibly at a more rapid pace than in the case of overemphasis, depending upon the existing balance between non-preventive and preventive maintenance.

A good scheduled maintenance program would therefore keep maintenance performance at a high level and maintain tight control on the cost of the maintenance program as a whole. There is little need to wonder why scheduled maintenance is so important in today's transit industry.

Since a good scheduled maintenance program would keep road calls to a minimum and fleet availability at a maximum, schedule adherence problems due to maintenance would be minimized. As a result, less operator time would be wasted by road calls and the drivers themselves might be happier and more productive knowing that everything has been done to make the buses they drive safe and reliable.

2.3.5 The Consumers' View

The consumer will obviously also benefit substantially from the implementation of a well-planned scheduled maintenance program. Break-downs are minimized, schedule adherence is good and the total cost to the public is kept low. Furthermore, riders can be comfortable riding the bus as well as knowing that everything possible to assure their safety has been done.

2.4 The Level of Industry Effort Presently Applied to the Different Types of Maintenance Activities

The paucity of available data concerning maintenance practice in the transit industry precludes an accurate determination of the relative level of effort which is presently placed on scheduled and unscheduled activities. The data presented in Tables 2 and 3, and the M.I.T.R.E. finding that 50% of maintenance labor hours are allocated to daily servicing activities, give an indication of the level of effort applied to scheduled maintenance.

Data concerning the resources allocated to unscheduled maintenance was more difficult to obtain. Unfortunately, no data was available at all to determine the level of preventive unscheduled maintenance activity.

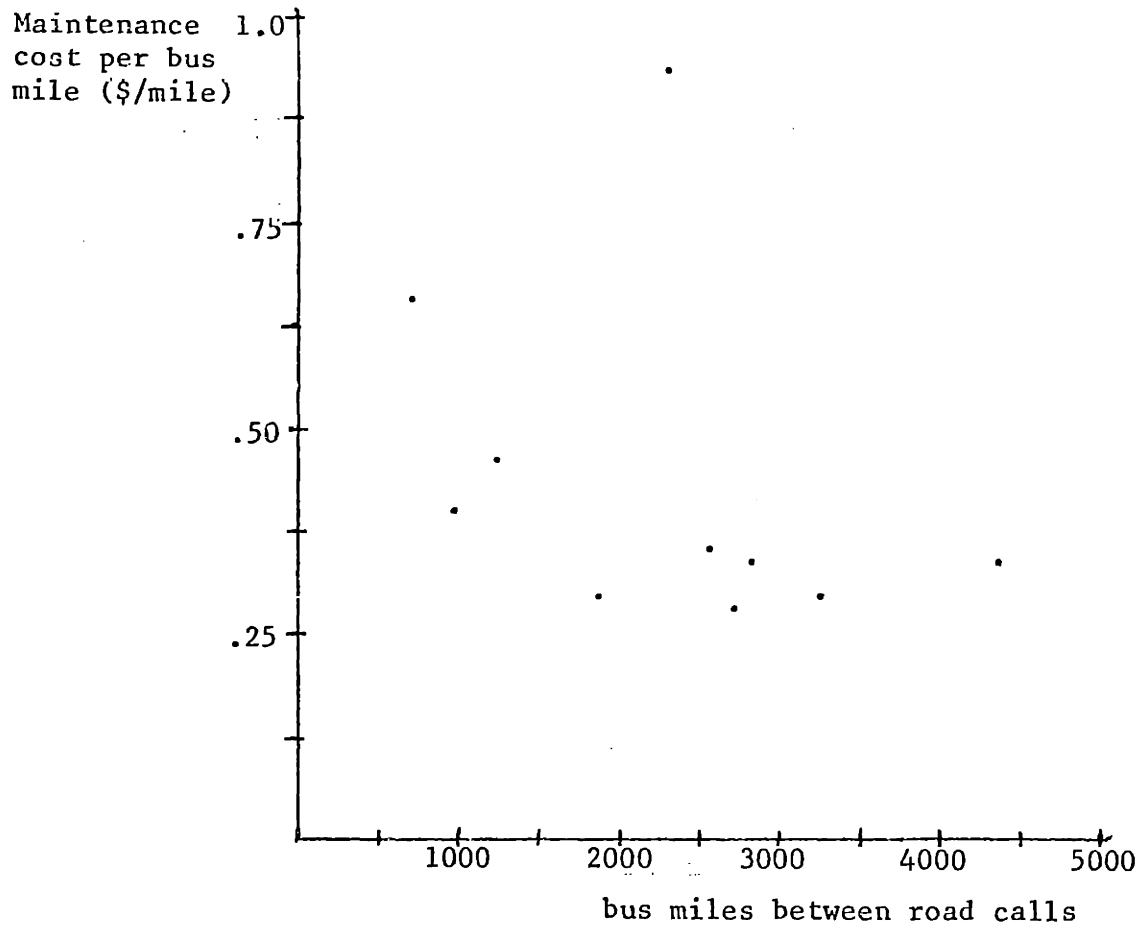
Some data was available on road calls, the major non-preventive unscheduled activity. However, it was available in a form which would only allow very general comparisons. This data consisted of the preliminary data from the first round of Section 15 reports which transit agencies must now submit annually to U.M.T.A. In any case, the data had a mean and median which were both between 2200 and 2400 miles between road calls for ten agencies of moderate size (250-1000 buses, mean and median between 600 and 625).

Thus, according to this data, the average bus would be 'road called' approximately 30 to 33 times in a 72,000 mile period. This compares to an approximate median of 160 labor hours and 80 stall hours allocated to inspection activity. In addition, it must be remembered that 50% of all maintenance labor hours are allocated to daily servicing.

The shortcomings of this data are evident. Some types of activities which are also significant parts of the program are not included (unscheduled preventive, P.P.R.). No information on the amount of labor and stall hours which result from a road call is given. Further, comparisons of labor hours and/or stall hours allocated does not take into account the skill and wage levels of labor assigned to different tasks, not does it account for resources allocated other than labor (i.e. parts).

Further, any assertion that an average level of resource allocation is representative of the transit industry's maintenance practices should be greeted with a good deal of skepticism. The differences in agencies'

Figure 2: Maintenance Cost per Bus Mile VS. Bus Miles Between Road Calls



conclusions on this data would ignore the interagency differences which were discussed in section 2.3.2 following Tables 2 and 3.

Thus until this type of data can be studied further, no firm conclusions based on it can be justified.

2.5 The Purchasing Department and Its Importance to Maintenance

The role of the purchasing department⁴² in a transit agency is to supply the maintenance department with the spare parts which it requires to meet its objectives. It is therefore charged with the responsibilities of purchasing and where applicable, keeping an inventory of the parts

⁴²Here this will include what is often referred to as the purchasing and stores departments.

needed by maintenance. In recent years this task has become increasingly complex, due in particular to the proliferation of different types of new buses, each of which often requires different parts.

There are two basic types of spare parts with which the purchasing department is concerned. These are stock items and non-stock or direct purchase items. A part which is a stock item is bought by the purchasing department in quantity, well in advance of the specific need for that part, so that when demand for the part does arise, the time between the detection of the need by the maintenance department and its fulfillment by the purchasing department can be minimized. A part should be a stock item when it is certain that the maintenance department will need it in the relatively near future. Parts which are used regularly and on a recurring basis are the most important to keep as stock items.

The method which is in widespread use in the industry to determine stock item inventory policies is rather simple. Taking into account the average rate of use of a part and the expected 'lead time' between ordering and receiving new parts, a minimum inventory level is set. When a part's inventory reaches this level, a quantity which will last for a predefined period of time based on the rate of use by maintenance, is ordered by the purchasing department.

Parts which as policy are not kept in inventory, and therefore are ordered only when the demand for them occurs, are non-stock items. The use of these parts may not be a certainty and thus their purchase may result in wasted resources. In addition, a part may be classified as 'non-stock' if it is required so infrequently that the cost of providing the space to keep it in stock is not worth the savings which would result. The lead time involved in a direct purchase of the part is therefore an important

factor since it is an important part of the cost saved by keeping a part in stock.

Thus the purchasing department's decision of whether a part will be a stock or non-stock item is basic to the proper functioning of the maintenance department. This decision should not be made unilaterally by the purchasing department, but jointly with maintenance. Once this decision has been made the cooperation of the two departments must continue.

The minimum inventory level and order size for stock items should be established through this cooperation. In addition, maintenance should inform purchasing of its changing needs. If it becomes clear that a non-stock item is or will be needed in the relatively near-term, purchasing should be informed immediately. It may take longer than expected to locate, order and receive a part which would fulfill the need. Purchasing should be informed if any irregularities in demand for a part should be anticipated. This may occur not only when special projects are implemented, but also when an unusually large number of buses in the fleet are approaching a major inspection or part replacement interval at the same time. If purchasing is informed far enough in advance it can react by reordering the part despite the fact that its inventory is not at the minimum or reorder point and/or by placing a larger order than normal for the part. This type of cooperation would therefore reduce the incidence and magnitude of wait time before purchasing provides the part required by maintenance.

Another important way in which maintenance is influenced by the purchasing department is that the characteristics of the parts which are bought and supplied by purchasing have a strong effect on the demands which are placed on the maintenance department. Thus where a choice of

manufacturers or suppliers of a part exists, the maintenance department should play a strong role in the purchasing decision. The purchase price should not be the only consideration. The cost of maintaining the part for its lifetime and more importantly for a fixed period of time (due to differences in expected lives of the part) should also be an important consideration.

Thus the relationship between the maintenance and purchasing departments is extremely important to the smooth operation of the maintenance department and its ability to meet its objectives. The importance of the relationship seems to warrant the establishment, within the maintenance department, of a liaison position between the two departments.

The main concern of this liaison would be to ensure the continued efficiency of the relationship between the departments. Familiarity and full understanding of the problems encountered by the purchasing department in filling its role, would obviously aid communication. The liaison would then be in a strong position to aid in evaluation of alternative part manufacturers and the stock/non-stock decision. In addition, the liaison would aid in establishing a part's reorder point and order size through use of past needs and more importantly, in accordance with predicted future demand for the part (thereby taking into account any forthcoming irregularities in demand). The computerization of the inventory system does not replace the need for this liaison, unless it is tied to a computerized maintenance system which not only records what is occurring at the moment, but also allows the prediction of the future parts needs of the maintenance department.

2.6 Summary

In this chapter, the goals and related objectives of a maintenance

department were defined and discussed. They included safety, fleet reliability, supply, cost minimization and service comfort. The types of scheduled and unscheduled actions which are commonly employed by today's transit industry to meet these goals and objectives were then described.

The effects of each of these action types on the transit agency and the users of the service it offers were summarized. It was found that unscheduled activities, particularly those which were non-preventive (i.e. road calls), had the greatest negative effect on the agency and its patrons. On the other hand, scheduled activities, consisting of daily servicing, inspection, and preventive parts replacement/repair, which are preventive by definition, were shown to positively affect not only the agency's patrons, but the agency itself. This positive effect is experienced as long as the program is well planned, scheduled and executed as well as well developed.

The level of effort presently being applied to the different types of maintenance activities was then discussed using the limited data which was available. This data points out the need for improving the industry's maintenance program development procedures.

Finally, the importance of cooperation between the maintenance and purchasing departments to the efficiency of the maintenance task was demonstrated. The need for a liaison between the two to ensure this cooperation was noted and the situations in which this liaison would be an asset were discussed.

CHAPTER 3

ASSESSING THE BENEFITS OF PREVENTIVE MAINTENANCE

In this chapter, the various purposes of performing preventive maintenance are clearly defined. For each of these purposes, the full cost savings which may accrue will be specified, and the ways in which these cost savings relate to the achievement of the maintenance goals and objectives outlined in section 2.1, will be discussed.

Consideration of the potential benefits of preventive maintenance in any more than a very general manner, requires an understanding of what these types of actions will be performed on. Section 3.1 addresses this need.

The remainder of the chapter is then devoted to specifying the cost savings which may accrue from the performance of preventive maintenance for each of the seven purposes identified at the beginning of section 3.2. Any discussion of the cost savings of preventive maintenance actions must of course include the cost of those actions which were necessary to accrue these savings. This is considered near the end of section 3.2.

All of the effects of preventive maintenance action, whether they are short-term or long-term, are considered as potential cost savings. Vehicle maintenance should be a tool not only to provide service today but also for many days, months and years to come. Actions which are taken in one program period, often have effects on actions which must be taken in subsequent periods.

Thus, long-term effects should be included in the analysis of an action's cost savings estimate, and should also be an important part of program development. There do exist some special instances which are exempted from this 'rule'. For example if new buses are scheduled to be put into service to replace older buses, the performance of actions with

long-term benefits may not be suitable for some period prior to the buses' retirement. However, even this type of situation may be occurring less frequently due to a trend toward continued use of the older buses (i.e. for service expansion, stockpiling for use during a gasoline shortage or some other potential emergency, use as spare parts, sale as used bus or parts, storing as 'insurance' against early problems with new buses).

3.1 Identification of Bus Systems/Subsystems/Parts

An absolute necessity in the development of a vehicle maintenance program or in understanding such a program, is the realization that no single balance of preventive and non-preventive maintenance applies to an entire vehicle. In fact, there are hundreds of different parts on a bus, each of which has different maintenance needs. However, programming each of these parts separately would be extremely difficult as well as inefficient.

It is possible to cluster groups of parts together into subsystems and to further group these subsystems into different systems. Each of these systems has a distinct function in the operation of the vehicle. Further, each subsystem has a particular 'job' to do, so that the system can perform its function. For example, the steering linkage would be a subsystem of the steering system, because it transfers the motion of the steering gear to the steering knuckle. However, the linkage consists of a number of parts which allow this transfer to occur, including the pittman arm, the tie rods and the various ball and socket joints.

An excellent model which could be used to generate this 'system/subsystem/part' list is that developed for the Vehicle Maintenance Reporting Standards or VMRS. VMRS is a maintenance records system

developed by the American Trucking Association and adopted by many trucking firms to aid in maintenance management. This typology divides a truck into 63 systems, of which 40, believed to be common to motor buses, are listed in Table 4. Each of these systems includes between two and thirty-seven subsystems which are broken down further into specific parts. There may be a few systems, subsystems, and/or parts which are part of a transit bus but are not listed in the VMRS as part of a motor truck and so some modifications would have to be made to this list. It does however give a good indication of the level of detail required in such a list.

A further distinction must be made between the different manufacturers or suppliers from which the transit agency receives parts. Significant differences in the characteristics of parts obtained from different suppliers are known to exist and should be accounted for in the development of a maintenance program.

Since transit buses presently in use are essentially composed of the same systems, subsystems and parts, it would be most efficient if the task of generating such a list would be done once, by a central authority such as U.M.T.A.. This task will undoubtedly be tedious if it has never been done before. However, the benefits of compiling this list will far outweigh the energy spent in its development.

It will simplify and allow a more precise definition of the 'parts groupings' which will be considered together in developing the vehicle maintenance program. In fact, the systems which are defined may often be the most desirable grouping of parts for program development. This is because the parts and subsystems of a system are working together for some common purpose in vehicle operation, and thus their maintenance needs will often interact.

Table 4

Vehicle Systems

Air Conditioning, Heating and Ventilating System	Cranking System
Cab and Sheet Metal	Ignition System
Instruments, Gauges (All) and Meters	Air Intake System
Axles Front - Non-Driven	Lighting System
Axles Rear - Non-Driven	Cooling System
Brakes	Exhaust System
Frame	Fuel System
Steering	Power Plant
Suspension	Electric Propulsion System
Tires	General Accessories
Wheels, Rims, Hubs, and Bearings	Electrical Accessories
Automatic Chassis Lubricator	Expendable Items
Axle Driven - Front Steering	Horn and Mounting
Axle Driven - Rear	Radio Equipment
Clutch	Spare Wheel Mounting
Drive Shaft(s)	Hydraulic Systems - Special Applications
Power Take Off	Body
Transmission-Main-Automatic	Rear Door
Transmission-Auxiliary and Transfer Case	Trim and Miscellaneous Hardware
Charging System	Safety Devices

The act of developing the list will reduce the risk of a part or subsystem somehow being excluded from consideration in the vehicle maintenance program development.

Finally, the list establishes a good foundation for collection of useful information concerning vehicle maintenance needs, and will also enable the maintenance department to determine the extent to which its program is satisfying the objectives which have been set for it.

3.2 Potential Benefits of Preventive Maintenance

The potential benefits of performing preventive maintenance on a system may be classified into seven basic types. These are;

- 1) reducing the likelihood of system failure,
- 2) reducing the likelihood of road calls due to system failure,
- 3) reducing the need for major unscheduled repair due to system failure,
- 4) reducing the likelihood of failure endangering safety,
- 5) providing an acceptable level of service comfort,
- 6) improving a system's performance, and
- 7) extending the life of a system or some part of it.

It may appear redundant to distinguish between reducing the likelihoods of system failures, road calls and major unscheduled repair due to system failures. However, each of these, and the remaining benefit types, affect the achievement of the maintenance objectives in different ways.

In the remainder of this chapter, the potential cost savings associated with the seven benefit types identified above will be defined, and their relevance to the maintenance objectives (see section 2.1) discussed. The discussion of the costs of the preventive maintenance actions necessary to obtain these savings will follow the discussion of the seven

benefit types. This may be done instead of discussing them with each benefit type, since the cost of preventive maintenance will be formulated and discussed so that it may be applied to each of the benefit types sought, as well as each form of preventive action practiced on any of the vehicle's systems.

3.2.1 System Failure Prevention

A system failure does not necessarily cause either a road call or the need for major unscheduled repair. These negative effects may not be incurred until well after the failure has occurred. This type of failure may be detectable to drivers, daily servicemen and/or inspectors. For example, failure of the exhaust or suspension system may be detected by the driver, but the bus may be kept in service until it is returned to the garage at the end of its service day. Similarly a slow leak of fluid in one of the bus systems will not cause immediate problems. Reducing the likelihood of this type of failure is a potential benefit of performing preventive maintenance. It may be possible for example, to reduce the risk of a fluid leak by checking the condition of the fluid lines or even replacing them at certain intervals.

The ensuing discussion of the cost savings which accrue from preventing this type of system failure, is oriented toward consideration of the costs involved in a particular level of severity of failure of a particular system. The general consequences of the failure would therefore be familiar to those involved in a maintenance program.

3.2.1.1 Parts Cost

The parts cost is simply the cost of those parts which would need to be replaced due to the system failure.

3.2.1.2 Labor Cost

The cost of the labor which is required to repair the failed system must be estimated. In order to designate a labor cost, the number of mechanics to be assigned to the failure repair job and the number of hours each would work on the job should be estimated. The wage levels corresponding to each of the mechanics should also be known.

3.2.1.3 Availability Cost

This is the cost incurred by the agency as a result of the failed bus being unavailable for service. It should be thought of as the product of the down time of the failed bus and the 'value' of that time.

The availability cost is sometimes the most significant cost of a failure, yet its estimation is certainly the most difficult. This is mainly because the value of the down time and sometimes the down time itself is dependent on the time of day during which the failure occurs. If a failure which requires a few hours to repair occurs just prior to a peak period, it will make the bus unavailable for service during that peak. On the other hand, if the bus had failed just after the peak, it would have been possible to complete the repair and make the bus available for service before the onset of the next peak period. There are generally fewer spare buses available during the peak period. Therefore the likelihood that a failure will cause some scheduled 'runs' to be missed is generally greater if the failure causes the bus to be unavailable during a peak period. The potential dependence of down time on the time of day during which the failure occurs, is explained in the subsequent discussion concerning 'wait time'.

The bus' down time includes stall time and wait time components. Stall time is the number of hours which the bus must be worked on in the

garage in order to repair the failure and return the bus to acceptable operating condition.

The wait time is the remainder of the bus' down time, which it spends not being worked on due to the lack of a stall, a mechanic or the spare parts which are necessary for completion of the repair of the bus. Wait time may be significant since the required maintenance is unscheduled. If the work required is not generally done during the workshift in which it failed then it will have to wait until the shift during which it is regularly done, thereby increasing the expected down time. This can often be avoided through adept scheduling.

However, even if the failure does occur during a shift in which such work is done, all of the garage's stalls may be occupied. The bus would then have to wait for a stall to be freed in order for a mechanic to work on it. The average length of this type of delay is almost certain to be greater for the unscheduled action than if the action were scheduled. This is true because of the lesser degree of control over the flow of buses into the garage for unscheduled maintenance. The difference between the peaks and valleys in the demand for unscheduled maintenance will therefore be greater than for scheduled maintenance. Thus, an increased average wait time for a stall will be experienced and/or the maintenance task will have to be scheduled at a smaller percent below that which would meet peak needs - an inefficient use of maintenance resources.

The component of wait time which may currently be most significant and is certainly the most openly discussed, is that due to lack of spare parts. Since the maintenance is unscheduled, the need for the part can not be predicted. When the part needed is not a stock item, it may be necessary to have the part delivered from the central store. Finally,

the part may not be in the inventory even if it is a stock item, due to the perturbations in demand for the part which are likely to occur when the part is maintained on an unscheduled basis. This would not only increase the bus' wait time but may result in a higher price being paid for the part due to the short notice involved. Improved communication between the purchasing/stores and maintenance departments may help to reduce the incidence of these type of events.

In order to determine the periods of the service day during which the bus will not be available, an estimate of the time of day at which the failure will occur is necessary. Assuming that the failure is equally likely to occur during any mile which the bus is operated⁴⁴, then the distribution of failures throughout the day can be estimated by the distribution of bus miles operated during the day. For example, if 35% of the total bus miles operated in a day are in the morning peak period, then 35% of a day's failures are expected to occur during the morning peak. More accurate estimates, taking experience into account, should be possible, particularly when only minor adjustments are being contemplated to an existing program.

By adding the down time to the time of each of the intervals it is possible to find out the portions of the service day for which the bus is likely to be unavailable. When the wait component of the down time varies significantly according to the time of day at which failure occurs (as previously discussed), then it would be advisable to take this into

⁴⁴This may tend to underestimate the probability of a failure during peak periods due, among other things, to the common practice of using the less reliable buses only during peak hours.

account here, by using estimates of down time which correspond to failures which occur during each period of the day.

In order to determine the value of the down time, it is necessary to know how the failure is likely to affect fleet usage. For each period of the day⁴⁵, estimates are needed for the number of buses needed for service and as spares to replace road call buses, and the number of buses which are scheduled to be in maintenance or otherwise disabled. When the sum of these estimates is subtracted from the fleet size, the remainder should be the number of extra buses which are not used during that period.

This is the number of buses available to replace buses which are down for unscheduled maintenance, like the bus which has failed, before other more costly means must be found to meet service needs. It would therefore also be necessary to estimate the number of other buses which are likely to be down due to previous periods' failures. If this number exceeds the number of extra available buses, then one of the spare buses which was allotted for road call response would probably be placed in service. If the sum of the deficit in extra available buses and the number of road call response buses which are actually needed is less than the initial number of spare buses⁴⁶, then the response still has not resulted in any costs aside from headaches and gray hair.

⁴⁵ Since the availability cost is likely to be most significant during the peak periods, they should be examined first. If costs are significant in the peak then the next most demanding periods should probably be examined as well.

⁴⁶ The probability of this happening can be found by estimating the probabilities of different numbers of road call response buses which would be needed, or the 'road call bus distribution'.

However, if the number of spare buses is insufficient, then either a bus must be released which was scheduled for maintenance⁴⁷ or the service schedule cannot be met. The expected cost of delaying the scheduled maintenance can be estimated as discussed in chapter 4. Finally, the cost of a missed 'run' should include the revenues lost in the short term due to aborted passenger trips, revenues lost in the long term due to the negative impact on users' subsequent choice of using transit and the cost of paying operators who have no bus to drive.

Thus the estimation of availability cost is rather difficult. Use of past experience and data would be a tremendous aid in estimating such things as the likelihood of different numbers of road calls during an interval and the number of buses which can be expected to be down for unscheduled maintenance. From the predictions made on this basis a program can be developed. If the program results in significantly different outcomes, then iterations could be made. In any case the importance of the availability cost must not be ignored, since both of its elements, down time and the value of that time, are extremely important factors in finding the balance of preventive and non-preventive maintenance best for the transit agency.

3.2.1.4 Objectives Served by System Failure Prevention

Thus the cost savings which accrue from preventing a system failure which would not cause either a road call or the need for major repair, are mainly availability cost savings. The maintenance objectives which may be served are those of supply and cost minimization of the

⁴⁷This is unlikely since a bus should not be 'scheduled' for maintenance during peak hours. (see section 3.2.8)

maintenance task.

The unscheduled nature of the maintenance needs caused by this type of failure, means that the timing of the need is not controlled (and thus may occur at undesirable times, like just before or during a peak period), and that the expected wait time is longer than it would be for scheduled maintenance. Prevention of this type of failure would therefore increase the probability that the maintenance supply objective would be met.

Avoiding or even easing the supply effects of those failures which are not prevented, can only be accomplished by increasing the cost of the maintenance program. This would involve scheduling the use of the maintenance resources in a less efficient manner and either keeping a larger inventory of the parts involved in the failure, at the garages and the central store, or paying a higher price for the part needed on such short notice.

3.2.2 Prevention of Road Calls Due to Failures

In attaching a cost savings to the prevention of a road call and its effects, it must be kept in mind that a road call is only the response of mechanics to a 'distress' call from an operator. The effect of road calls will differ according to each individual incident. A replacement bus may or may not be dispatched, the bus which has been road called may be fixed and returned to service or it may have to be driven or towed back to its garage, and a major repair may or may not be necessary. A number of different combinations of these effects may also occur. Thus in estimating the cost of a road call caused by a particular system's malfunction, the probabilities of the various effects should be estimated as well as their costs.

3.2.2.1 Mechanic Labor Cost

Mechanic labor may be the largest and is certainly the most obvious cost involved. One of the unfortunate characteristics of road call response is not only that mechanic labor time is consumed, but that it is consumed at a rather low rate of productivity. The time spent gaining access to the road call site is wholly unproductive time, while that spent working on the problem bus is probably spent less productively than if the same job were being done under more favorable conditions at the garage. It is appropriate then, to include an opportunity cost as well as the direct labor cost of the access and on-site time, in the total mechanic labor cost.

This opportunity cost would become important if the road call assignment caused the mechanics to fall behind on their scheduled work. Thus any overtime costs incurred to catch up on this work or any consequences of delaying the work should be estimated and included in the opportunity cost. Such a cost may be difficult to estimate, nevertheless it should be taken into account since it may be significant.

3.2.2.2 Service Vehicle Use and Ownership Costs

Another important cost of road call response involves the ownership and use of the service vehicles. Costs result from the fuel which is consumed and maintenance needs which develop due to the use of the service vehicles for road call response. These costs may be estimated using the expected access distance and the vehicle's per mile maintenance costs and fuel consumption or by splitting the total expected cost of maintenance and fuel among the road call responses.

The total cost of owning these vehicles and the proportion of their use which is associated with road call response must be known in order to

determine the ownership cost which should be apportioned to road calls. An estimate of the total number of expected road calls would then provide the cost allocated to an individual road call.

3.2.2.3 Availability Cost

There is a bus availability cost associated with a road call due to the delay it imposes on the users of the system. In the short term, some users up the line from the road call may stop waiting for the bus and in the long run, the 'bad experience' may influence subsequent mode choice negatively with respect to transit.

In addition, the time which the driver of the disabled bus spends without a bus to drive is unproductive time due directly to the road call. Thus the wages earned by the driver during that time should be included as part of the availability cost.

3.2.2.4 Parts Cost

Finally, the cost of any parts or materials used by the mechanics while working on the road called bus, is also directly attributable to the road call.

3.2.2.5 Road Call Replacement Bus Costs

A road call, as was pointed out earlier, may lead to other actions being taken by the transit agency, each of which has an associated cost. One of these potential actions is the dispatching of a spare bus to replace the bus which has been road called. If taken, this action would usually occur either directly following notification of a road call or after it has been determined that the bus causing the road call cannot be returned to service before going to the garage.

There is an operator labor cost involved in the dispatch of a

replacement bus due to the need for an 'extra' driver to operate the replacement bus. Generally a transit agency will employ a greater number of drivers on a shift than the number needed to meet scheduled service. The extra drivers are needed to stand in for absentees and/or to drive replacement buses to drivers of road called buses and subsequently to stay with the disabled bus until it is delivered to the garage.

The operator labor cost associated with a road call replacement might be estimated by the time an extra driver would spend on a road call due to the part malfunctioning. However, this cost estimate neglects the fact that the extra driver cannot be hired only to respond to that particular road call. The extra is paid at the same rate for the time spent waiting for a 'job' to come along. A better formulation would therefore allocate the total wages earned by extras employed for replacement bus driving, to each of the replacement bus trips expected.

The fuel, maintenance and other operating costs associated with moving the replacement bus from the garage to the point at which it begins service, may in some cases be significant. More important though, is that the availability of a spare bus to carry out this operation not be taken for granted. The need for maintenance to supply a larger operable fleet than would be necessary if the road call did not require a replacement bus, produces a cost which should be considered, particularly for road calls occurring during peak periods. Supplying additional buses during the peak hours is likely to be most costly because supply must already be at its peak to meet scheduled service. Also during off-peak hours additional buses are usually available with no added maintenance effort because some buses which were maintained for peak hour service are not being used in off-peak service.

A cost which applies nearly exclusively to peak period replacement bus trips is the cost of owning a larger fleet than would otherwise be necessary. Peak period replacement actions often require the use of a bus which would not be owned if the fleet met only service needs, not including peak spare bus needs. This is due to the fact that peak bus needs determine the necessary size of the operable fleet and therefore the replacement bus needs for that period must be met through ownership of a larger fleet than would be necessary to meet the service schedule needs alone.

The estimate of this cost should include the cost of purchasing an additional fleet of this size, spread over the expected life of these buses. The cost of owning the extra fleet for a program period would then be apportioned equally to each of expected peak period replacement actions⁴⁸.

The magnitude of a road call's availability cost depends on the length of time for which a bus is not available to meet scheduled service. Therefore, unless the disabled bus can be repaired and returned to service prior to the arrival of a replacement bus, the expected length of time between the failure/road call and the arrival of a replacement bus for scheduled service is important in determining the availability cost of a failure. This time should be estimated based on the agency's replacement bus dispatching policy as it applies to the type of failure being considered and the average access time from the garage to the road call site.

⁴⁸This requires estimation of the number of road call replacement bus actions and their distribution during the service day as discussed for failures in 3.2.1.3.

3.2.2.6 Cost of Bus Not Repaired at Road Call Site

It may be necessary, after the mechanic's work at the road call site is complete, to return the bus to the garage. If the mechanic cannot render the bus operable at all then the bus will have to be towed. It will be driven to the garage in the case where the bus cannot be returned to service but can, due to the mechanic's patchwork, be driven as far as the garage. Also, if the bus is completely fixed but a replacement bus has already been sent into service, the fixed bus would be driven back to the garage.

The only cost not yet taken into account in the case of the drive back to a garage (extra operator labor cost has been allocated to replacement bus action) is the actual operating cost of the move (i.e. fuel consumed, maintenance needs developed). Towing however, involves yet another vehicle and more labor if the agency does its own towing, or a fee if it contracts out its towing.

In cases where the bus is being taken to the garage to be repaired, it is appropriate to attach to the action the cost of this repair. This cost would include labor, parts and availability costs analogous to those defined in sections 3.2.1.1-3.2.1.3 for simple failure prevention.

3.2.2.7 Total Cost of Road Call Effects

In order to arrive at a figure for the total expected cost of a road call, the probabilities of the potential effects of the road call, replacement bus dispatch and return to the garage, must be estimated. These probabilities should be based on past experience and data concerning road calls due to particular systems' malfunctioning.

3.2.2.8 Objectives Served by Road Call Prevention

Thus, prevention of road calls can obviously result in a wide variety

of significant cost savings, related to the achievement of three maintenance objectives defined in section 2.1 - fleet reliability, supply and cost minimization.

Since a road call results in the interruption of scheduled service, the reliability of the fleet supplied by maintenance diminishes with every road call. This 'reliability failure' is the direct cause of an immediate 'supply failure', because the service schedule is not met. In addition, when a replacement bus is needed, it becomes more difficult and more costly to meet the supply objective, particularly when the action occurs such that the disabled bus is unavailable for peak period service.

The achievement of the supply objective is affected in another more subtle way. Since the 'flow' of road calls is not controlled, there will be peaks and valleys in the number of occurrences from day to day. When the peaks occur, additional mechanics will need to be assigned to road call duty and they will consequently fall behind in their regular assignments. This may reduce the probability that the supply objective will be met at some time subsequent to the road call.

Despite the importance of all of the above effects, the effect which road calls have on the cost of the maintenance program may be the most significant and is certainly the most obvious to transit managers. There is the cost of using and needing to own a service vehicle fleet and the high labor cost involved in responding to road calls.

The road calls which require replacement buses increase the cost of the program due to the need to supply the spare buses. Further, there are capital costs involved in ownership of a larger fleet to respond to road calls which occur during peak periods, and the cost of employing a larger

operator force to drive these replacement buses.

Finally, if the bus must be moved to the garage, there is the additional cost of towing or driving the bus back to the garage. In these cases major repair may be necessary - the subject of section 3.2.3.

Thus prevention of road calls can obviously be quite an important benefit of performing preventive maintenance. Significant costs to the maintenance department and the rest of the agency would be avoided, fleet reliability would be improved and the likelihood that the maintenance supply objective is met would be increased.

3.2.3 Prevention of Major Repair Due to Failure

This section concerns the cost of major repair due to system failures, whether or not these failures cause road calls. The separation of the potential for major repair and simple failures, is warranted if there is more than one clearly distinct degree of failure for the system being considered. This is the case for a number of systems of a bus. The failure may affect only a part of the system or it may be propagated to other parts of the system and sometimes to other systems of the bus as well. The failed system may be damaged to different degrees affecting the amount of maintenance effort required. The probability of each degree of failure may be estimated along with its associated cost, from past experience and data. The costs of doing major repair work on a system can be characterized in the same way as was done for repair due to simple failure in sections 3.2.1.1 - 3.2.1.3. However, the magnitude of the variables' values will likely be very different. Thus, the importance of preventing the need for major repair to the objectives of supply and cost minimization is exacerbated.

3.2.4 Prevention of Failures Endangering Safety and Objectives Served
by Such Actions

Deciding what level of maintenance effort is warranted in the interest of safety is philosophically an extremely difficult matter due to the inability to assign a monetary value to a human life or limb. Any value which is put forth is subject to criticism as being unrealistic and arbitrary.

For those who insist on understanding the 'costs' involved in a safety failure, or an accident, there are a number of substantial costs which may be cited, even beyond that which might be associated with loss of human life or limb. Any lawsuit which may arise from an accident, particularly one caused by neglect, would likely be very costly. Certain actions may be imposed upon the agency and its maintenance department which may be substantially costlier than the action which would have been necessary to prevent the accident. The bus involved in the accident may require a great deal of repair work in order to restore it to operable condition, and would therefore involve high parts, labor and availability costs. Finally, the mode choices of riders and potential riders, particularly those with a good alternative (i.e., auto), will be negatively affected by news of an accident, especially one due to neglect. In some cities, the relative safety of transit may be an important factor in attracting ridership. Any accident, but again particularly one caused by maintenance neglect, would certainly tarnish the image of safety.

Thus, there do exist a number of significant cost-related effects of a safety failure. A maintenance manager must be extremely wary of using only such costs to determine maintenance effort to ensure safety, for their use implies that a value can be assigned to human life or limb.

Fortunately, there are few systems which have a direct bearing on the safety of the bus. Ensuring the adequate operation of the brake system is probably the most important safety-related maintenance action. The frequency of such actions should be chosen conservatively and should eliminate as much safety risk as is feasible.

Since a safety failure or accident, involves a road call and usually results in the need for major repair of the vehicle involved, the objectives which are served by preventing such a failure include not only the safety objective, but the entire goal of the maintenance function as it was defined in section 2.1 - to provide a safe and reliable fleet to meet the needs of the transportation department at the least possible cost.

In the previous sections the distinctions between simple failures, failures causing road calls, failures requiring major repairs and safety failures have been made clear. However, in developing a maintenance program for a system which may experience different types of failures, it may be best to think in terms of the cost of a failure of a system by attaching probabilities to the various potential effects of such a failure.

3.2.5 Service Comfort

A maintenance task which would directly serve one of the objectives defined in section 2.1 is that of providing an acceptable or improved level of comfort for the system's users. Many maintenance actions which are taken for reasons other than improving the level of comfort, do nevertheless have an impact on it. However, there are some actions

which could be taken by maintenance which have as their main goal, improvement of rider comfort. These types of actions include keeping the windows and the entire exterior and interior of the bus clean, prompt repair or replacement of broken or missing windows, broken seats, and heating and air-conditioning units, and correctly functioning destination signs.

The potential benefits of these types of actions are mainly those of upgrading the image of the transit system and thereby increasing ridership, and improving public sentiment toward the transit agency. This latter effect, though difficult to quantify, may become important in some of the more political situations which occasionally affect transit agencies.

Quantification of the potential ridership gains due to increasing the level of comfort is a difficult, if not impossible task. In order to determine the effect of a comfort adjustment on ridership, the value placed on this adjustment by potential and existing riders must be estimated. This task would be too difficult and expensive to be undertaken as a separate task, rather, it should be implemented as part of a larger research effort by another department (i.e. marketing, planning).

In any case, a maintenance policy concerning the level of effort to be applied to improving service comfort should be developed and implemented on a consistent basis. It should be realized that this policy should reflect not only the goals of the maintenance department, but also those of other departments and of the agency leadership.

3.2.6 Performance Improvement

A potential benefit of preventive maintenance which addresses only the objective of minimizing the maintenance cost of bus operation is that

of improving bus system performance. This mainly involves decreasing the buses' rate of fuel and oil consumption. The performance of many different parts and systems affect this measure of performance.

Data must be collected in order to determine the level of performance of individual buses and/or of the fleet as a whole. Using the latter method eliminates any opportunity to treat the buses individually which may have enabled the performance improvement strategy to have a greater effect. Thus it is most desirable to collect fuel and oil consumption data during daily servicing activities for each bus.

The actual performance improvement action may consist of adjustments (tire pressure level, carburetor adjustments, timing, cleaning plugs) or the replacement of a part prior to the time it might have been replaced to prevent system failure (oil and filter change, spark plugs, air and gas filters, etc.).

The cost savings associated with a performance improving action depends on the cost of the action and the expected improvement in the average performance level. Both the cost of the action or performance improvement program which it is a part of, and the change in performance level are likely to be influenced by the frequency with which the action is taken. Methods by which the change in performance level associated with performing a particular action at a particular frequency may be estimated, are discussed in detail in section 4.2.2.3.

3.2.7 System Life Extension

Extending the life of a system may be accomplished through either adjustment or replacement of a part within that system or of a different system. The aim of these types of actions is essentially to minimize

the cost of maintenance for the systems involved. Examples of this type of action are abundant and include lubrication of moving parts, changing engine, transmission and differential oils and filters, wheel alignment and balancing, flushing the cooling system, and preventive replacement of voltage regulators to ensure continued protection of the electrical system. The potential cost savings of system life extension activities involves parts, labor and availability components.

3.2.7.1 Parts Cost

The parts cost savings component would involve the cost of the parts whose lives have been extended and the expected lives of the parts before and after the action. The expected part lives (before and after) may be estimated through the use of any data which may exist comparing buses for which action was taken at different times and/or from consultations with well seasoned mechanics who are specialists with the bus system being considered.

3.2.7.2 Labor Cost

Performance of the life extending action may reduce the labor cost of maintaining the system whose life has been extended. This may be accomplished by reducing the frequency of the system's failure and/or a reduction of the frequency at which a system failure preventing action needs to be performed. These frequencies are influenced by the frequency at which the life extending action occurs, which in turn should be influenced by the estimates of the system's life before and after the action. Thus the labor cost saved due to life extension activity involves the labor cost of either the system's failure, or failure preventing action, and the magnitude of the decrease in frequency of the incurrance of these

costs.

3.2.7.3 Availability Cost

Reductions in availability cost due to life extending actions may also be experienced. Again this is due to the decreasing frequency with which the availability and other costs of either system failure or failure preventing actions, are incurred.

3.2.7.4 Objectives Served by System Life Extension

The objective most clearly served by system life extension is that of maintenance cost minimization. However, other objectives may also be served, depending upon the impact which such actions have on the rest of the system's program.

If the program does not include failure prevention actions, then system life extension would decrease the frequency of failure. Thus, the same objectives which apply to preventing the system's failure (see section 3.2.1.4) and its subsequent effects (see sections 3.2.2.8, 3.2.3), would be served to a lesser extent by system life extension.

However, if failure prevention actions are taken then the frequency of failure will be influenced to a much lesser extent, if at all, but the frequency with which the failure prevention actions must be taken may be reduced. The objectives served by this effect depend upon the cost of the preventive actions, which is the subject of the next section.

3.2.8 Cost of Preventive Maintenance

This section is included here to stress the fact that the benefits of performing preventive maintenance must be weighed against its costs in order to arrive at decisions concerning the level of maintenance effort to be applied to various tasks. The cost of any preventive

maintenance action is made up of the same basic components, although their magnitudes will depend on the form of action being taken, benefits sought by such action, and the system being considered.

3.2.8.1 Scheduled Preventive Maintenance Action

Scheduled preventive actions occur at regular intervals, specific tasks are carried out each time and a certain number of stall hours and labor hours are allotted to the action. Therefore, the parts, labor and availability cost components (analogous to those defined in sections 3.2.1.1 - 3.2.1.3) should be fairly simple to estimate.

In addition, if the action is scheduled to be performed prior to the completion of the bus' scheduled service day then a replacement bus will be necessary. It would therefore also be necessary to assign operator labor and spare bus use and ownership costs analogous to those defined in section 3.2.2.5, to the preventive maintenance action⁴⁹. Since the return of the bus to the garage was not part of scheduled service, the cost of this movement must also be included in the cost of the preventive maintenance action. It should be possible however, to avoid these additional costs through proper scheduling of preventive maintenance (see section 4.4).

3.2.8.2 Unscheduled Preventive Maintenance Action

Of course, not all preventive maintenance actions are scheduled. Most unscheduled preventive maintenance actions arise as a result of a scheduled action. In fact, an on-condition type of program is designed

⁴⁹ It is assumed that the replacement process itself will be carried out so that it will have no effect on scheduled service adherence.

such that a relatively minor scheduled task is performed on a system during daily servicing or inspection in order to determine whether or not a more major task should be performed. The flexibility of this type of program is discussed in Chapter 4.

If the unscheduled work needed is relatively minor, it may be completed within the time allotted to scheduled preventive maintenance. In these cases the availability cost of the scheduled preventive maintenance will not be changed, but the parts and/or labor costs will increase.

Labor cost may be increased due to assignment of one or more additional mechanics to complete the action, or the extension (to no longer than the stall time) of time which individual original mechanics spend working on a bus.

Otherwise, additional stall time and labor hours would obviously be necessary. In this case, parts, labor, and availability cost are all likely to increase. Whether or not parts cost will increase and if so by how much, depends on the type of job required. An increase in the labor hours involved is certain, either through the use of additional mechanics, or the use of the same mechanics for additional time.

The availability cost will almost certainly increase due to an increase in the down time and possibly also an increase in the value of the down time. The down time will increase not only due to the additional work time, but possibly also from an increased wait time which may occur between scheduled and unscheduled actions. Thus the probability that another bus will be needed to meet the service schedule is almost certain to increase. The increased down time may also increase the likelihood of the bus being unavailable during a peak period which would substantially increase the value of the down time, due to the

increased cost of making a spare bus available during the peak and the increased potential for missed runs.

3.2.8.3 Types of Preventive Actions and Their Likely Cost Magnitudes

A brief review of the various forms of preventive maintenance identified in Chapter 2 will reveal that the cost components defined above are representative of any type of preventive maintenance action.

Daily servicing tasks will have a major labor cost component, while parts and materials cost will usually be limited to oil and fuel. Availability cost is virtually non-existent unless a defect is noted, and unscheduled preventive maintenance becomes necessary. Scheduling daily servicing activities to occur following a day's run could minimize but not completely eliminate the effect that this additional down time would have on the availability cost to the agency. In any case, the correction of a defect through an unscheduled maintenance action will result in an added labor cost. Whether the work is done during scheduled or unscheduled time, it may result in added parts cost, depending on the type of defect involved.

Periodic scheduled inspections will be even more labor-intensive than daily servicing activities since they generally involve checking, adjusting or measuring various parts, with parts cost being extremely limited. The availability cost associated with scheduled inspections can be minimized through skillful scheduling of tasks. The higher level or less frequent inspections however, may call for extended down times which may be more likely to interfere with bus needs, thereby increasing availability costs.

Unscheduled maintenance due to scheduled inspections may or may not

result in a greatly increased parts cost, depending upon the type of work required. Labor cost will most probably increase, possibly substantially, depending again on the particular task necessary, and availability cost may not increase at all or may increase quite substantially. While availability cost will also depend on the type of work necessary, it may be minimized by scheduling the preceding inspections in anticipation of the need for unscheduled post-inspection action. This would mean scheduling those inspections with the greatest potential for requiring more lengthy unscheduled work, at a time which would allow a bus to be down for such an extended time without interfering with scheduled bus needs (i.e. third shift inspection - first shift unscheduled post-inspection tasks). Again, these factors are largely dependent upon the parts being worked on and the defect involved.

P.P.R. will obviously have a larger parts cost component than other preventive maintenance actions, but the labor cost incurred may also be quite significant, particularly when major repairs are made. Availability and particularly labor costs will be strongly dependent on the specific task involved, due to differences in the times necessary to repair or replace different parts of different systems. Availability cost can again be minimized by scheduling the actions such that the interference with peak service periods is minimized.

Finally, unit rebuild/overhaul will probably be the most labor-intensive preventive maintenance action. Parts cost may be quite low but availability cost may be high in cases where the rebuild/overhaul is done with the system on the bus. It is sometimes possible to greatly reduce availability cost by first replacing the unit, thereby enabling the bus to be released back into service, and then rebuilding the unit.

In cases where such a process is possible but not necessary, the relative cost of the removal process and of availability if the task were to be performed with the part on the bus, will determine whether removal is cost effective.

3.3 Summary

In this chapter, the potential benefits of performing preventive maintenance on a system, were classified into seven types. Each of these benefit types has effects on the maintenance department and the entire agency, as well as its users. Methods which can be used to take such effects into account, as potential cost savings of performing preventive maintenance, were suggested and discussed. The potential cost savings associated with an action of each benefit type, were related to the achievement of the maintenance objectives defined in Chapter 2.

Finally, the costs of scheduled and unscheduled preventive maintenance actions were broadly defined, followed by a discussion of how these general costs apply to the different maintenance tasks identified in Chapter 2.

Thus, the role of preventive maintenance is a multi-faceted one. It is an indispensable part of a maintenance program which strives to achieve each of the established objectives.

CHAPTER 4

DEVELOPING A TRANSIT VEHICLE MAINTENANCE PROGRAM

In this chapter, a framework is proposed which can be used to develop a transit vehicle maintenance program which satisfies the maintenance objectives defined in Chapter 2, through definition of the proper balance of resources applied to preventive and non-preventive maintenance.

Programs are developed for each vehicle system, in order that the significant interacting maintenance needs which often exist within these systems can be taken into account more easily.

In order to define the structure of the maintenance program, the systems whose parts require the most frequent maintenance, primary systems, are programmed first. Through coordination of these primary systems' programs and the intervals at which their maintenance actions are scheduled to occur, a minimum interval is established at which the vehicle maintenance program's most frequent scheduled actions are performed (excluding daily servicing). All other scheduled actions, for both primary and secondary systems, can only be carried out at multiples of this minimum interval.

In developing any system's program, a decision must be made as to whether or not preventive maintenance will be performed on its parts and if so, the form which the preventive maintenance action will take, must be defined. For each program form, the costs defined in Chapter 3 are applied in order to define the program which provides the benefits sought at minimum cost.

Following the definition of the single least-cost program for each system, the vehicle maintenance program's tasks are scheduled, so as to minimize the conflict between the transportation and maintenance

departments, thereby minimizing the cost of the program to the transit agency.

The chapter's final section is a brief summary of how the framework may be implemented in the program development process.

4.1 Defining the Structure of the Preventive Maintenance Program

In the following sections, the way in which different preventive maintenance program forms may be considered for a system is described. It will become evident, that developing each system's program completely independently of other systems' programs, would greatly complicate the formation of a unified vehicle maintenance program which would not significantly interfere with the needs of the transportation department. Through coordination of the development of the systems' programs, a vehicle maintenance program can be defined, which will reduce the conflict between the needs of the transportation and maintenance departments, and minimize the cost of the program to the transit agency.

Such coordination can be achieved by the establishment of a 'minimum interval' at the onset of the program development process. This minimum interval is the scheduled time, or mileage, between arrivals of a vehicle at the garage for the scheduled maintenance task⁵⁰ which is performed most frequently. All other scheduled maintenance tasks would be performed only at intervals which are multiples of the minimum. The process of establishing this minimum interval is described below.

The first step in this process should be the identification of the vehicle's critical parts. This should be undertaken on a system by system basis for reasons of orderliness and completeness as well as another,

⁵⁰excluding daily servicing

perhaps more important reason which will soon become clear. A critical part is one which may result in system or vehicle failure when functioning improperly, and/or whose condition will affect performance and/or the life of other parts of its system or vehicle.

The critical parts which are likely to require the most frequent preventive maintenance should then be identified. These parts are likely to be those whose preventive maintenance may involve a relatively minor task which may yield the more major types of benefits related to the safety of vehicle operation, or the prevention of failures which lead to road calls and/or major repairs.

The systems having these most frequently maintained critical parts as components, may be termed primary systems, while the remaining systems may be classified as secondary systems. Maintenance programs should now be developed for these primary systems, utilizing the costs and benefits defined in Chapter 3, as described later in this chapter. The entire system, and all of its critical parts should be programmed simultaneously, because of the interaction between the maintenance needs of different parts within a system. These interactions are taken into account through simultaneous programming of a system's critical parts thereby resulting in the 'best' program for the entire system.

Initially, the programs for each of the primary systems should be developed independently, so that each achieves the optimal balance of preventive and non-preventive maintenance. However, once each of the primary systems' optimal programs have been defined, they should be coordinated such that a single minimum interval emerges for the vehicle maintenance program. This can be accomplished by evaluating the cost effects of operating at slightly longer and shorter intervals than those

which result from individual optimization.

In carrying out this process, the effect which the length of the minimum interval has on the flexibility of programming tasks which are not performed at the minimum interval should become clear. Briefly, this flexibility increases with decreasing minimum interval length, by allowing the 'non-minimum interval tasks' to be programmed more closely to their individually optimal intervals. This implies that ideally, the vehicle maintenance program's minimum interval be set by considering its effects on all of the intervals of each system's program. This procedure however, would become increasingly unwieldy as more systems with different optimal task intervals are included.

In any case, this type of simultaneous development of scheduled intervals can be most beneficial when applied to the setting of the shorter intervals. This is best demonstrated by a hypothetical example. In adjusting a program's minimum interval from 1500 to 2000 miles, the cost of adjusting a task's interval from 3000 to either 2000 or 4000 miles, is likely to be more significant than that of adjusting a task's interval from 27,000 miles to either 26,000 or 28,000 miles. Thus when setting a program's minimum interval, in addition to considering the cost effects on the primary systems' entire programs, the cost effects on all systems, primary and secondary, which are involved in the next shortest interval, should also be taken into account.

Following establishment of the primary systems' programs and thus the minimum interval, determination of the cost minimizing intervals for the secondary systems' scheduled maintenance tasks should be much simpler. This is because only multiples of the minimum interval are considered. It may be advantageous, following identification of the optimal interval

for each of these tasks, to examine the effects of operating at slightly longer and shorter intervals for each of them, in order to determine whether it would be better to perform the task slightly early or slightly late. The impact on the effectiveness of the minimum interval task for that and the subsequent interval should also be taken into account in such a determination.

4.2 Programming a System

Development of a vehicle maintenance program involves the programming of each of the vehicle's systems, such that their maintenance results in minimum cost to the transit agency. As discussed in the previous section there is an important difference between programming primary and secondary systems. The intervals which may be considered for scheduled maintenance actions on secondary systems are limited at the start to multiples of the minimum interval which is defined through programming of the primary systems.

Nevertheless, the basic process of developing the 'best' program for a system, whether it is primary or secondary, is essentially the same. The identification of the system's critical parts is the first step in program development for either system type. Further, the basic process of considering the different forms of maintenance programs is not affected by the system's classification. The only difference is in the degree of flexibility available in choosing the time at which specific actions will be taken within a program form.

Thus the discussion in the following sections, concerning the consideration of different program forms, can be applied to primary and secondary systems. It is assumed that the critical parts of the system being programmed have been identified, as have the potential benefits of

performing preventive maintenance on each of them. Thus the various program forms are actually being considered for the preventive maintenance actions which may be taken on the critical part, to gain the potential benefits corresponding to its preventive maintenance.

The three basic program forms involve the performance of,

- 1) no preventive maintenance,
- 2) preventive maintenance action on a scheduled basis, and
- 3) preventive maintenance action on an unscheduled basis, but whose performance depends directly on the results obtained from a minor scheduled, or monitoring, action.

These program forms will be referred to respectively as; no preventive maintenance, hard-time maintenance and on-condition maintenance. Each of these forms should be considered for each of the system's critical parts, unless the part's maintenance involves the safety of the vehicle's operation. In such cases, only the two forms of preventive maintenance should be considered.

For each of the preventive program types, a maintenance program which achieves an optimal balance between preventive and non-preventive maintenance should be defined. This will involve the estimation of the cost of each type of program action and the frequency at which they will be performed. Since the frequency of scheduled action determines the frequency at which other actions will need to be performed, the process of determining its frequency is employed in development of the maintenance program and estimation of its cost. The frequency setting process will first be discussed for scheduled actions for failure prevention, followed by those for performance improvement and part life extension.

In considering an on-condition type of program, there are different

degrees of flexibility involved in scheduling program actions. The degree which applies to a particular part depends upon its monitorability, a characteristic which is defined and discussed in section 4.2.3, which concerns the development of an on-condition program. In any case, for each of the three basic program forms, the cost (to the agency) of the system's maintenance which is attributable to the critical part's program will be estimated utilizing the costs developed in Chapter 3. The program form which results in the least cost to the agency should be the one implemented.

In cases where a system has more than one critical part and the benefits accrued from their maintenance interact, then the system's program will need to be developed through an iterative process. This is due to the fact that when programming one critical part, the effects of its program on a part whose program has not yet been developed, may not be able to be fully and accurately accounted for. The iterations which will probably be necessary may be minimized by ordering the parts' programming such that the parts whose maintenance may yield more significant benefits are programmed first.

4.2.1 No Preventive Maintenance

When preventive maintenance is not performed on a part, the only time a mechanic sees the bus for maintenance on that part is either when a defect is reported, usually by the driver, or upon interruption of service due to system failure caused by the part's malfunctioning. In estimating the cost of this type of program then, it must always be kept in mind that system failures may have different cost magnitudes than those which occur when the part's maintenance program includes preventive maintenance actions.

The main cost involved in a 'no preventive maintenance' program will usually be the cost of the system's failure and its effects. In addition, the failure rate of some other systems may be increased either due to the lack of preventive maintenance which would have extended the life of this other system, or as a result of the propagation of the system failure to this other system. This increased failure rate can sometimes be mitigated or eliminated through increased scheduled maintenance on this other system. In such cases, the sum of the costs of the added scheduled actions and of any residual increase in the failure rate may be substituted for the cost of the full increased failure rate, provided of course that the substitution reduces the total cost.

Further, the performance level of the system not being maintained, or of some other related system, may be affected by the level of preventive maintenance action. If so, the cost of operating the fleet at the level of performance corresponding to the no preventive maintenance program, should somehow be included in the program cost. Finally, if a part's maintenance program has an effect on comfort, any ridership adjustment which may result from a program's implementation should be taken into account.

4.2.1.1 Cost of System Failure

In estimating the cost of a failure caused by a part which has a no preventive maintenance program, a number of decisions and estimations need to be made. The expected extent of damage to the system needs to be estimated. If more than one level of severity of failure is possible the probability of their individual occurrences should be estimated. From this information, the relative frequencies of failures resulting in parts repair or parts replacement should be estimable. These relative frequencies would in turn enable the estimation of an expected parts cost for a failure.

A decision must then be made concerning the number of mechanics (and their corresponding wages) and the stall time which would be assigned to perform the expected jobs. To reach this decision, the relationship between the number of mechanics assigned and the down time of the vehicle, as well as the total labor hours and their corresponding cost needs to be understood. The decision should result in the minimization of the sum of the labor and availability costs which are directly incurred due to the stall time scheduled for the maintenance activity.

The estimate of wait time in the calculation of the availability cost of the failure should take into account any effects which the maintenance program may have on the availability of parts from the purchasing department. For example, a no preventive maintenance program might result in a higher expected wait time due to lack of parts, or alternatively the inventory of the part may need to be increased relative to that which would be necessary for a preventive maintenance program.

Finally, the probability that the part's failure would cause a road call and the expected cost of such a road call must be estimated. Included in these costs are the cost of a replacement bus if one is needed and the cost of moving the failed bus to the garage if such action is necessary.

Having calculated an approximate cost of each level of failure severity and the relative frequencies of these failure types, in order to estimate the contribution which they make to total program cost, the frequency of failure must be estimated. This should be done through the estimate of the mean time between failure (MTBF) and the number of fleet miles to be operated in the period being programmed.

The MTBF may be somewhat difficult to estimate, particularly if preventive maintenance has been consistently practiced on the part and

limited data on the part has been collected in the past. If preventive maintenance has been practiced and data collected, then any parts which for some reason missed their scheduled maintenance and subsequently failed, may be one source of information. The mechanics' experience might help and so might communication with other transit agencies using the same part under similar conditions.

A strategy which in many cases may be most suitable is that of experimentation with a small but significant subset of the fleet. Such experimentation would involve allowing the system to operate until its failure is imminent.

In cases where a part's condition can be ascertained by performing a minor monitoring action, then such actions should be performed quite often in order to reduce the risk of in-service system failure. If this type of observation is not possible, the chance of failure may be limited by adjusting the experimental methodology. It may be possible through system disassembly, to estimate the part life which has not been used or simply whether or not the part was about to cause failure (i.e. transmission and differential gears and bearings, engine's pistons and rings). In such cases, experimentation with the point in the part's life at which it is disassembled would yield the information necessary to determine the MTBF.

Thus the total cost of failures associated with the part's no preventive maintenance program can be estimated for the program period, using the estimates of the mean time between failure and the expected cost of a failure, along with an estimate of the number of bus miles which will be operated during the program period.

4.2.1.2 Effects on Performance Level

In some cases, a part's maintenance program has an effect on the

average performance level at which that part's system, or that of another system, operates. In the event that the performance of the system being programmed is influenced (i.e. oil and filter change and fuel consumption, engine overhaul and oil consumption), then the cost of operating at the average level of performance which would be experienced with a 'no preventive maintenance' program should be included in the cost of the program. The alternative program types to be considered should include an analogous cost.

When the performance of another system is influenced by the part's maintenance program (i.e. tires and fuel consumption), the added cost to the program may be more difficult to estimate. It should not include the total cost of the other system's performance level, but the difference between the cost of operating at the level of performance associated with the no preventive maintenance program and 'that which it would otherwise be operating at' should be included.

This last phrase may be impossible to define due to the fact that the program of another system affects it and so there simply may be no 'otherwise'. Thus, the effect should be noted and when alternate program types are developed a comparison can be made. If other program types result in increasing the other system's performance level above that associated with the no preventive maintenance program (which will usually be the case if there is any effect at all), then the cost savings of these effects should reduce the cost attached to these program types. In cases where the other system which is affected has not yet been programmed, it may be necessary to estimate these effects and adjust them accordingly once the other system has been programmed.

4.2.2 Hard-time Preventive Maintenance

Now that the cost of a no preventive maintenance program for the critical part has been estimated, the desirability of performing preventive maintenance on it may be determined by estimating the cost of such a program. There are two basic types of preventive maintenance program; hard-time and on-condition. As explained earlier, the main difference between them is that in a hard-time program the preventive action which realizes the benefits sought is performed on a scheduled basis, while in an on-condition program, only a monitoring action is scheduled, but information obtained in performing this action is used to decide whether and/or when the preventive action should be taken.

The hard-time type of maintenance program will be considered first. This type of program involves the temporary removal of each vehicle from service availability, at a uniform established interval, in order to perform a predefined preventive maintenance task. Upon completion of this task the vehicle's service availability would be restored. Again, a number of decisions and estimations must be made in order to develop a hard-time maintenance program which would minimize the total cost incurred due to the part's maintenance. Specific actions must be defined which could deliver the benefits being sought. After estimating the cost of an individual action, the cost minimizing frequency of the action must be determined as well. The best, or most cost effective program would thus be chosen to represent the hard-time preventive maintenance alternative for the part's maintenance program.

The types of actions which are usually associated with a hard-time preventive maintenance program are replacement or repair of a part. These actions are most often implemented in order to prevent failures. Hard-time

programs may also yield benefits related to performance improvement and life-extension usually through actions involving relatively minor adjustments.

As will be pointed out throughout this section, a system's complete maintenance program may involve more than one benefit type. When this is the case, it is essential that any interactions between the benefits which accrue from the performance of the program's actions are accounted for in the development of the system's overall program. Treating each benefit type as a separate program may be a good starting point. The system's optimal program however, will probably be quite different after adjustments are made for the interacting benefits referred to above. This adjustment process can be made least cumbersome by first developing a program for the more significant benefit types (i.e. failure prevention).

4.2.2.1 Cost of Scheduled Action

The definition of the scheduled action to be taken should include the number of stall hours and workers to be assigned to the action, the labor hours which each worker will contribute and the wage levels of the assigned workers. As in the repair of a failure in the 'no preventive maintenance' program type, the best definition of the action can only be derived if the relationship between stall time and the number of workers and their corresponding labor hours, is fully understood. The resulting action definition should minimize the sum of the labor and availability costs which are inherent in the stall time scheduled for the maintenance activity.

The replacement bus needs, and the cost associated with these needs must also be estimated in order to arrive at an accurate estimate of the full cost of the scheduled maintenance action. The likelihood of the need

for replacement buses due to this activity is largely dependent on the bus' total down time and the workshift during which the action is to occur. A short down time should enable the scheduling of most if not all of the actions in a way which would avoid interference with in-service bus needs, regardless of the shift employed. However, somewhat longer down times may require that the action be scheduled to occur during the first or third shifts in order to avoid such interference. If the potential for conflicting needs is found to exist, then some type of policy limiting the extent of such a conflict should be promulgated.

Finally, the occurrence, and therefore the cost of unscheduled maintenance should be extremely limited. This is true since the task is well defined in advance and carried out uniformly. The minor differences which are bound to occur should be accounted for in estimating the average number of labor hours necessary to complete the task.

4.2.2.2 Frequency for Failure Prevention

For reasons which will become clear later in this section, the type of actions which will be relevant to the initial discussion of failure prevention action frequency are part replacements or repairs which return the condition of the part to 'as good as new'. The precise definition of this state will also be clarified later in this discussion.

The cost of the part's total maintenance program will include the cost of scheduled maintenance actions as well as that of unscheduled actions which result from failure caused by the part. Thus the frequency of scheduled action must be chosen such that failures will be held to a minimum as long as the added cost of the scheduled maintenance causes an equal or greater reduction in the cost which would otherwise arise due to failure. The cost of the individual scheduled actions and that of an individual

failure are therefore of obvious importance in determining the frequency of scheduled action.

The cost of an individual hard-time scheduled maintenance action has been discussed in this section and in a broader sense in section 3.2.9. The cost of a failure can be estimated in the same manner as it was for the no preventive maintenance program type. However, a number of differences may be noted in the magnitude of the cost of a failure for the two program types.

The factor of wait time which is related to a lack of spare parts should be lower for the hard-time preventive maintenance program due to the ability to more closely predict the rate at which the part will be needed.

Often more significant though is the fact that the severity of a failure in any preventive maintenance program may be less than that associated with a no preventive maintenance program. This is particularly true of parts which do not immediately cause service interruptions when they malfunction. The malfunctioning part may be detected during scheduled maintenance, prior to its causing a costly road call. Further, allowing the bus to be operated with a malfunctioning part until a road call occurs, may result in a performance deterioration or even damage to or failure of another part or system. In these cases, the scheduled maintenance program may reduce all cost components of the failure, including parts, labor, availability, and replacement bus costs. The extent to which such a cost reduction is possible, depends upon the way in which a system failure occurs when caused by the part, and also the frequency with which the scheduled maintenance is performed.

In any case, a factor which is of at least as great an importance as the cost of the scheduled and unscheduled actions is the variability about

the mean of the distribution of the part's life. The variability of the part life distribution determines qualitatively, the potential effectiveness of the scheduled hard-time action in preventing failure without greatly reducing the average life of the part.

The development of this distribution is based on the notion that all parts of a given type, for whatever reason, do not fail at the same age (in terms of use or any other measure). They normally fail within a certain age range, the size of which depends upon the particular part type being considered. The distribution defines this range and theoretically, attaches a probability of failure to each point of time within that range. Practically however, it may be necessary to attach these probabilities to a moderate number of equally small age intervals within the range. Such data, which may be obtained through the same type of experimentation recommended in section 4.2.1 in the discussion of the no preventive maintenance program, would yield the information needed to construct a part life distribution.

From this distribution the mean time between failures and the variability about the mean may be determined. It may be more difficult to determine the frequency with which action should be taken on a part with a high failure variability. In such cases, when the frequency of action which would minimize the combined program costs of scheduled and unscheduled actions is finally determined, the program cost will be substantially more than it would have been if the part's life was characterized by low variability. This is due to the fact that in order to maintain a part with a highly variable life, it is necessary to either endure a significant number of failures, or perform the hard-time action at a rather high frequency. Such a choice is not necessary when a part has a low life

variability.

The previous discussion involves all replacement actions and only repairs which return the condition of the part to 'as good as new'. In this context 'as good as new' means that the life distribution which applies to a new part also applies to the repaired part. Thus many repair actions cannot be considered to be in this category, usually because the variability of the life of the part after repair is significantly greater than that of a new part and/or the mean life of the part after repair is significantly shorter. For whatever reason, if the life distribution of the repaired part is significantly different from that of a new part, then the process of choosing a frequency of action must be repeated using the life distribution of the repaired part. Thus, it may not be most cost effective to use a single interval to determine when hard-time repairs should be conducted.

It is possible that a part's failure prevention maintenance program may influence not only its system's failure rate but also its level of performance. The program might also affect the performance level and/or the failure rate of another system. The influence on the failure rate of another system may be a result of prevention of failure through propagation of the programmed system's failure, or by extending the life of a part of the other system.

When performance of the system being programmed is involved, then the cost of operating at the average performance levels which result from alternative frequencies of action should be estimated, and included in the cost of the alternative programs corresponding to these frequencies.

Any cost savings which accrue from a program which improves another system's performance or decreases another system's failure rate, should be

subtracted from the cost of that program. Thus the cost saved by reducing the failure rate of another system, due to failure prevention, may be estimated using the information necessary to develop a failure prevention program for that system. The other cost adjustments discussed above may also be estimated, through use of the same information which would be necessary to develop a maintenance program to improve performance or extend the life of a part. The development of such programs is discussed below.

4.2.2.3 Frequency for Performance Improvement

Sometimes it may be appropriate to develop a maintenance program for a part in order to improve its or another system's performance thereby decreasing the cost associated with operating the system. This type of program may simply consist of carrying out the action which is used for failure prevention at a shorter interval (i.e. tune-up, tire pressure check, gas and oil filters change, etc.). The cost of such a program would include the cost of the scheduled maintenance actions which would not otherwise have been taken and the cost of operating at the average level of performance associated with the program.

Depending on the part's failure prevention program, the performance improvement program may significantly reduce the system's failure rate to a greater extent than that which would have been economical in the name of failure prevention. Thus the chosen frequency of scheduled action should minimize the cost of operating the system, as long as the cost of the scheduled maintenance results in a performance improvement, possibly combined with a failure rate reduction, which effects an equal or greater program cost reduction.

Excluding the cost of the scheduled maintenance action and the life

distribution of the part involved, which were discussed in sections 4.2.2.1 and 4.2.2.2, the only other important factor in determining the optimal frequency of scheduled action, is the degree to which it improves performance. The potential effect of the action may be demonstrated by the part's age-performance relationship. This would show the average or expected level of performance of the system throughout the part's life, assuming that no direct action (such as that which is now being considered) is taken to influence it.

If the scheduled maintenance action involves part replacement or otherwise returns the system's performance to the same level as when the part was new, then with the performance-age relationship and scheduled action cost, the frequency of action which minimizes the program cost can be estimated. However, if performance is restored to some other level, the average performance level would be different for the periods before and after the action, implying that the same frequency of action may no longer be applicable. In such cases, the frequency which has been defined applies only as a one-time action. The process of choosing a frequency of action must be reenacted in order to determine when subsequent performance improvement actions should be taken.

As in the case of failure preventing maintenance programs, any cost reductions which the performance improvement program causes due to performance improvement or life extension of another system or part, should be credited to the cost of the program.

4.2.2.4 Frequency for Life Extension

Finally, a hard-time preventive maintenance program may also be developed in order to extend the life of the part being programmed (i.e. lubrication of steering system parts, universal joints, etc.) and/or some

other part. This type of program may also only involve the more frequent execution of a failure preventing and/or performance improving actions (i.e. oil and filter change, wheel alignment, tune-up).

The cost of scheduled action which would otherwise not have occurred, needs to be known in order to determine the point in a part's life when such action should be taken. The degree to which the part's life is extended and the cost savings of that extension should also be estimated before any such decision can be reached.

It may be difficult to attach a cost savings to such actions, due to the potentially broad range of savings which may result. The most direct and estimable savings result from the less frequent need to repair or replace the part, which saves not only parts costs, but also the labor and availability costs associated with the part's repair or replacement. However, additional indirect savings are possible as well. The life extension may cause a reduction in the frequency of the system's failure, particularly if there is no additional program for the system which has that objective. If there is a failure preventing program already, the life extending act will have a much smaller effect on the failure rate, but may have the effect of reducing the frequency with which the failure preventing action should be taken. Lastly, the life extending action may also serve to improve the performance of some system. When this is the case, the cost of operating at the performance levels corresponding to the programs of various frequencies of action, should be considered as part of the cost, or cost savings of the program.

4.2.3 On-condition Preventive Maintenance

Parts which undergo on-condition preventive maintenance have their condition monitored either by periodically scheduled checks or tests, or

through the regular collection of data. These monitoring actions are carried out as part of the daily servicing or inspection tasks. When the part's condition fails to meet some set standard, then and only then is further maintenance action called for. This further action may involve preventive part replacement or repair, or a more minor life extending or performance improving action.

Thus, there exists a rather basic difference between a hard-time and an on-condition preventive maintenance program. A hard-time program involves subjecting all parts of the same type to a uniform, established schedule of preventive maintenance actions. No accommodations are made for the condition of any individual part. Thus a major advantage of this type of maintenance activity, is that once the optimal interval is implemented, an ongoing collection of information concerning individual parts' performances or conditions is unnecessary, except to ensure that the interval remains optimal. Again, the part type is treated as a whole as a basis for maintenance program decisions.

A hard-time type of program can however, become a rather expensive one to practice. This is particularly true if the characteristics of individual parts varies significantly within the part type. Fortunately, an on-condition type of program is available as an alternative preventive maintenance strategy for most parts. In an on-condition preventive maintenance program, only decisions concerning the execution of the monitoring activities (checking, testing, data collection), are usually based on the characteristics of the part type as a whole. On the other hand, decisions concerning any preventive maintenance action involving a greater degree of resource allocation and effort will, to the greatest extent possible, be based on the observed condition and performance of the individual

parts.

There is one part characteristic which determines the feasibility of, and the flexibility involved in applying an on-condition type of program to a part type. This characteristic will be referred to as monitorability. The question which must be answered is; 'To what extent, if any, can the condition of the part be monitored?'. Again, monitoring involves relatively minor actions like visually inspecting a part or physically testing it against some standard (i.e. pressure, current tests; fuel, oil consumption standards). These types of actions should require a relatively low level of effort and should not involve system disassembly. There are three basic degrees of part monitorability, which may be characterized by;

- 1) the ability to distinguish between a properly functioning part and one which has failed,
- 2) the ability to recognize a part which is in the process of failing as well as one which is functioning properly or has failed, and
- 3) the ability to estimate remaining part life through a monitoring action, as well as whether the part is functioning, failing or failed.

The degree of monitorability of a part depends primarily on the way in which the part fails. For some parts, like brake linings and tires, the process of deterioration begins immediately upon the part's initial operation, or a relatively long time before failure becomes imminent. The deterioration of these parts is usually measurable and they would therefore be at the third level of monitorability. Many other parts, such as starters, batteries, oils, most exhaust system parts, and any joints showing wear prior to failure, will only begin noticeable deterioration in the final stages of their lifecycles, and as a result may be considered

to be at the second level of monitorability. Finally, parts, including light bulbs, and brake, oil, fuel and air lines, which fail without exhibiting any noticeable signs of deterioration beforehand, correspond to the first level of monitorability.

As mentioned earlier, a part's monitorability is an important factor in determining the feasibility of developing an on-condition program for it. There is only one situation in which the development of such a program for failure prevention is precluded. This is when a part is monitorable only to the first degree (1), and the part's failure can cause a nearly immediate road call, safety failure or some similar event which would result in a significant cost to the transit agency. If such effects are unlikely then even parts at the first level of monitorability can be treated by on-condition maintenance.

Any part may be subject to an on-condition program to improve performance or extend part life, as long as a monitorable decision variable exists, whose value determines whether further preventive action is warranted.

The important influence which a part's monitorability has on the flexibility with which an on-condition program may be applied, will be pointed out repeatedly in the following sections. In these sections, the process of developing this type of program and estimating its cost is discussed. First estimating the cost of each type of preventive action within the program is addressed. Then choosing the frequency with which the monitoring action will be performed is discussed. Since this frequency will influence the frequency at which the unscheduled preventive and non-preventive actions will need to be performed, the choice of the monitoring frequency is used as the basis for defining the minimum cost

on-condition program.

4.2.3.1 Cost of Preventive Maintenance Actions

In order to develop an on-condition preventive maintenance program which minimizes the total cost related to the maintenance of a part, both the minor scheduled maintenance or monitoring task and the unscheduled maintenance task which may be performed subsequent to it, must be defined. The number of workers, labor hours and stall hours which each task requires should be specified as should the skill⁵¹ and/or wage levels of those workers to be assigned to them. Availability cost and replacement bus needs should be estimated although it should be possible to keep them to a very low if not insignificant level, particularly for the monitoring actions. The longer down times usually associated with the unscheduled actions increases the potential significance of these costs; however, it is usually possible to minimize or eliminate them through proper maintenance scheduling. This would involve scheduling the monitoring actions at a time when the occurrence of conflicting bus needs would be minimized even if unscheduled maintenance action becomes necessary.

4.2.3.2 Monitoring Frequency for Failure Prevention

For programs with the objective of failure prevention, there are two important factors, aside from the cost of the individual actions discussed above, which influence the monitoring frequency decisions. These are the

⁵¹For failure preventing on-condition programs, the monitoring action, which would require relatively little time, is used to prevent failures which, if they occurred, would require significantly more labor time and be much more costly overall. It seems logical then, that the more experienced and better skilled mechanics should be assigned to monitoring activities to better ensure their being executed with minimal error.

part's life distribution and the type of information which can be gleaned from the monitoring action which is taken. This last factor, concerning the information made available through monitoring, is basically dependent upon the part's level of monitorability. There is a notable difference in the way which this factor influences the monitoring frequency decision for parts of the first or second level of monitorability, and for those of the third and highest level. I will first discuss frequency selection for parts of the first and second levels.

While all parts grouped in the second level of monitorability are eligible to be considered for an on-condition failure prevention program, only those first level parts whose failure does not immediately cause a road call, or a related costly event, may be considered for this type of maintenance program. Therefore, for parts at both these levels, the monitoring actions must occur within a defined period of time to prevent either a part's failure (second level) or its failure's effects (i.e. road call) (first level). For first level parts, this is the period of time following part failure but prior to its having any serious negative effects, and for second level parts it is the period prior to part failure during which an imminent failure can be detected through execution of the monitoring action.

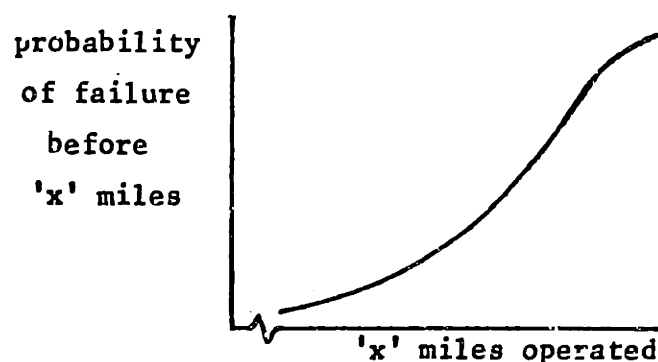
Thus, with the approximate length of this period along with an estimated part life distribution, it is possible to estimate the number of part failures/'failure's delayed effects' and the number of monitoring failures which would characterize any monitoring interval selected. Using the cost estimates for the monitoring action, the post-monitoring failure action and a part failure or its delayed effects, it would then be possible to choose the monitoring frequency which would minimize the total

expected cost of the part's maintenance program. One important difference should be noted, related to the costs associated with the programs of first and second level parts. For first level parts, there may be a cost involved in operating a vehicle with a failed part. In cases where such a cost exists, it should be estimated and added to the cost of the post-monitoring failure action.

The interval which is set through the above procedure will often be applicable only to the first monitoring action following the part's initiation into service. The use of this interval to perform subsequent monitoring actions would imply that those parts which do not fail the initial 'test', would in a sense return to the point on the part life distribution which coincides with the introduction of a new part into service. This is usually not the case unless there is little or no correlation between the part's age and its reliability or failure rate.

Thus, in order to determine when the best time in a part's life would be to perform each subsequent monitoring task, the original part life distribution should be used, but only from the point of the previous action. For the many parts which have a cumulative life distribution of a type shown in Figure 3, this would mean that if the preventive maintenance

Figure 3: A Cumulative Part Life Distribution



program is to include only on-condition actions then it would be desirable, as the part's age increases, to perform the monitoring task at increasingly shorter intervals, until the interval is as short as the part's failing period. This may result in a very costly program, with a disproportionate share of that cost being incurred to maintain the part at the later stages of its life.

For this reason it may become a great deal more cost-effective to perform a hard time repair or replacement action at some time in the later stages of the part's life instead of continuing with the least cost on-condition program of increasingly frequent on-condition actions.

This point is reached when the cost of testing the parts is no longer justified by the benefits accrued from those parts which pass the test. These benefits are a result of the decreased frequency of the need for part replacement or repair and more generally, the reduction in the number of complete maintenance cycles which are carried out on the part. Therefore, the potential benefit of performing the monitoring test on a single part may be characterized by:

$$B_t = P(P) \left(\frac{EOL - OL}{OL} \right) C_{mol}$$

where 'EOL' is the extended operating life of the part including its life after the monitoring test is passed, 'OL' is the operating life of the part up until the test, 'C_{mol}' is the total cost of the part's maintenance program up until the test and P(P) is the probability that a part will pass the test.

Thus, when considering a monitoring action at a point 'OL' in the operating life of the part, if $B_t < C_t$, where C_t is the cost of a monitoring test, then the part should be repaired/replaced on a hard-time basis and

not tested on an on-condition basis.

All parts at the third level of monitorability are eligible for failure preventing on-condition maintenance. These parts' programs may be developed in the same way as those for first and second level parts. However, they may also be developed by taking advantage of the increased flexibility which is offered by the higher quality of information which can be harvested from performing monitoring action on the part. That is, the ability to predict the part's remaining life through a monitoring action could be used to decrease what would otherwise be the cost of the part's maintenance program. The lower cost would be accomplished by reducing the number of monitoring actions which are necessary to maintain a low, if not decreased level of system failure.

A monitoring action would have the dual purpose of determining whether or not unscheduled maintenance should be performed, as well as setting the point at which the next action should be taken on the part. This subsequent action may be hard-time repair or replacement, or it may be a repeat of the monitoring action.

In order to successfully implement this type of program, more information is needed about the part than its overall life distribution. In particular, one would need to know the part's life distributions which are associated with the potential range of values which the measurable indicator of remaining life can have. In other words, if the indicator is at a certain point, what is the remaining life distribution of the part. This information is vital in determining when the next action should occur and whether that action should be a hard-time or on-condition action.

In implementing this type of program, it is unnecessary for the responsibility of the mechanic to exceed that of measuring the 'remaining

life indicator'. The decisions concerning the time and type of the next maintenance action on the part which correspond to the range of the indicator's potential values, should be made beforehand and implemented as general policy.

This type of program may be the most cost effective on-condition program for any part of third level monitorability. However, relative to other potential preventive maintenance programs, it may be most effective with a third level part which has a high variability of life. This is a result of the program being based more strongly on characteristics of the individual parts instead of the part type as a whole.

4.2.3.3 Monitoring Frequency for Performance Improvement

The objective of improving a system's performance level may also be fulfilled through an on-condition preventive maintenance program. This type of program can be applied to any part which exhibits a correlation between system performance and part age, provided that the system's performance level can be determined at any time of the part's life through monitoring.

The methods used in applying an on-condition performance improvement program are rather similar to those outlined for an on-condition program with a failure prevention objective. Thus the approach used in developing this type of program is quite different from that taken for hard-time programs with the same objective.

Basically, a monitoring action is performed which either directly measures performance of the part or the part's condition (which affects performance). A decision is made based on the results of this action, on whether or not to perform an unscheduled preventive maintenance task on the part, in order to upgrade its system's performance.

The decisions in this program then, do not revolve directly around the specific average performance level desired, but on the performance level (or part condition level) at, or below which a part should be subjected to the performance improvement action. Therefore, the program's average performance level and thus the cost of operating the system at the program's average performance level, cannot be determined directly from the point at which action is taken, as it is in hard-time programs. This is a result of the fact that on-condition programs are not based on a single age-performance relationship, as hard-time programs are, but on the age-performance relationship of each individual part.

One type of performance improving on-condition program is similar to the failure preventing on-condition program for parts of first and second level monitorability. A set schedule for performing monitoring actions would be established and implemented uniformly on the entire part type. The sole purpose of these actions would be to determine whether a performance improving action should occur. This type of program does take into account the variation in the performance-age relationship between individual parts within a part type. This is evident from the fact that parts which maintain adequate performance levels for longer periods of time are not subjected to the performance improving action at the same rate as those which are characterized by a more rapidly deteriorating performance level.

A second type of on-condition program which can be applied to improve performance is similar to that suggested for failure-preventing on-condition programs for parts at the third level of monitorability. In these programs, the monitoring action would again have a dual purpose. It would be used to determine whether or not a performance improving action is

warranted and if not, to establish when the part should be looked at again by the maintenance department and what type of action (hard-time or monitoring) should be taken at that time. The additional information which would be required to implement this type of program consists of the expected performance-age function corresponding to the range of measured performance or part condition levels. That is, if a part is observed to be performing at a given level or to be in a certain condition, what is its expected performance as the part ages, and what variability may be observed in the performance level as the part ages. This information will aid in deciding when and what type of subsequent action should be taken.

4.2.3.4 Monitoring Frequency for Life Extension

Finally, it is also possible to develop an on-condition program in order to extend the life of a part. There must exist, however, some measurable variable by which it can be determined whether or not a life extension action is warranted. This variable may be binary, such that the life extension action is executed if it takes one value and is not if it takes the other, or it may involve a range of values which may be continuous. In any case, a value or set of values must be defined which if found to exist, would result in the life extension action being taken.

If the variable is binary, then the information which is needed to decide the cost minimizing time to perform the monitoring action, is the distribution of the age at which the part takes on the value which leads to carrying out the action. This is analogous to the use of the part-life distribution in the on-condition failure prevention type of program for parts at the first and second levels of monitorability.

On the other hand, if the variable may take on a number of ordinal values, and an 'action level' is set such that if the variable is observed

to be at one side of that level the action is taken and otherwise it is not, then the flexibility involved in program development may increase. This added flexibility is analogous to that for an on-condition failure prevention program for parts of third degree monitorability. If for each value preceding the 'action level', the distribution of the expected life before the action level is reached is known, then monitoring action can be used to determine not only whether the life extending action should be taken at that time, but also when subsequent action should be taken and whether it should then be a hard-time or monitoring action.

Thus, a program can be developed which maximizes the favorable difference between the benefits accrued due to life extension and the cost of the actions necessary to obtain them.

4.3 Forming a Single Vehicle Maintenance Program

As explained in section 4.1, the critical parts of the primary systems are programmed first. Each of these primary systems is initially programmed independently. Each of the three maintenance program forms which is applicable to a system's critical parts is considered. A minimum cost program which achieves the benefits sought is developed for each form, and the one with the least cost is chosen to be implemented.

Once programs have been developed and chosen for each primary system, the programs are coordinated in order to define the vehicle maintenance program's minimum interval. This is accomplished by making the least cost adjustments to the programs. The scheduled preventive maintenance tasks which are executed most frequently, will be performed at this minimum interval. Further, all other scheduled preventive maintenance actions, for both primary and secondary systems, will be executed at multiples of the minimum interval.

Having defined the structure of the vehicle maintenance program by adopting a minimum interval, the secondary systems may now be programmed. Each system is programmed individually as the primary systems were, except that their scheduled preventive actions are already limited to occur only at multiples of the minimum interval.

In this way, all of the system's programs which are developed are coordinated such that a unified vehicle maintenance program emerges. This program, just as the systems' programs do, optimizes the balance between preventive and non-preventive maintenance, such that the total cost to the maintenance department, and the transit agency, is minimized.

4.4 Scheduling the Maintenance Task

Following the consolidation into a single program, the responsibility for each of the maintenance tasks, preventive and non-preventive, must be assigned to a specific workshift. The main objective of this process is to minimize the availability cost of the maintenance program.

Table 5 below, uses a task's expected down time (in number of shifts) as a basis for assigning it to a specific shift. Besides assuming that the peak vehicle needs for service occur at the very beginning and end of the second shift, this table is developed assuming that the task being performed can be picked up by one shift where the previous shift left. Since this may often not be most desirable or feasible, a discussion of the implications of not being able to transfer a task between shifts is included in this section.

Scheduled tasks which have a short down time and can therefore be completed between the peaks without interfering with the supply objective, should be assigned to occur at that time during the second shift. However, if the task requires more time than that but no more than one shift, it

Table 5
Scheduling Tasks by Down Time

	First Shift	Second Shift	Third Shift
	(midnight - 8 a.m.)	(8 a.m. - 4 p.m.)	(4 p.m. - midnight)
Task's	medium ($\frac{1}{2}$ -1 shift)	short (between peaks or $\frac{1}{2}$ shift)	long (1-2 shifts)
Expected	long (1-2 shifts)	failure response and repair - a.m. peak	longest (2 shifts)
Down	longest (>2 shifts)	longest (>2 shifts)	failure response and repair - p.m. peak
Time	some daily servicing		most daily servicing

should be scheduled for the first shift. Both of these types of tasks may be scheduled for other shifts as well without interfering with supply. However, since their being scheduled during the second and first shifts does not interfere with it, as tasks with longer down times would, they should be assigned as specified. In addition, since these tasks do not require more than one shift to complete, the subject of transferral between shifts is not relevant.

If the expected down time associated with a task is between one and two shifts, then it should be scheduled to begin during the third shift, so that it may be completed during the first shift, prior to the onset of peak vehicle demands. Scheduled tasks with down times of more than two shifts should begin during the third shift, so that the vehicle may be returned to service availability having missed as few peak periods as possible.

In cases where down time is expected to be longer than one shift, task transferability between shifts becomes important. Where a non-transferable task is one continuous scheduled action, it should be scheduled for either the first or third shifts. However, if it is an on-condition type of program action where the tasks' expected down time includes not only performance of a scheduled act but also of unscheduled actions found necessary in performing it, the scheduled action should occur during the third shift. The subsequent unscheduled action should be taken on the next full shift, the first, with one important exception. The unscheduled action should also occur during the third shift, if the expected down time can be reduced to the next lowest whole number of shifts. For example, let's say a scheduled action requires $\frac{1}{2}$ shift and the unscheduled action $1 \frac{3}{4}$ shifts. Performing the unscheduled action

subsequent to the scheduled action, which was initiated at the beginning of the shift, would only reduce remaining down time to $1\frac{1}{2}$ shifts and should therefore be begun during the next full shift, the first, and not in the third shift. However, if the total unscheduled action required only $1\frac{1}{2}$ shifts then down time could be reduced below 1 shift to $\frac{3}{4}$ shift and should therefore be initiated following the scheduled action during the third shift.

Although failure response may be required whenever vehicles are operated, the major requirements will occur during the peak periods. The responsibility for initiating repair of vehicles brought to the garage for repair, is therefore mainly that of the second and third shift. This is the case where tasks may be transferred between shifts, because if repair is not completed during the shift in which the failure occurs, then the task may be transferred to other shifts so that it is completed as quickly as possible.

When such a transfer is not feasible the job of failure repair should be assigned to the next full shift with two important exceptions. If the repair can be completed within the shift in which it occurs then this should be done. The second exception is essentially the same as the one for unscheduled action which follows scheduled action. The repair should also begin during the shift in which it occurs if the expected down time can be reduced to the next lowest whole number of shifts (see previous example).

Finally, most daily servicing activities can and should occur during the third shift and/or early in the first shift, so that when action must be taken to correct defects, it may be completed by the onset of the morning's peak needs.

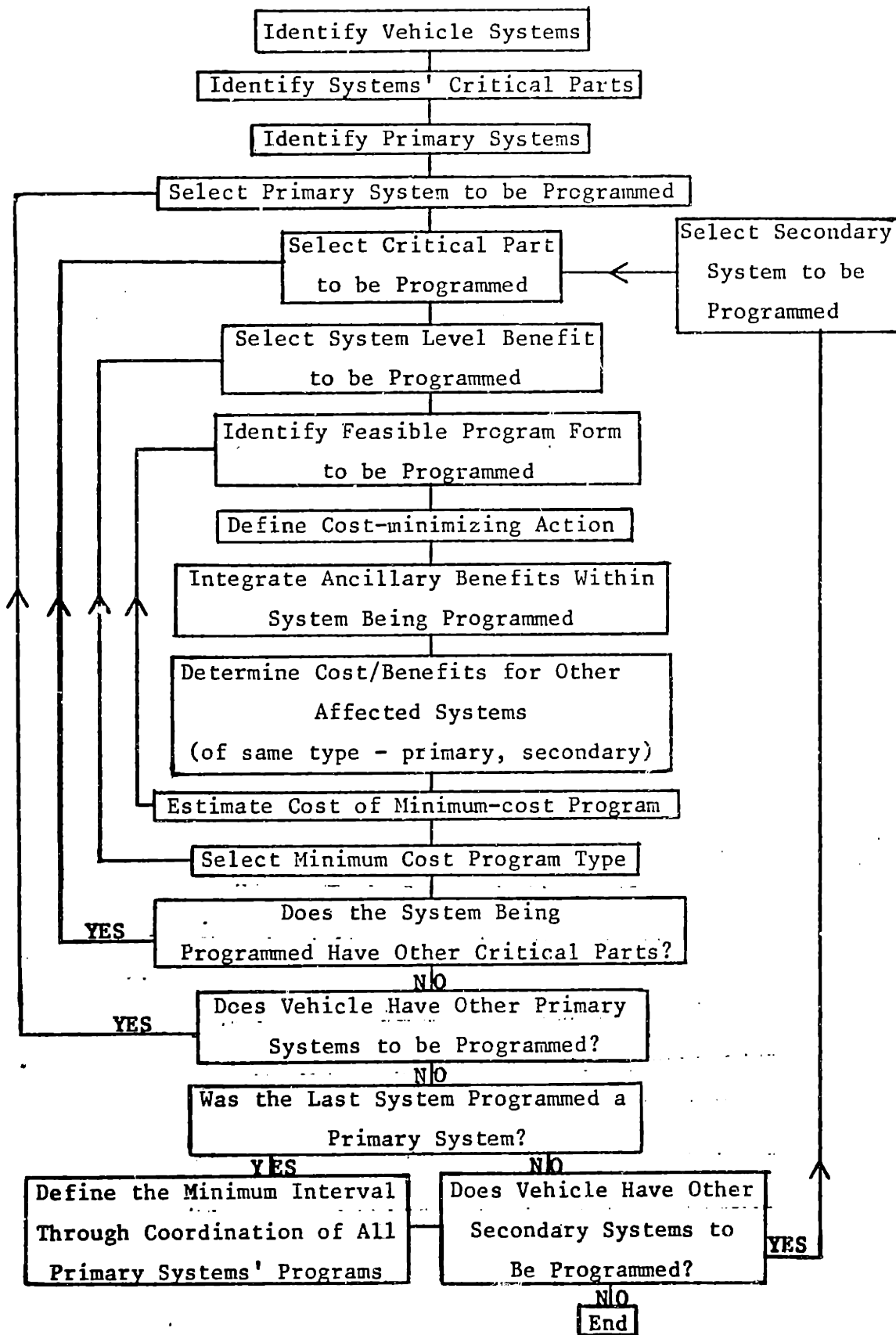
One factor which may, in some areas, prevent the use of the usually less desirable (to the worker) first and third shifts, is the lack of an adequately skilled labor supply to fill jobs during those two shifts. In other cases, where the physical capacity is a given, the maintenance workload may be small enough so that it is not necessary to have three full workshifts. When this type of situation exists the availability cost savings which accrue from the use of three shifts rather than two and/or one shift, should be estimated. If it is more than the non-mechanic related costs of running the extra workshift(s) then three shifts should be employed - otherwise they should not.

4.5 Implementing the Framework

In the following section, the steps to be taken in implementation of the framework defined in this chapter are reviewed. The general structure of the framework is illustrated in Figure 4, while a more detailed description is presented in the section's text.

A number of characteristics of a bus and its parts, which are important in the development of a maintenance program have been defined. The listing of the bus' systems and their corresponding subsystems and parts, is a useful first step for data collection and in defining the program's structure. The identification of each system's critical parts, and the relative frequency with which they will need to be maintained to provide the benefits sought, are also important in establishing the structure of the vehicle maintenance program. These critical parts may be identified through examination of the way in which the system functions in bus operation, and by finding the parts which cause system failures or influence their performance, instead of those which are affected by system failure or performance. Once again, since the great majority of the systems,

Figure 4: The Basic Framework



subsystems and parts of different buses in the transit industry's bus fleet are similar, these tasks could most efficiently be performed once, by a central authority such as U.M.T.A..

The systems which require the most frequent maintenance are programmed first, and are coordinated in order to define a minimum interval for scheduled actions. The remaining systems are then programmed, using this minimum interval as the basis for their preventive maintenance programs.

When programming a system, the relative benefit which may be gained by implementing a preventive maintenance program for each of its critical parts should be examined. The critical part with the greatest potential benefit should be programmed first.

Several questions must be answered in deciding what forms a critical part's program may take. First, if the part directly affects the vehicle's operational safety then some type of preventive maintenance is required. Second, a part of first degree monitorability, whose failure will result in significant cost cannot have a failure preventing program which is on-condition. Third, a performance improving or life extending on-condition program can only be developed for parts which have a measurable decision variable - that is, some basis for deciding from monitoring, whether or not to perform further preventive maintenance. A more flexible type of on-condition program can be developed if the part has a decision variable which is monitorable to the third degree - that is, if it takes on a number of ordinal values, and for each value predictions can be made concerning the time remaining before the value reaches the 'action level', or the level at which further preventive action is to be taken.

In developing a program of each applicable form for a part, there are a number of interactions which should be taken into account. If

performing preventive maintenance on a part could result in more than one type of benefit, then the type likely to yield the greatest benefit should be used as the basis for development of the part's program. In some cases, the action taken for the different benefit types is the same but the frequency at which it should be performed is affected. In such cases, programs for the different benefits should be developed simultaneously. In other situations, the program's actions may differ despite the fact that performance of an action for one benefit type has the ancillary effect of providing benefits of another type. Here, the ancillary effect should be taken into account in development of the program, but another program will still need to be developed for the part's other benefit type.

Further, when a maintenance action taken on a critical part, results in benefits related to another critical part of the system, then these effects should be accounted for in an analogous way. If the parts' programs consist of the same action, then the parts should be programmed simultaneously. If the parts' program actions differ but action on the part being programmed does affect the other part, then this effect should be noted and accounted for, but the other critical part will still need to be programmed for the benefit type affected. This can be extended to critical parts of other systems of the same class (primary, secondary), although simultaneously programming critical parts of different systems may be a more difficult task.

After programming one of the part's benefit types is completed and the program form chosen, a program should be developed for the most significant of the part's remaining potential benefit types. The same procedure which was used for the first type should be applied in programming for subsequent benefit types. Each succeeding benefit type should be

programmed until all potential benefits of performing preventive maintenance on the critical part have been included in the part's program.

If the system being programmed has any additional critical parts, they should be programmed in order of greatest remaining potential benefit. The programming of these parts proceeds in the same fashion as described for the first part.

When all of a system's critical parts have been programmed, then another system is programmed. Programming those systems which have been affected by previously programmed systems (provided they are of the same type - primary, secondary), would probably enable the interactions between the systems' maintenance programs to be more easily and accurately estimated.

The information which is needed to arrive at the 'best' decisions concerning any critical parts' program, depends upon which of the seven benefit types are sought, and the program form (no preventive, hard-time, on-condition) being considered.

The development of any type of failure prevention program should apply information concerning the critical part's life distribution. The mean time between failure is the only life-distribution information needed to estimate the cost of a no preventive maintenance program. The development of a cost-minimizing hard-time preventive maintenance program and estimation of its cost, requires the use of the part's entire life distribution. Further, if the hard-time action involves repair, not replacement, then the life distribution of the repaired part should also be known. These requirements hold true for on-condition programs for parts of first and second degree monitorability, except the characteristics of the 'detection period' would also need to be known. For a part of third

degree monitorability, the life distribution corresponding to various values of the monitorable decision variable need to be known.

In developing a life-extending program, the only added information needed is the effect of the preventive action on part life, when action is taken at various times in the part's life.

A system performance - part age relationship is usually needed to develop a performance improving program. However, if the part's effect on performance cannot be accurately measured by the part's age, then the relationship between some other measure of the part's condition and system performance is needed. The extent to which this relationship needs to be known is also dependent on program type, in ways analogous to a failure prevention program.

Numerous cost estimates need to be made in order to develop the best maintenance program for any system. These estimates are often influenced by the degree to which the maintenance objectives would be met. It is assumed that the safety objective is firm - safety will be maximized. It is also assumed that the comfort objective is established through cooperation between the maintenance and marketing or planning departments, in considering the costs and benefits associated with comfort providing maintenance.

However, only the part of the supply objective which includes service demands, is known prior to program development; the number of spare vehicles which need to be supplied is not known because the fleet reliability objective is not specified at the outset of the program development process. Instead, the costs and benefits of providing a reliable fleet are used to establish the program's inherent level of reliability. If this level is found to be unacceptable then the cost estimates used to

internalize this objective may need to be adjusted.

The availability cost estimate is most likely to need adjustment, since it relates strongly to both the supply and reliability objectives. It takes into account the service effects of failing to meet the supply objective, which is an unavoidable consequence of a fleet reliability failure, or road call. However, the problems of estimating an availability cost are also encountered, and in an even more serious way when considering any maintenance action which makes a vehicle unavailable for service for any period of time. This is because the probability of a supply failure must also be estimated, a task which may pose an even larger problem than estimating the cost of such a failure.

In any case, some estimate of availability cost must be included in program development, if the maintenance program is to meet the maintenance objectives at minimum cost to the agency.

Thus, whereas a complete method for quantifying the transit vehicle maintenance program development process has not been defined, a sound quantitative structure has been presented which can be used to take into account the factors which should be considered in order to develop more productive programs.

CHAPTER 5

OTHER APPLICATIONS OF THE FRAMEWORK AND ITS CONCEPTS

In this chapter, a few important examples of how the framework and its concepts can be an important aid in dealing with the dynamic aspects of maintenance planning are presented. There are undoubtedly many other types of situations encountered by a maintenance manager, to which the concepts developed here could also be usefully applied.

In section 5.1, methods of dealing with demand for a stall type, or for stalls as a whole, which exceeds capacity are discussed. The cost estimates which should be made to determine the best strategy, can be developed through application of the framework's concepts.

The relationship between the fleet size and the cost of meeting the supply objective is then discussed. Through application of the framework, the maintenance manager should be able to discover whether fleet expansion to reduce the operable ratio associated with the peak supply objective, would be cost-effective for the transit agency.

Decisions concerning the choice of manufacturer of a part is then addressed. This may be an important issue under normal conditions and also under conditions where physical capacity and/or the peak supply objective act as constraints to an 'optimal' maintenance program.

Finally, the utility of the framework in the budget-making process is described. It may be used to lobby against budget cuts, respond to them or to react to changes in interdepartmental demands.

These few examples are cited to point out that the framework presented in this thesis, remains useful even after a program has been developed through its application. It may be used in special situations, as well as in making the more day to day maintenance decisions.

5.1 Dealing with a Physical Facility Constraint

5.1.1 Scheduling the Maintenance Task and Physical Facility Capacity

In scheduling the maintenance tasks to be carried out during particular workshifts, the physical capacity of the garage for any given shift as well as the entire workday must be considered. More specifically, different maintenance tasks either require or are better suited to the use of a particular stall type. It would therefore be most desirable to schedule the tasks so that the capacity of any particular stall type does not interfere, during any shift, with the optimal matching of stall types and maintenance tasks.

There are three basic types of stalls; hoists, pits and flat spaces with neither hoist nor pit. Hoists and pits allow access to the underside of a bus where a large percentage of the maintenance work is carried out. There are some fundamental differences between a hoist and a pit, which sometimes results in the ability to carry out a maintenance task more efficiently through the use of one type of stall. For example, it is easier and usually much faster to position and ready a bus to be worked on in a pit, rather than on a hoist. This would tend to encourage the use of pits particularly for high volume tasks, or tasks which must be done often and completed quickly. Another potentially important advantage of a pit is that it enables work to be done simultaneously at more than one height level (i.e. side and under, front top and rear bottom). On the other hand, hoists are much more flexible than pits. It is possible to raise a bus to whatever height is necessary or most comfortable for the mechanic, resulting in the completion of some tasks more quickly and in a more efficient manner.

On a more general level, although keeping a hoist operational does

require more maintenance than would a pit, it lends to supervision of the garage while pits do not, and they greatly reduce the complexity of cleaning the garage. Also, hoists generally offer a higher quality working environment, particularly for the mechanic, a fact which is bound to affect the attitude and thus the productivity of the mechanics.

In any case, for each of the final program's maintenance tasks (including non-preventive tasks), each stall type which can be used should be considered and the full 'cost' of using each of them understood, so that the optimal assignment can be made. Following task assignments to stall types, the number of hours per defined time period (i.e. week, day) for which each type of stall needs to be used during each of the work-shifts, should be determined. This can be done by using the estimates of down times for the various maintenance tasks, the mileage interval at which they occur, the expected average mileage for a single bus and the number of buses in the fleet (which are used in estimating the average mileage figure). It can now be determined whether the capacity of any single stall type during any single shift is exceeded by the demand for its use.

Care should be taken when stall type capacity is defined since a stall can not be utilized for the full eight hours in a shift. There are work breaks, time passes between the completion of work on one bus and the initiation of work on the next bus and perhaps most importantly, there are likely to be significant day to day differences in demand for stall types. Thus, when defining stall type capacity for a time period, a 'slack factor' should be built in to account for these effects.

5.1.2 Alternative Strategies to Deal with the Constraint

The cost-minimizing program may cause demand for a stall type during

a particular shift to exceed its capacity. This also may occur when so much past maintenance has been deferred that in order to 'catch up', the amount of maintenance work which must be done is much greater than normal. The first step which should be taken in these cases is to develop what would be the minimum cost program under normal conditions. This would help to determine which of the strategies discussed below are best suited for the situation.

Several strategies can be used to alleviate the capacity constraint. I will first discuss four non-capital intensive strategies, followed by a discussion of the capital intensive strategy.

5.1.2.1 Non-capital Intensive Strategies

Each maintenance task should be examined in order to estimate how important it is that the task be accomplished through use of the stall type assigned. The tasks which may be carried out on another stall type at the least increase in cost should be identified. The cost increase would consist of availability and labor components which arise as a result of the additional stall time, and therefore added down time required to complete the task. These tasks may be reassigned to another stall type within the same shift if other stall types have the available excess capacity.

A different strategy may be employed whether or not other stall types have excess capacity enabling the within shift stall type switch discussed above. This would not involve a change in the stall type but in the shift during which the task is to be carried out. The cost increase associated with this type of change would be that of availability cost. Presumably, the tasks had been scheduled so as to minimize availability cost (see section 4.4), and as a result any change can only

increase availability cost. In order to make this type of change however, one of the other shifts must have excess capacity for the stall type in demand.

In some cases, combining the above two strategies may be necessary. This would mean assigning the task to a different shift and a different stall type as well. Adopting this approach would result in the incurrence of both costs associated with the two previous strategies. Availability cost would increase due to the increased value of the down time caused by the shift change. In addition, both labor and availability costs would increase due to the additional stall time and therefore down time needed to carry out the task using the different stall type. The increase in availability cost then would be greater than the sum of the parts (the costs of the two strategies individually), since both the down time and its value are increased. This strategy should therefore only be considered when there is insufficient excess capacity for both other stall types within the scheduled shift, and during other shifts for the scheduled stall type.

The last, most drastic non-capital intensive strategy would be the elimination of some maintenance demands. This strategy should be embraced only after it has been demonstrated that reasonable application of the strategies discussed above cannot eliminate the capacity constraint. These adjustments may be made by revising the availability cost estimates upward for the entire program so that the total demand is decreased.

Revising the availability cost associated with the individual problem shift is also a possibility, however extreme care would be necessary to ensure that the balance which had been achieved in any individual part's program is not broken. For example, the interval at which a part's

performance improvement action is executed may have an effect on the interval at which that or another part's failure preventing action should occur. Therefore, adjusting the performance improvement interval for the purpose of reducing maintenance demand, without accounting for the full effect on the failure preventing task would not be optimal. This is only one example of the problems involved in making these types of changes. The care which is required in making them is evident.

On the other hand, the effort which is required to revise the entire vehicle's maintenance program makes it a rather unattractive alternative unless the gap between demand for and capacity of the available physical facilities is rather significant. Thus, looking for potential decreases in maintenance demand may in some cases be the correct strategy.

It may be tempting to cut back on safety measures on the premise that the need for them has been estimated very conservatively. However, this is the worst type of program to experiment with because failure can be disastrous for the transit agency and its users.

Decreasing the level of effort put into actions which are taken to prevent failures which may result in major repairs could easily backfire and result in the bus demanding more instead of less maintenance time than before. Again, it may be tempting to cut back here since the effects are often not felt in the very near term. However, they are likely to cause an even greater problem in the longer term than the one which is being faced immediately by the maintenance department.

Life extension activities often result in an overall decrease in the time a bus is out of service during its life as well as decreasing the parts cost involved in the part's maintenance. It is possible that a tradeoff between decreasing parts cost and smaller increases in availabil-

ity cost have been made in some parts' programs. These may be prime candidates for decreasing the demand for maintenance time, which would of course come with an increase in parts cost and cost to the agency as a whole.

Other candidates for reducing the demand on maintenance facilities are, actions taken to prevent comfort failures and 'simple' failures, and performance improving measures. The types of performance improvement measures which should be the primary candidates for elimination, are those which affect only the direct cost of operating the bus. These actions may be carried out less frequently or not carried out at all, depending of course on the cost effects of such action. It may be difficult to find performance improving actions which do not affect the failure rate of some part on the bus, but if they exist they should be seriously considered in reducing demand for maintenance.

Other reductions may be possible for actions which prevent a 'simple' failure, or ones which do not affect safety and do not result in a major repair or road call. Such a change would reduce the total stall time of the bus. There would be increased cost involved since wait time may increase, due to the change from a scheduled to an unscheduled visit to the garage. Further, the need for a replacement bus would probably increase and thus the maintenance demands created by its use must not be ignored when considering this type of adjustment.

Finally, reducing the frequency of comfort providing actions is usually a popular way of reducing maintenance demand. As a result, the level of comfort may be allowed to deteriorate year after year, leading to an erosion in ridership levels as well as attitudes toward transit. In the short run, this type of adjustment may be the most desirable and feasible

one to make, but such adjustments should not become habitual or the agency is likely to pay for it in the longer term. The comfort level which is provided should not be thought of as a bonus which the agency is providing out of the goodness of its heart. It is an inherent part of the public service which the agency has been given a mandate to fulfill.

5.1.2.2 Capital Intensive Strategy

It is clear then, that reducing the maintenance demand inherent in a minimum cost program, in any more than a minor way, may be difficult in the medium to long run, and would in any case, come at a potentially rather significant cost. Therefore, using it as a short-term strategy during the 'lead-time period' required to increase the physical capacity of the program, may be a rather attractive alternative.

Where demand for one stall type is greater than capacity, and that for another is consistently below capacity for all shifts, the conversion of a stall of one type into another type may be a suitable response. If this is not a desirable or feasible solution then the addition of a stall should be considered. The cost of such a capacity expansion will vary widely depending on the individual situation. There may be enough space in the garage to simply add a stall, or the layout of the garage may be adjusted so that the added space can be provided. On the other hand, it may require an expansion of the building or even a new garage location.

There are obviously differences in the order of magnitude of the cost of expansion in different situations. The cost which applies to the specific situation should be identified. This cost should then be compared with the least cost program adjustment strategy. In making this comparison it is absolutely necessary to take into account the long-term cost effects of the two strategies. An understanding of the demands which will be made

on maintenance in the periods beyond that presently being programmed is indispensable in the decision on how best to deal with present problems.

Therefore, if the capacity problem is temporary due to past maintenance deferral, and the minimum cost program would not be constrained by capacity, then facility expansion may not be the optimal solution. On the other hand, where maintenance needs are expected to increase in future years due to planned service expansion or for any other reason, the sound long-term strategy would more often be capital intensive improvement than if the plan called for service contraction or stagnation. Further, when facility expansion is planned, it ought to be tailored not to present maintenance demands, but to predicted future demands. Otherwise, when construction of the new facilities is finally completed, one may find that physical capacity is still a constraint because maintenance demand increases have kept pace with capacity increases.

Thus through application of the framework and use of its concepts, it is possible to develop an estimate of the cost of dealing with the capacity constraint in a non-capital intensive manner. If the maintenance manager feels that this cost is great enough to warrant a capital-intensive response, he may then approach his superiors (or whoever must ratify the decision) with a concrete estimate of the savings which would result from such an expansion.

5.2 Fleet Size and Achievement of the Supply Objective

Another factor which may act as a constraint on the maintenance program, whether or not physical capacity does, is the fleet size and in particular, the relationship between fleet size and peak bus needs. The proportion of the fleet which is in service during periods of peak bus needs, may be referred to as the peak to fleet ratio. Although this ratio

is important in maintenance scheduling, the 'operable ratio' or the proportion of the fleet which, during peak periods is either in service or needed in order to meet replacement bus needs during the period, is often considered to be most important. This is because the operable ratio determines the number of buses which may be unavailable for service due to maintenance needs.

It is almost inevitable that some buses are inoperable during peak periods. Unless the stall capacity or some other factor acts as a binding constraint on the amount of maintenance work which can be scheduled for the off-peak workshifts, it should be possible, through the maintenance scheduling process, to limit the number of inoperable buses during a peak period to those which are out of service for two reasons. Scheduled maintenance tasks which require more than two consecutive shifts to complete, will cause the bus being worked on to be unavailable for at least one peak period. In addition, when a bus has failed and the unscheduled maintenance required to repair the bus could not be completed before the onset of the peak period, that bus will be unavailable for that peak and any subsequent one until the work is completed.

Thus, if the maintenance program which has been developed results in too many buses being out of service during the peaks, then the reasons for their being out of service should be examined. Any buses which are in the garage for preventive maintenance during peak periods should be the first to be investigated. Was it necessary for these actions to occur during this time period? If so, when the program was being developed were the full availability and replacement bus costs corresponding to peak period maintenance work, accounted for? (see section 3.2.9)

One problem which may apply to scheduled maintenance activities but

is probably more applicable to unscheduled maintenance activities due to failures is that of excessive wait times before work is even initiated on the bus. If too many buses are experiencing excessive wait times (and consequently are unavailable for more peak periods than the work time would require), it is probably a result of overscheduling maintenance activity either during the workshift in question or some other shift which may adversely affect the ability of the original workshift to complete the activities scheduled for it.

Overscheduling may result from underestimating, for any of a variety of reasons, the work time required to complete particular tasks. Failing to allow enough 'slack time' either for work breaks or between tasks performed on different buses, may be a contributing factor. It is possible that the excessive wait times are a result of the entire maintenance program being overscheduled. This should lead to the question, 'Was the wait time component of availability cost given enough 'weight' in developing the maintenance program?'

Another possible explanation for the excessive number of inoperable buses during the peak is that there were simply more unscheduled maintenance tasks due to failure than had been anticipated. These failures may be occurring during the peak itself, thereby directly requiring replacement buses. They may also be occurring prior to the peak, but the unscheduled maintenance which is required to return the bus to operable condition requires a long work time and therefore could not be completed in time for the peak.

Questions to be posed in such situations include; 'Did the maintenance program which was developed, predict this number of failures? for the peak period? If yes, were the full availability and replacement bus

costs of peak period failures accounted for in the development of failure prevention programs for the parts responsible for so many failures? And if the number of failures was not predicted accurately, were the life distributions of the parts which are failing 'too often' estimated correctly and was the proportion of failures predicted to occur during peak periods accurate?'

Finally, whether or not the number of failures or the proportion of them which would occur during the peak were predicted accurately; 'Was the cost of a failure accurately estimated in program development? Was the proportion of failures resulting in road calls underpredicted and if so, are the resulting additional labor hours which are spent responding to the added road calls, causing a backlog in the other work which was scheduled to be done thereby causing excessive wait times (the effects of which have been discussed earlier)?'

It may be that every possible source of the peak availability problem which has been discussed thus far is not a characteristic of the minimum cost program which has been developed, or of whatever program is being examined. However, if they are part of the minimum cost program, then eliminating them (reducing failures, wait times, peak scheduled maintenance) will increase the cost of the program by an amount which is estimable through application of the framework and use of its concepts.

It may be found that the maintenance resources which must be applied to meet the high operable ratio are greater than those which would be needed to enlarge the fleet and thereby enable the maintenance department to operate at a more efficient operable ratio. If the maintenance manager believes that this is true, then through use of the framework he may approach those who must approve his plan, with a tangible estimate of the

savings which would be accrued through the proposed fleet expansion⁵².

5.3 The Maintenance Program and Parts' Quality

It has been tacitly assumed throughout most of this paper, that the characteristics of the parts to be used in maintenance are the same as those which have previously been used. It is often the case however, that there is more than one manufacturer from which a certain part may be obtained. The parts available from the different manufacturers may, despite being the same type of part, be priced differently and their characteristics may vary. Whether the alternative part source is known during program development or is discovered after the program has been developed and possibly implemented, use of the framework developed here can aid substantially in determining which of the sources' parts would best fit the maintenance program's needs. (see section 2.4)

In order to estimate the cost of maintaining any part, the part's life distribution must be known⁵³. The parts' expected lives should not be used as the basis for the part choice decision because the variability of the distribution around the parts' mean lives may be widely disparate. A part with a longer mean life will often reduce the parts cost associated with maintenance of the part type. However, if the same part also has a

⁵²Although it is possible that the problems which a maintenance department has in meeting the agency's required operable ratio stem from an insufficient fleet size, the great majority of such problems in today's industry appear to be caused by implementation of a less than optimal maintenance program. However, as ridership and service increase and fleet expansion lags behind (see Chapter 1), the likelihood of this scenario will increase.

⁵³This level of information will usually not be made available by the manufacturer. Therefore, obtaining such information would involve communication with other agencies which have used and collected data on the part under similar conditions and/or experimenting by purchasing a small but significant number of those parts for which life distribution data is not available.

greater variability of life, then it may be necessary to perform significantly more maintenance work on the part, thereby increasing the labor and availability costs involved in the part's maintenance. These increased costs may result in the part with the shorter mean life being the optimal purchase.

If the part is, or may be maintained with an on-condition program, the part's monitorability should be identified. If the part is of the first or second level, then any difference in the length of the period between failure and service interruption (first) and that during which the part's imminent failure may be detected (second), must be noted. When part performance is applicable, the average expected performance should be known and if maintenance actions exist which can influence the part's performance then an estimation of its age-performance relationship should be known. Finally, if the part affects other parts' performances, failure rates or lives any differently from the part presently being used then this too should be accounted for in the part's maintenance program cost.

Following the development of the optimal maintenance program for the part, the program should be adjusted to coordinate with the overall vehicle maintenance program and the cost of these adjustments added to the part's maintenance cost. The cost of maintaining the different parts over the program period should then be added to their respective purchase prices. The part with the least total cost would then be the part which should be used to minimize total maintenance cost.

Aside from the ability to minimize maintenance program cost under normal or unconstrained conditions, the consideration of use of alternative parts' manufacturers may be an important strategy to take when the program is constrained by physical capacity and/or peak bus needs. Under

these circumstances it would be worth paying more than usual for a part which would reduce availability cost. A similar argument could even be presented if a disproportionate increase in the cost of labor occurs.

Thus in order to make the correct decisions on which manufacturer's part will be used, it is necessary to estimate the total cost of maintaining the different parts under the conditions which the maintenance program would be operating. This may be accomplished through application of the framework detailed in this thesis.

5.4 Applications in the Budget-making Process

Finally, and perhaps for maintenance managers most important, is the potential for the framework to be used in the budget making process. It can be an irreplaceable aid in developing a maintenance budget which will best serve the objectives of its department as well as its agency.

The parts and labor costs directly attributable to vehicle maintenance can be estimated for the program period, directly from those which were used in program development. Further, if any changes in the budget are proposed by the director of operations, general manager, budget office and/or the board of directors, the effects of such changes can be predicted by the maintenance manager and explained to those proposing the change.

Thus, if budget cuts are proposed, the maintenance manager could figure out what actions would be necessary in order to minimize the impact on maintenance performance. If these actions involved such things as deferral of needed maintenance, the inevitability of either spending the resources in subsequent program periods, or negatively affecting the level of service immediately and/or in the longer run, can be explained. In fact, it should be possible to determine approximately when the negative effects of the deferral will be incurred and what level of severity they

will involve. Thus the framework can be used as a strong, tangible, rational lobbying tool for the maintenance budget.

When adjustments are ordered despite the lobbying, the framework would be applied to make those changes which would minimize the total long and short term cost effects. If desired, information gathered in program development through framework application could be used to identify those changes which would defer the cost effects for as long as possible or until a defined 'more opportunistic time' arises to incur them.

Another advantage of using the framework in the budget-making process is that the effects of any change in the demands placed on the maintenance department by departments which it supports (i.e. transportation, marketing), can be predicted and accounted for in the program development process.

For example, the marketing department may find that a 'clean bus campaign' may be warranted to increase ridership or some other reasonable purpose. The transportation department may be scheduled to operate more bus miles and/or may need more buses and a higher operable ratio during peak periods. The optimal strategy to deal with the increased demands can be found by applying the framework under these new conditions. The increase in the cost of maintenance for the period being programmed can then be estimated. If the new demands cause not only direct costs of performing the additional work, but indirect costs as well, due to the facility capacity and/or fleet size/operable ratio beginning to act as a constraint on the program, then this can be predicted, and the total expected cost increase resulting from the new demands can be determined.

Thus, the framework can be a useful tool during all phases of the

budget-making process, from the development of an initial budget by the maintenance manager, to responding to proposals of budget cuts, to implementing programs to best deal with less than optimal budgets.

5.5 Summary

This chapter has demonstrated that the utility of the framework and its concepts, extends well beyond the development of a vehicle maintenance program. Its use in other situations does, however, assume that it has been used in program development.

The framework can aid in determining the best strategy for dealing with a physical capacity constraint and with problems in meeting the supply objective. In so doing, the cost effectiveness of maintenance deferral is determined, as are the expansion of maintenance's physical capacity and the agency's fleet size.

The choice faced when parts with different characteristics, but of the same type, are available can be important in tailoring maintenance demands to the ability to meet maintenance demands.

Finally, application of the framework in the budget-making process can benefit the maintenance department and also the entire transit agency. Interdepartmental planning can be improved and a generally improved understanding of the maintenance task and the reasoning behind its operation, can be propagated to other departments and the leaders of the transit agency.

CHAPTER 6

CONCLUSION

6.1 Summary

The need for the maintenance function of the transit industry to be approached in a rational and systematic fashion is growing each day as demand for transit service grows. This thesis offers a framework for maintenance program development, which may be applied to meet this need. This framework is based on one basic premise; that the vehicle maintenance program which best meets the system's objectives can, under any set of circumstances, be found by properly allocating resources between preventive and non-preventive maintenance.

Before presenting this framework, the transit vehicle maintenance function as it now exists is described. The main goals and objectives of a maintenance department - fleet reliability, operational safety, supply, cost minimization and service comfort - are discussed. The basic components of a typical program to meet these objectives, are classified by two basic characteristics - scheduled vs. unscheduled and preventive vs. non-preventive.

Following the description of these program components or action types, the level of effort presently applied to them is discussed. The limits placed on this discussion by data availability problems, were pointed out.

Finally, the importance of the purchasing department is noted and the need for effective communication between the two is underscored.

Concepts which are applied throughout the framework for program development, are then defined and discussed. A listing of vehicle systems, subsystems, and parts is used as a basis for organizing data collection

and in program development. Benefits of performing preventive maintenance are classified into seven basic types - failure prevention for its own sake and for reasons of safety, road call prevention and major repair prevention, service comfort, performance improvement and system or part life extension. The components of the cost savings associated with each of these benefit types and the objectives which each may serve are specified. The cost component which is found to be most difficult to define, despite its importance to the achievement of the supply and other maintenance objectives, is that called availability cost. The cost components of preventive maintenance actions themselves are identified in general and by type of action.

The framework for development of vehicle maintenance programs which meet the maintenance objectives most efficiently is then presented. The program is based on classifying the vehicle's systems as either primary or secondary, according to the probable frequency with which the system's critical parts will need to be maintained in order to yield the benefits sought. A critical part is defined as one which may result in system or vehicle failure when functioning improperly, and/or whose condition affects performance and/or the life of other parts of its system or vehicle. Programs for the primary systems, those with the most frequently maintained critical parts, are developed independently at first, and then coordinated in order to define the vehicle maintenance program's minimum interval. This defines the highest frequency at which any scheduled action may occur and provides a program structure since all scheduled actions corresponding to the maintenance of primary or secondary systems, can occur only at multiples of this minimum interval.

The system's critical parts may be maintained by an on-condition or hard-time preventive maintenance program or with no preventive maintenance at all. A hard-time program involves the performance of scheduled preventive actions at set intervals, whereas in an on-condition program, a monitoring action is scheduled to occur at set intervals and the performance of further preventive action may or may not ensue, depending upon what is found during monitoring. The frequency of scheduled action is used as a means for program development in both types of preventive programs, because this frequency determines the frequency with which the other program's actions will need to be performed.

Following systems' program development using the idea of the minimum interval, the vehicle maintenance program's tasks are scheduled to occur during shifts such that the program's availability cost is minimized.

Finally, it is pointed out that the application of the framework and its concepts need not be limited to program development. Their utility in solving problems with physical capacity and fleet size, and in making decisions concerning different part manufacturers is demonstrated. The advantages of its use in the budget-making process are also portrayed.

It may appear at first, that the data needs of applying this type of framework are insurmountable. However, the data required includes only that which is necessary to perform the maintenance function most efficiently.

The critical part life distributions and the system performance - part age relationships which are necessary to develop the 'best' of each of the three program forms, can be developed from past experience or through experimentation to 'artificially' develop such experience. To develop the best program for a part, it is also necessary to estimate the

cost of each type of program action (scheduled, unscheduled preventive, unscheduled non-preventive) and the frequency with which each of these costs would be incurred, for each of the applicable program forms. These cost estimates include both tangible and intangible costs. The tangible costs (parts, labor, service vehicle, etc.) should be fairly simple to estimate from collected data. The intangible availability cost is quite difficult to estimate, however, due to its importance in meeting the maintenance objectives it should somehow be estimated and considered in program development.

There is no denying that the data needs for application of the framework presented here are considerable, but again they are only the needs required to develop productive maintenance programs.

6.2 Recommendations

This thesis and the suggested framework for program development, is only the 'tip of the iceberg' in the study of the transit industry's maintenance function. The stress in past research into the transit industry, on the operational and service planning aspects of transit, has left open the study of the maintenance function - an aspect of transit which, though possibly less glamorous, is of critical importance in the provision of high quality transit service as an alternative mode of urban transportation.

Thus, the recommendations for further research into transit maintenance planning and operations are quite broad in scope. However, a critical step in this continued research effort, is the establishment of ties to the transit industry itself, and the development and use of 'hard' data in order to ensure that the research is oriented toward addressing problems being and likely to be encountered in the transit vehicle

maintenance function.

The Urban Mass Transportation Administration (U.M.T.A.) can and should play an important role in the process of improving the transit industry's maintenance practices. Some of the more important policies and actions whose implementation should be strongly considered in developing this role are;

- 1) encouraging adoption of maintenance management information systems, offering guidance in increasing efficiency of their use at the agency level,
- 2) listing vehicle systems/subsystems/parts, critical parts, potential benefits of preventive maintenance on critical parts, primary/secondary systems to upgrade efficiency of M.I.S.'s at industry level,
- 3) acting as repository for data developed by agencies' M.I.S.'s to increase efficiency of their use at the industry level,
- 4) sponsoring demonstration projects to aid in development of a maintenance data base,
- 5) acting as middle man in bus procurement, and
- 6) expediting the maintenance facility construction process.

As an increasing number of agencies turn to the use of management information systems in an attempt to improve the efficiency of maintenance management, the potential to base program development on hard data and to collect and analyze the most useful data for this process, grows rapidly. The adoption of such information systems for maintenance management is an important step, and one which should be encouraged by U.M.T.A..

The efficient application of these systems however, is a more important and more difficult task. The opportunity exists for U.M.T.A. to simultaneously guide and increase the efficiency of this process. They

should perform those tasks which can be done once for the entire industry. These tasks include, listing vehicle systems, subsystems and parts, identifying systems' critical parts and the potential benefits of performing preventive maintenance on them, and classifying the systems as primary or secondary.

Further, U.M.T.A. should act as a repository for data generated by the transit agencies, including such things as critical parts' life distributions and age-system performance relationships. They should also consider acting as an aide in the development of this data, by sponsoring the types of experimentation suggested in this thesis, at various agencies across the country. Availability of this data would enable study of the effects of environmental conditions (i.e. weather, road conditions, inter-stop spacing, fleet composition, etc.) on the performance of the maintenance function.

There are additional ways, outside the realm of data collection for maintenance program development, in which U.M.T.A. can potentially increase the efficiency of the industry's maintenance function. The proposal that U.M.T.A. guarantee the purchase of a certain number of manufacturers' buses in a given time period should, among other things, lead to U.M.T.A. having its own new bus fleet. This would presumably be used to decrease the delays encountered by agencies procuring new buses. This would not only enable more rapid expansion of service, but could be used to increase the efficiency with which the maintenance function is planned and carried out.

Expediting the process of construction of maintenance facilities with U.M.T.A. capital grants would also increase the potential efficiency of maintenance planning. These facilities should be planned and constructed

such that any potential future expansion can be accomodated relatively easily.

The transit agencies themselves need to become more oriented toward maintenance planning for the short and long-term, instead of reacting to whatever may occur. Interdepartmental cooperation, as well as cooperation between the agency and the public, U.M.T.A. and other levels of government, and even between agencies, is essential to the efficacy of such a planning effort. In addition, the collection and use of the proper data is necessary for the development of any rational, systematic method of maintenance planning and program development.

The framework presented in this thesis, rationalizes the maintenance program planning and development process so that the public may best be served by the transit agency. Although some shortcomings may exist in this particular model, they would not negate the strong need for application of this type of framework to today's transit industry and its maintenance function.

The 1980's and the important shifts which are already occurring in the nation and the world, pose a challenge to the transit industry. A rational, logical response to it by all involved would undoubtedly have an important positive impact on our nation's economy.

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APPENDIX A

Telephone and Other Interviews

Telephone Interviews

28. Greater Cleveland Rapid Transit Authority (G.C.R.T.A.), Mr. Dan Hurley, maintenance management official, 11/79 and 4/80
29. Massachusetts Bay Transportation Authority (M.B.T.A.), Mr. John Cunningham, garage supervisor, 5/80
30. New York City Transit Authority (N.Y.C.T.A.), Mr. George Schwarz, maintenance management official, 4/80
31. San Diego Transit Commission (S.D.T.C.), Mr. Todall, assistant manager of maintenance, 4/80
32. Seattle Metro, Mr. Jim Burton, director of maintenance, 11/79 and 4/80
33. Southern California Rapid Transit District (S.C.R.T.D.), Mr. Rich Davis, director of maintenance, 4/80, and
34. Mr. George Caria, assistant general superintendent of maintenance, 11/79 and 4/80
35. The MITRE Corporation, Mr. Virgil Thurlow, 10/79
36. Toronto Transit Commission (T.T.C.), Mr. Doug Mayer, director of operations, 11/79
37. Tri-County Metropolitan Transportation District (Tri-Met), Mr. Dick Wood, maintenance management official, 11/79 and 4/80

Other Interview

38. Mr. Fred Salvucci, Secretary of Transportation and Construction, Commonwealth of Massachusetts, 1975-1979, 5/79