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Cost Savings Potential From Improvement In Railcar Reliability and Maintainability

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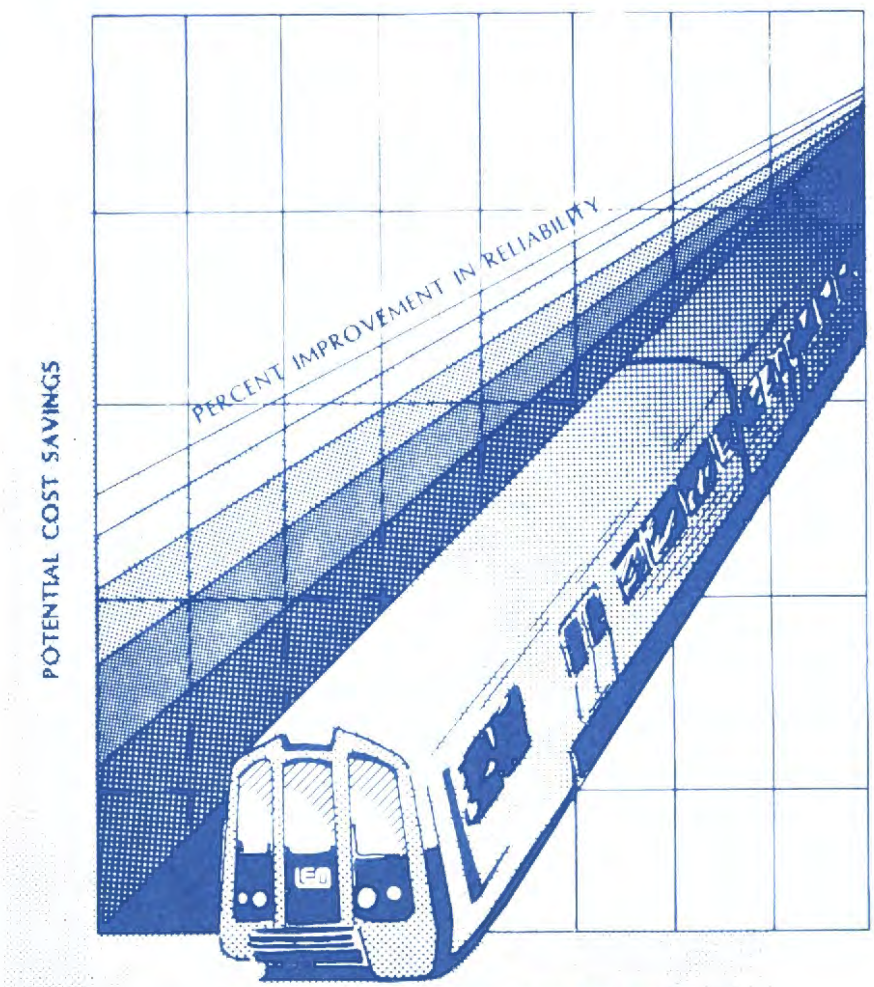

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16. Abstract

Potential benefits from proposed improvements in transit equipment performance must be quantifiable so that transit managers and other decision-makers can justify expenditures incurred on such improvement programs. This report presents a mathematical tool that will permit the estimation of cost savings potential from improvements in railcar reliability and maintainability. Rail transit improvements are expressed in terms of two major performance indicators--Mean Time Between Failures and Mean Time To Restore a Car to Service Condition. The tool is designed to estimate potential benefits (in dollars) achievable through improvements. It does not address the costs incurred or the actual mechanism for realizing these improvements.

Various models for estimating operating, maintenance, and fleet cost savings have been developed. These are then calibrated using data from the Washington Metropolitan Area Transit Authority. Also presented are example applications of the models in either areas including cost savings from subsystem improvements and life cycle cost comparisons for making decisions to rebuild or buy new cars. While the models have been developed on the basis of performance related to unscheduled maintenance, they can be extended to include scheduled maintenance. It is cautioned that the results from the calibrated models should not be extrapolated to other transit authorities without a close examination for conformity. Although the models have been developed for rail transit, they can be adapted for use in the bus industry, for automated small vehicle systems, or for other types of transit systems.

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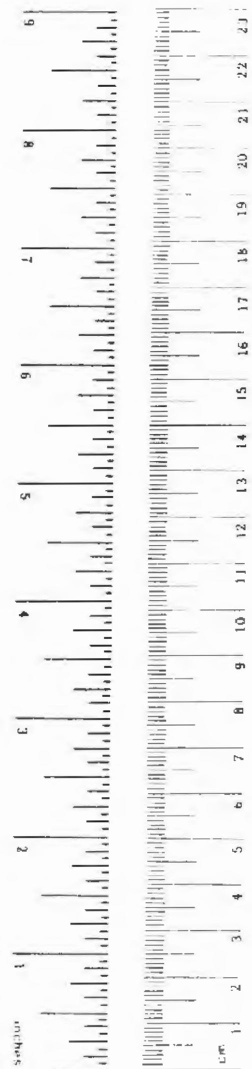
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

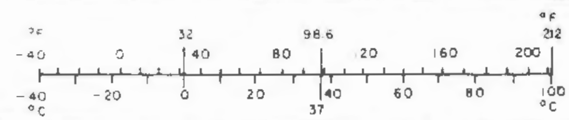
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

This report presents a mathematical model that permits the estimation of cost savings potential from improvements in railcar reliability and maintainability. The project is funded by the U.S. Department of Transportation, Urban Mass Transportation Administration (UMTA) through its Office of Technical Assistance.

The cooperation received from UMTA and the Washington Metropolitan Area Transit Authority (WMATA) whose data were used in calibrating the models has been commendable. In particular, the project team is deeply indebted to Mr. Erich Vogel, General Superintendent, Car Equipment, for his support and cooperation throughout the project.

The project team consisted of Mr. Donatus Muotoh, and Mr. Charles P. Elms. Special acknowledgments are made to Dr. Walter Diewald and Mr. Dwight Eldredge for their contributions to the section on example applications of the models. Finally the project team wishes to acknowledge the valuable guidance and support provided by Mr. Jeffrey Mora, UMTA Contracting Officer's Technical Representative.

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EXECUTIVE SUMMARY

Potential benefits from proposed improvements in rail transit equipment must be quantifiable so that these benefits can be assessed against those from competing alternatives. To date, there has been no consistent procedure available to transit authorities to facilitate the estimation of such benefits. As a result transit managers and decision-makers have hitherto resorted to rough estimates of cost benefits in order to justify expenditures planned for car-related improvement projects. A method is presented that permits the estimation of cost savings potential from improvements in railcar reliability and maintainability. The method employs mathematical models to express potential savings in costs as a function of car reliability/maintainability indicators. Three separate models have been developed to express potential operating, maintenance, and fleet capital cost savings as functions of improvements in car Mean Time Between Failure (MTBF) and Mean Time To Restore (MTTR).

RATIONALE FOR COST MODELS

Car failures can result in service delays, lost car-hours and increased operating cost. The operating cost model estimates the potential cost savings that can be realized by reducing service-related failures and system downtime.

The maintenance cost model estimates both potential labor and spare parts cost savings from improved reliability/maintainability. While labor cost saving derives from reduced failure rate and /or mean time to repair failed cars, the spare parts cost saving results only from reduced failure rates. Because maintenance costs are incurred from all maintenance actions, the maintenance cost savings model takes into cognizance both service and non-service-related failures.

Savings in fleet cost is reflected in the reduction in spare car requirement realized as a result of improved car reliability and maintainability. Car-hours are lost from failures occurring in service as well as failures detected when the car is in the shop for other maintenance. Hence the fleet cost model also considers both service and non-service-related incidents.

CALIBRATING AND USING THE MODELS

The three mathematical models discussed above have been calibrated and tested using actual data from Washington Metropolitan Area Transit Authority (WMATA). To facilitate their use, the results have been presented as families of curves which can be employed without reference to the mathematical formulation once the defining parameters have been established. Because the models have been calibrated on the basis of a single data source, it is important to recognize the need to recalibrate them for use at each transit authority. In the following examples for WMATA, only unscheduled maintenance performance was modeled. The same procedure can be applied to include scheduled maintenance by relating the costs to the mean time between maintenance (MBTM) actions and mean time to maintain (MTTM) cars.

Operating Cost Savings

Figures 2-1 and 2-2 show the potential annual operating cost savings for various levels of improvements in railcar MTBF and MTTR. For known percent improvements in MTBF and MTTR, the expected annual operating cost savings can be determined from the figures. The results show that maximum annual operating cost savings for WMATA is $61,000 which is only about 0.6 percent of the total estimated WMATA annual operating cost. Such small potential to save on operating costs is expected since most transit authorities typically operate at high service availabilities even where such availabilities require the provision of greater spare levels.

Maintenance Cost Savings

Figures 2-3 and 2-4 show the families of curves that predict the potential annual maintenance cost savings for various levels of MTBF and MTTR improvements. In general, it can be observed that railcar maintenance cost is highly sensitive to transit performance improvements. For example, an annual maintenance cost savings of $3.7 million (or approximately half of WMATA estimated annual maintenance budget) can be realized by keeping MTTR constant and cutting the number of failures in half.

Fleet Cost Savings

Fleet capital cost savings from transit performance improvements can also be substantial. Figures 2-5 and 2-6 show the total fleet cost savings due to a reduction in fleet size resulting from improved MTBF and MTTR. For no change in MTTR and 50 percent reduction in number of failures (i.e., 100 percent increase in MTBF), there is a potential for saving about $4 million in fleet costs.

EXAMPLE APPLICATIONS OF MODELS

Besides their use for estimating cost savings from overall improvements in car performance, the models have several applications. Two example applications are illustrated. The first involves the estimation of benefits from subsystem improvements and the second involves a life cycle cost comparison for making decisions to rebuild or buy new cars.

Cost Savings From the Substitution of AC Propulsion for an Existing DC Propulsion Subsystem

This example uses the NYCTA R-44 rapid railcar to illustrate the estimation of potential benefits from subsystem improvements. It estimates the potential cost savings from the introduction of an AC propulsion over the existing cam-controlled DC propulsion subsystem. The mathematical formulations for maintenance labor, parts, and fleet cost savings have been calibrated and separately plotted in Figures 3-1, 3-2, and 3-3. For 60 percent improvement in MTBM and 52 percent improvement in MTTR obtained by using AC propulsion, the annual maintenance cost savings are $4,900 per car and $1,220 per car for labor and parts respectively. On a fleet of 352 R-44 cars, these savings translate to a total annual maintenance cost savings of about $3 million. Also resulting fleet cost savings is approximately $18 million.

Decision To Rebuild or Buy New Cars

Transit authorities have often been faced with the problem of deciding between a purchase of new cars or rebuilding existing cars. This judgment is one of the most classical applications of the models. The process examines the potential net benefits that can be realized by extending the life and improving the performance of an existing fleet against the net benefits from buying new and possibly more reliable equipment. Life cycle cost comparisons were made on the relative savings in fleet costs, maintenance costs, and other relevant costs due to improved reliability and maintainability. In making the comparisons, two very important parameters which influence the decision were taken into consideration. The first is the time value of money. The second is the "performance ratio" which expresses the relative reliability/maintainability of new cars over rebuilt cars. The life cycle cost comparisons between the two alternatives were made for varying time values of money and "performance ratios". The results are plotted in Figure 3-6 which present the life cycle cost boundaries between the two alternatives. In the figure, the region above the horizontal axis represents the conditions under which economics favor buying new cars. Below the axis, the choice to rebuild existing cars is more economical. Two values for "performance ratios" are indicated. In general, it can be seen that as the reliability/maintainability of rebuilt cars approach that for new cars ($R \rightarrow 0$), the choice to rebuild cars is favored at higher time value of money. Conversely, as the reliability/maintainability of rebuilt cars becomes worse than for new cars ($R > 0$), economics favor buying new cars at lower time value of money.

CONCLUSIONS

The following conclusions can be drawn from this work:

- o A realistic and practical method has been developed that relates costs with railcar reliability and maintainability.

- o Although the models have been used for rail transit, they can be adapted for use in the bus industry, people mover systems, or for other types of transit systems.

- o The method can be used by transit operators, suppliers and consultants.

  a. For the operator, it is useful in the following areas:

    - Choice between rebuilding and buying new cars
    - Comparison of cars with known reliability and maintainability
    - Justification for car improvement projects (subsystems)
    - Justification for maintenance improvement projects
    - Justification for changes in maintenance policy
    - Assessment of the impacts of variations in reliability and maintainability when life cycle costs are used in the procurement of new fleet
    - Spares and inventory control policy development or modification
    - Method for maintenance facility sizing and optimization

  b. For the supplier, it is useful in:

    - Comparison of his product with those of competitors
    - Justification for new product development
    - If specific objectives (or ranges) for improved reliability and maintainability are set in relation to the potentials to save

money, the method can be used in defining design goals for product or component improvement.

- Comparison of the cost-effectiveness of similar levels of improvements in car reliability and maintainability.

c. For the transit consultant, the method is useful as an analytical method to assist transit authorities in trade-off decisions relating to both rolling stock and fixed facilities.

1. INTRODUCTION

Potential benefits from proposed improvements in rail transit equipment performance must be quantifiable so that these benefits can be assessed against those from competing alternatives. Although various techniques have been developed in the past, there is probably no consistent procedure available to transit authorities to facilitate the estimation of such benefits. As a result, transit managers and decision-makers usually develop special methodologies or make crude estimates of the benefits to justify expenditures incurred on improvement projects.

The objective of this report is to develop a tool for estimating economic benefits from improvements in transit performance. Transit improvements are expressed in terms of two major performance indicators -- Mean Time Between Failures (MTBF) and Mean Time To Restore (MTTR) a car to service condition. The tool is designed to estimate potential benefits (in dollars) achievable through improvements in MTBF and MTTR. It does not, however, address the costs incurred or the actual mechanism for realizing these improvements. While the tool addresses only performance related to unscheduled maintenance, it can be extended to include scheduled (preventive) maintenance.

Different models are generated to estimate potential savings in operating, maintenance and fleet costs as well as the interrelationships between the capital costs of maintenance facilities and performance improvements. It is recognized that system performance improvements can result in increased transit ridership and, consequently, higher revenues for a transit authority. However, because of the difficulty in quantifying any resulting increases in ridership, the impact of transit improvements on revenues is not addressed in this report.

In addition to their use for estimating cost savings from improved car performance, the models may also be used in the following areas:

- If the contribution of a subsystem to overall system reliability is known, then the impact of improvements in this subsystem's performance can be investigated. Quantifiable benefits are useful in justifying proposed subsystem research and development efforts and/or subsystem retrofit projects.

- The effects of improvements in management, training, and rail transit operating policies may be studied. For example, since the total time to restore a failed car includes various delay components (such as line delay, retrieval time, shop time, etc.), the effect of any policy changes aimed at reducing a specific delay component may be investigated.

- The models may serve as a valuable tool in decisions involving new car procurements versus rebuilding older cars by permitting the estimation of net benefits from rebuilt cars and those from new cars.

- Although the models have been developed for rail transit, they can also be adapted for use in the bus industry or for peoplemover systems.

To gain insight into the actual magnitude of cost savings achievable from various levels of improvements, the cost models generated in this study have been calibrated on the basis of data obtained from the Washington Metropolitan Area Transit Authority (WMATA). Because transit costs depend largely on the operating policies adopted by the respective transit authorities, it is recognized that a model calibrated on the basis of only a single data source cannot be fully representative of the rail transit industry. Hence, the results of this study should not be extrapolated to other transit authorities without a close examination for conformity. It will, therefore, be necessary to recalibrate these models for use at each transit authority. A simplified step-by-step procedure for calibrating and using the tool is included in the report to facilitate the use of the models by transit operating and supply industry.

The remainder of this report is organized as follows: Section 2 presents the general procedures for estimating cost savings. It illustrates the results of the various models calibrated on the basis of data obtained from WMATA and presents a simplified step-by-step approach that can be used by other transit authorities to calibrate their systems. Section 3 shows example applications of the models in other areas including cost savings from subsystem improvements and life cycle cost comparison for decision-making in regard to rebuilding or buying new cars. The development of the models and the detailed calibration procedures can be found in Appendices A and B, respectively. Finally, Appendix C presents general relationships for sizes of maintenance facilities.

2. GENERAL PROCEDURE FOR ESTIMATING POTENTIAL COST SAVINGS RESULTING FROM TRANSIT PERFORMANCE IMPROVEMENTS

This section presents the basic procedures for estimating potential cost savings that can be derived from improvements in reliability and maintainability. The tool developed is a perturbation model which is calibrated using data on actual costs and performance of a transit system. Since it is a perturbation model it will be less accurate for large changes in reliability and maintainability. Such inaccuracies would lead to an overestimation of the cost savings. If the tool underestimated cost savings, it might fail to identify an important benefit. Therefore, for large changes in performance, the tool is conservative in that it will identify a cost savings potential and provide the justification for a more detailed investigation.

2.1 TRANSIT PERFORMANCE MEASURES

The performance of transit equipment is usually indicated by its reliability and maintainability. Equipment reliability is measured on the basis of the Mean Time Between Failure (MTBF) and reflects the probability that the equipment will be operational when required. Its maintainability, on the other hand, is determined on the basis of the Mean Time To Restore (MTTR).

Equipment malfunction results in system downtime, lost car-hours, higher level of maintenance and, consequently, increased operating and maintenance cost. To minimize delays in service, transit authorities should provide cars to serve as spares. This operating policy ensures continuity in service. However, it results not only in higher capital commitment for increased fleet size, but also in increased cost needed to provide larger maintenance and storage facilities. These requirements may be reduced by employing equipment with a high level of reliability. High equipment reliability means low failure rate and consequently reduced system downtime.

Availability is defined as follows:

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where MTBF = Mean Time Between Failure

MTTR = Mean Time To Restore

From the above definition, it can be seen that performance improvements can be realized in two ways:

1. by increasing the equipment MTBF, and

2. by reducing the mean time to restore equipment (reduce MTTR) to service and/or service condition.

Two major types of failures can be identified -- service and non-service-related. Service-related failures occur when the car is in service and may or may not result in system delay. Non-service-related failures are detected when the car is not in service, usually during maintenance.

For service-related failures, there are three possible scenarios of car failure based on the degree of impact such failure has on system operations. These scenarios are as follows:

CASE A

This scenario involves the failure of a car in a train. The failed car is not taken out of service until it is convenient to replace it with a spare car without sustaining excessive delays in service. The on-line delay due to this failure is D_a. However, the magnitude of D_a is such that no other trains in the system are delayed as a result of this failure.

CASE B

In this scenario, a car in a train fails. The failure is such that the failed car must be locked out of passenger service but remain in the train. The on-line delay, D_b, from time failure occurs to time service is restored may or may not cause delays to following trains. The time during which the locked-out car remains in the train on the line is t_1. An example of this type of failure may involve air-conditioning malfunction. Case B can be a special case of Case A above ($D_b = D_a$) or Case C below ($D_b = D_c$).

CASE C

This scenario involves the failure of a car in a train resulting in an on-line delay, D_c, which is long enough to cause all following trains to be delayed for a period of d_c. A typical incident that may result in this type of failure includes propulsion or brake problems which cannot be reset in a short time.

Each of the above scenarios of service-related failure can result in equipment downtime and lost car-hours. In general, five components of car downtime can be identified as follows:

(i) On-line downtime, D_1. This can be D_a, $D_b + t_1$, or D_c and d_c depending on the type of failure experienced.

(ii) retrieval time or time to recover a failed car from the line, D_r

(iii) time during which the car is in the yard awaiting repair, D_y

(iv) shop time or time during which a failed car is actually worked on, D_s

(v) time to inspect and approve the repair prior to certification of operational readiness, D_v

On the other hand, non-service-related failures can result only in car downtime in the yard or shop (i.e., D_y, D_s, and D_v).

The cost savings from a reduction in total car downtime can be studied. Also, by focusing on a specific downtime component, the effect of minimizing D_l, D_r, D_y, D_s, or D_v can also be investigated.

2.2 BASIC METHODOLOGY FOR ESTIMATING POTENTIAL COST SAVINGS

Because transit authorities provide sufficient spare cars to compensate for equipment failures, actual system downtime resulting from car failures is greatly reduced. However, car failures and their resulting lost car-hours are associated with system costs. Hence, to estimate potential cost savings from transit improvements, all lost car-hours due to failures must be taken into consideration whether or not such failures result in system downtime. In other words, the analysis must be based on the availability of all vehicles in the fleet as opposed to the system availability. This section discusses the basic methodology for estimating the various cost savings and illustrates the results for the models calibrated on the basis of data obtained from WMATA for the month of February 1983. It is recognized that February data may not be representative of the year's experience. Hence calibration based on such data is merely intended to demonstrate the use of the model. Detailed model developments and calibration procedures are contained in Appendices A and B, respectively.

2.2.1 Operating Cost Savings

System operating costs include all costs associated with the actual operation (not maintenance) of the system. Specific categories cover the costs of operational personnel, and support and handling equipment necessary for system operation. By improving the performance of the equipment, the service/operating costs associated with schedule delays can be minimized. Hence operating cost savings can be derived by reducing car-hours lost in service as a result of service-related failures.

Section 2.1 identified the various possible scenarios of service failures. For any period under consideration, total car-hours lost in service may, therefore, consist of:

- car-hours lost due to failed cars and other cars within failed trains
- car-hours lost due to locked-out cars remaining on the line during Case B failures
- car-hours lost from delays of following trains during Case C failures.

By improving fleet mean time between service failure (MTBF) and mean time to restore line service (MTTR), the total car-hours lost in service may be reduced. If the average operating cost per car-hour operated prior to the improvement is known, the savings in operating cost can then be calculated by multiplying this average unit cost by the reduction in lost car-hours realized through the improvements. The resulting expression (see Appendix A.1 for derivation) for this operating cost savings is given by

$$\Delta C_o = C_o\left(\frac{P_f+P_r}{1+P_f}\right)\left\{\frac{n_o R_l}{F_s} + \frac{R_b}{F_b} + \frac{n_l(n_{cl}-n_o)R_c}{F_c}\right\} \tag{1}$$

where

C_o = operating cost (exclusive of maintenance) prior to any improvements

P_f = increase in MTBF as a ratio of initial MTBF; $P_f > 0$

P_r = decrease in MTTR as a ratio of initial MTTR; $0 < P_r \leq 1$

n_o = average number of cars per train

R_l = mean time to restore line service

F_s = mean time between service failures

R_b = mean time to restore type B failures

F_b = mean time between type B failures

n_l = number of lines affected by failures

n_{cl} = average number of cars per line

R_c = mean delay for following trains during type C failures

F_c = mean time between type C failures

The above relationship has been calibrated on the basis of data obtained from WMATA. Annual operating cost savings for various levels of improvement in MTBF and MTTR are tabulated in Tables 2-1 and 2-2. The improvements in MTBF are given by P_f which represents the increase in MTBF as a ratio of the initial MTBF. Similarly, improvements in MTTR are given by P_r which represents the reduction in MTTR as a ratio of the initial MTTR. The data in Tables 2-1 and 2-2 are plotted in Figures 2-1 and 2-2 which show alternative methods of representing the results depending on which parameter is varied. The results show that, in general, savings in operating cost are small for improvements in MTBF and MTTR.

The maximum annual operating cost savings occurs when either the MTBF becomes infinite (i.e., no failures occur) or the MTTR is reduced to zero ($P_r = 1$). Therefore, the maximum possible annual savings would be about $61,000 which is only about 0.6 percent of the total estimated WMATA operating cost. Such small potential to save on operating costs should not be surprising since most transit systems typically operate at high service availabilities even if such availabilities require the provision of higher spare levels.

2.2.2 Maintenance Cost Savings

Maintenance costs are usually incurred in performing preventive (scheduled) and corrective (unscheduled) maintenance activities. The corrective maintenance cost depends heavily on equipment performance. Also, equipment performance and therefore corrective maintenance cost may be influenced by the preventive maintenance policy adopted by the transit authority. Only the effect of equipment performance on corrective maintenance cost is investigated in this study. However, the methodology can also be used to assess the benefits of improved performance obtained through better preventive maintenance programs. In this case, the cost for any additional preventive maintenance would have to be separately estimated.

Corrective maintenance cost includes labor and material costs. An increase in MTBF reflects fewer maintenance actions and consequently lower maintenance labor cost. Also, a decrease in mean time to repair, R_s, reflects lower labor requirements and, consequently, lower maintenance

TABLE 2-1: ANNUAL OPERATING COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME BETWEEN FAILURE

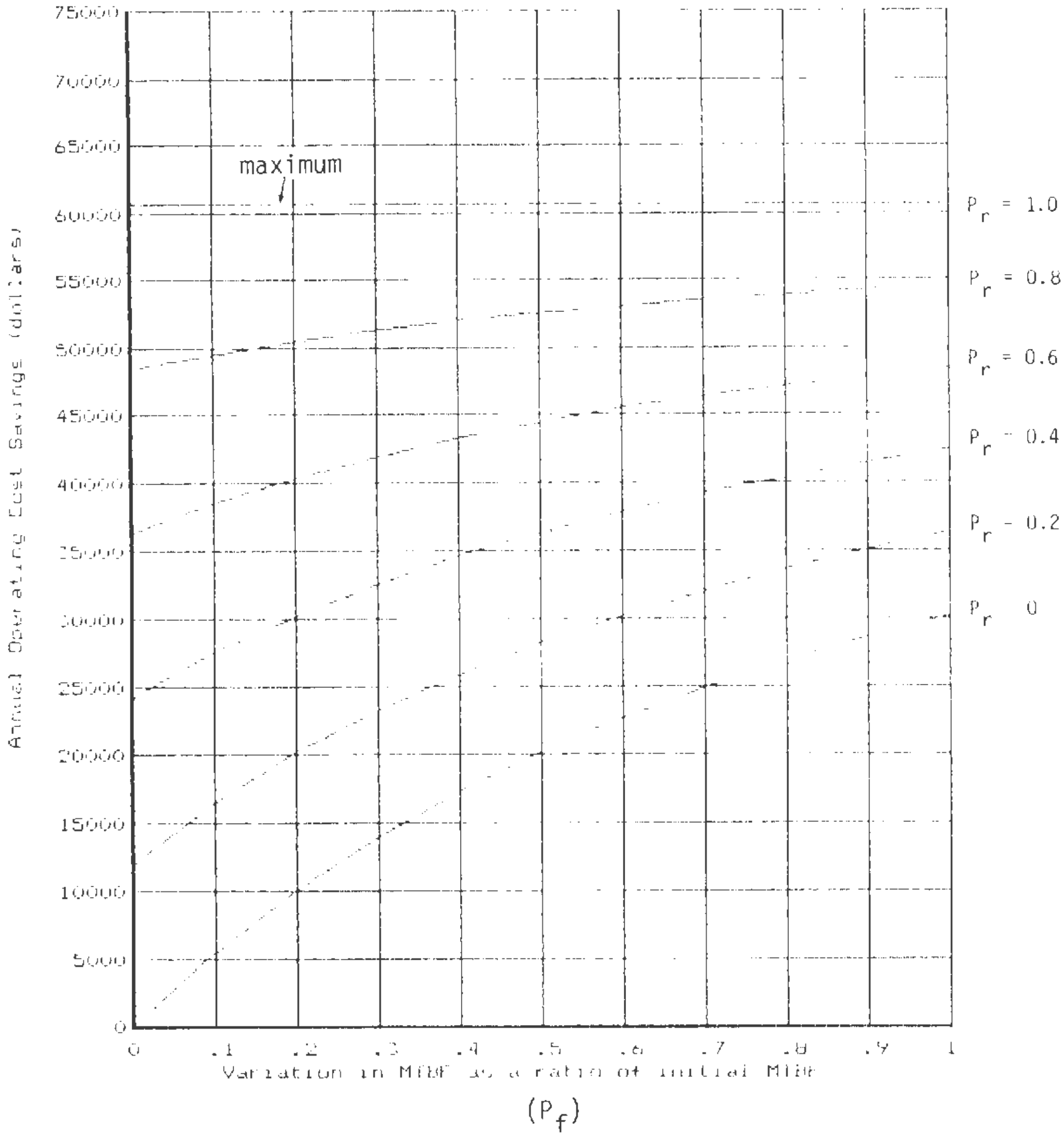
Annual Operating Cost Savings (dollars)

Pf \ Pr	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0.00	12137.00	24274.00	36411.00	48548.00	60685.00
0.10	5516.82	16550.45	27584.09	38617.73	49651.36	60685.00
0.20	10114.17	20228.33	30342.50	40456.67	50570.83	60685.00
0.30	14004.23	23340.38	32676.54	42012.69	51348.85	60685.00
0.40	17338.57	26007.86	34677.14	43346.43	52015.71	60685.00
0.50	20228.33	28319.67	36411.00	44502.33	52593.67	60685.00
0.60	22756.88	30342.50	37928.13	45513.75	53099.38	60685.00
0.70	24987.94	32127.35	39266.76	46406.18	53545.59	60685.00
0.80	26971.11	33713.89	40456.67	47199.44	53942.22	60685.00
0.90	28745.53	35133.42	41521.32	47909.21	54297.11	60685.00
1.00	30342.50	36411.00	42479.50	48548.00	54616.50	60685.00

TABLE 2-2: ANNUAL OPERATING COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME TO RESTORE

Annual Operating Cost Savings (dollars)

Pr \ Pf	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0.00	10114.17	17338.57	22756.88	26971.11	30342.50
0.10	6068.50	15171.25	21673.21	26549.69	30342.50	33376.75
0.20	12137.00	20228.33	26007.86	30342.50	33713.89	36411.00
0.30	18205.50	25285.42	30342.50	34135.31	37085.28	39445.25
0.40	24274.00	30342.50	34677.14	37928.13	40456.67	42479.50
0.50	30342.50	35399.58	39011.79	41720.94	43828.06	45513.75
0.60	36411.00	40456.67	43346.43	45513.75	47199.44	48548.00
0.70	42479.50	45513.75	47681.07	49306.56	50570.83	51582.25
0.80	48548.00	50570.83	52015.71	53099.38	53942.22	54616.50
0.90	54616.50	55627.92	56350.36	56892.19	57313.61	57650.75
1.00	60685.00	60685.00	60685.00	60685.00	60685.00	60685.00

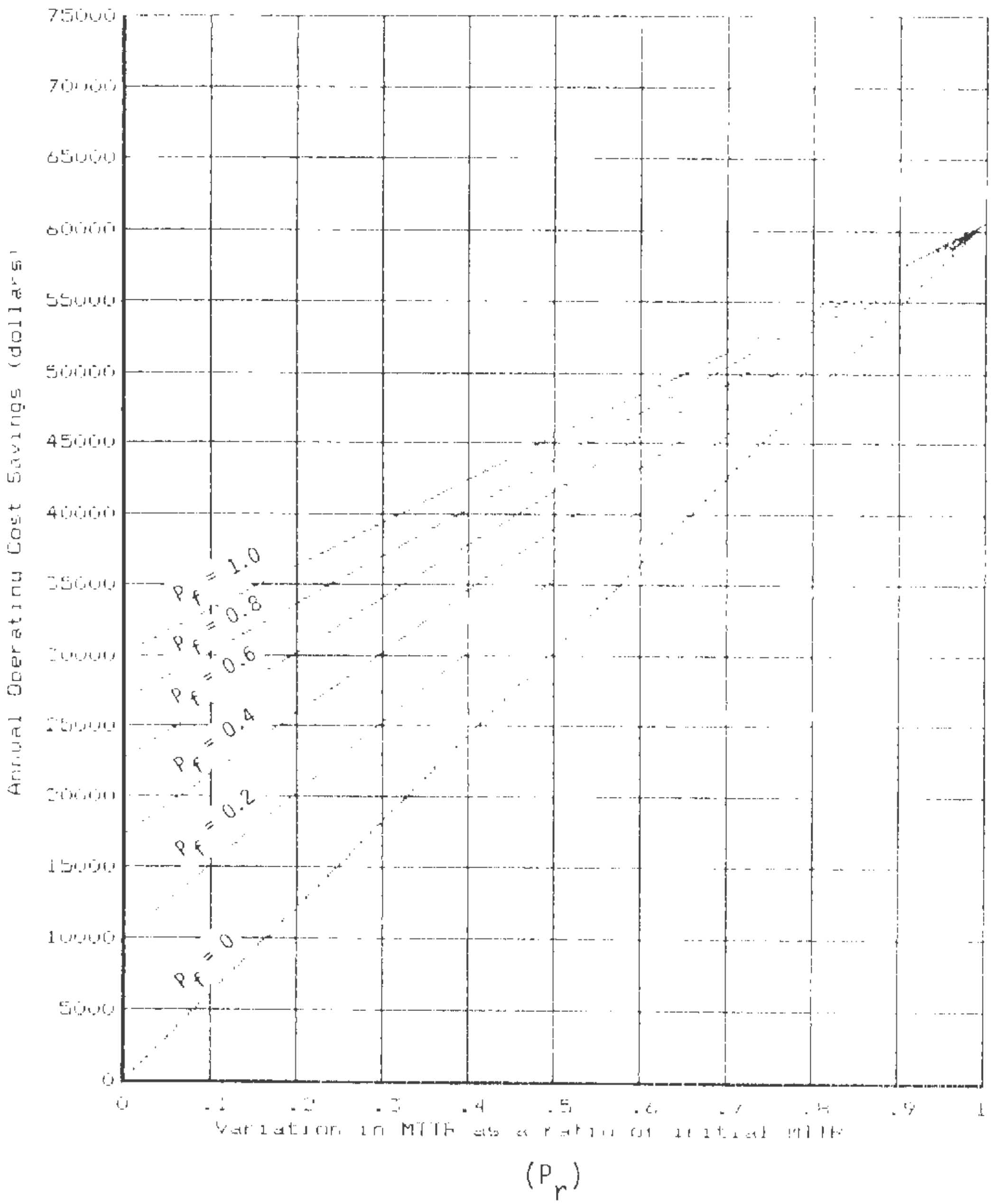


NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in MTTR}}{\text{initial MTTR}}$$

FIGURE 2-1: ANNUAL OPERATING COST SAVINGS (FIXED MTTR)



NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in MTTR}}{\text{initial MTTR}}$$

FIGURE 2-2: ANNUAL OPERATING COST SAVINGS (FIXED MTBF)

labor cost. On the other hand, the cost of materials or spare parts is only dependent on MTBF. If MTBF is increased (reduced number of failures), the need for spare parts is reduced. Note that in considering the effect of MTTR, only the time during which the car is shopped (time to repair) is considered relevant, since the other delay components usually depend on the transit authority's operating policy. It should also be noted that the MTBF and MTTR in this case are calculated on the basis of the total number of failures (service and non-service related) experienced during the period under investigation.

Corrective maintenance labor cost consists of personnel costs, related overhead, and any support activities associated with the accomplishment of unscheduled maintenance. For the purpose of this report, this combined cost is referred to as Maintenance Infrastructure Cost (MIC). Savings in corrective MIC can therefore be related to improvements in MTTR and MTBF.

The savings in spare parts cost due to improvements in MTBF must be added to the MIC savings to obtain the total savings in corrective maintenance cost. The resulting relationship (see Appendix A.2 for derivation) for total annual corrective maintenance cost savings is given by

$$\Delta C_{cm} = n_f \left\{ R_s K_s \left(\frac{P_f + P_{rs}}{1 + P_f} \right) + K_p \left(\frac{P_f}{1 + P_f} \right) \right\} \qquad (2)$$

where $n_f = \frac{H_o}{F}$ = total number of failures experienced in a given period

H_o = car-hours operated during the period

F = MTBF

K_s = corrective MIC constant. This is a constant of proportionality relating shop delay to cost for corrective maintenance. It is expressed in dollars per shop car-hour.

R_s = MTTR (shop time)

P_f = increase in MTBF as a ratio of initial MTBF; $P_f > 0$

P_{rs} = decrease in MTTR (shop repair time) as a ratio of initial MTTR; $0 < P_{rs} \leq 1$

K_p = spare parts cost constant; it relates spare parts cost to number of failures and is expressed in dollars per failure

It should be noted that the first part of Eq. (2) represents the savings in MIC and the second part gives the savings in spare parts cost. Tables 2-3 and 2-4 show the total annual maintenance cost savings calibrated using data obtained from WMATA. The data were extrapolated to reflect a complete operating year. In these tables, P_f represents the ratio of increase in MTBF to initial MTBF. Also, P_r represents the ratio of reduction in MTTR to initial MTTR. The cost savings in Tables 2-3 and 2-4 are plotted in Figures 2-3 and 24, respectively, as a family of curves for various levels of MTBF and MTTR. In general, it can be observed that maintenance cost is highly sensitive to transit performance improvements. For example, the maximum annual corrective maintenance cost savings would be approximately $4.2 million for a hypothetical improvement level of 50 percent in both MTBF and MTTR respectively. This amounts to approximately 56 percent of WMATA's estimated annual corrective maintenance budget. It is important to note that for zero MTTR reduction and a 100 percent increase in MTBF (which is equivalent to a 50 percent reduction in number of failures), an annual savings of about $3.7 million (or half of the estimated annual budget) could be obtained.

It is realistic to expect that the improvements in MTBF and MTTR will be smaller in fact than in the above hypothetical cases. The potential to realize performance improvements exists more at the subsystem level than at the car level. For example, a major subsystem may contribute only 10 percent in overall car reliability. For such a case a 50% improvement in MTBF and MTTR could save on the order of $420,000 per year at WMATA, demonstrating that the savings can be significant.

2.2.3 Fleet Capital Cost Savings

Savings in fleet capital cost can be realized by improving equipment reliability and by reducing the time during which failed cars are out of service. These improvements result in a reduction of the number of spare vehicles required to meet a given level of service. The reduction in required spare vehicles, and therefore fleet cost, is directly related to the total car-hours saved. The number of cars saved is given by the ratio of total car-hours saved and hours scheduled per car. If the cost per car is known, the total fleet capital cost saving resulting from any level of improvement is given by

$$\Delta C_v = \frac{C_v H_s}{h_s} \left(\frac{P_f + P_r}{1 + P_f} \right) \left\{ \frac{n_o R_l}{F_s} + \frac{R_b}{F_b} + n_l (n_{cl} - n_o) \frac{R_c}{F_c} + \frac{R_m}{F} \right\} \tag{3}$$

where C_v = cost per car

H_s = total car-hours scheduled for period under consideration

h_s = hours scheduled per car for the same period

P_f = increase in MTBF as a ratio of initial MTBF

P_r = decrease in MTTR as a ratio of initial MTTR

n_o = average number of cars per train

R_l = mean time to restore line service

F_s = mean time between service failures

R_b = mean time to restore type B failures

F_b = mean time between type B failures

n_l = number of lines affected by failures

n_{cl} = average number of cars per line

R_c = mean delay for following trains during type C failures

F_c = mean time between type C failures

R_m = mean time to restore (for all failures) based on all car downtime (excluding line delay component)

F = mean time between all failures (service and non-service)

Appendix A.3 presents the detailed derivation of the above relationship. The annualized fleet capital cost savings can be easily obtained by multiplying Eq. (3) by the capital recovery factor for a given discount rate and vehicle service life. Thus,

$$\Delta E_c = \Delta C_v \text{ (crf)}$$

where crf = capital recovery factor.

Using WMATA data, the annualized fleet cost savings for various levels of MTBF and MTTR are as shown in Tables 2-5 and 2-6. P_f is the ratio of increase in MTBF to initial MTBF and P_r is the ratio of reduction in MTTR to initial MTTR. The cost savings are plotted in Figures 2-5 and 2-6 respectively. The results show that fleet cost savings can also be appreciable. For no change in MTTR and 100 percent increase in MTBF, there is a potential for saving an annual capital cost of about a half million dollars assuming 30 years vehicle service life and a 10 percent discount rate.

TABLE 2-3: ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME BETWEEN FAILURE

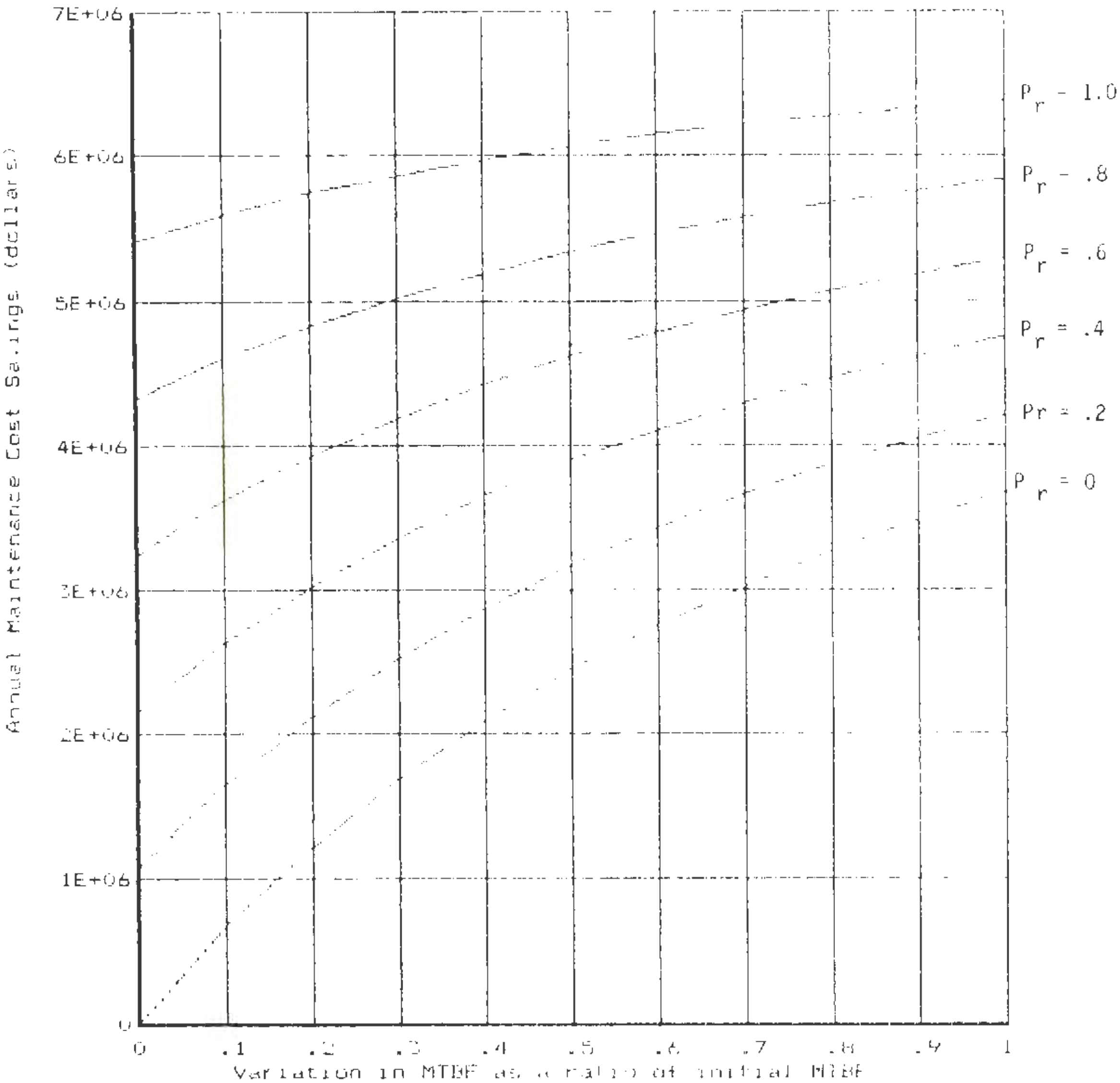
Annual Maintenance Cost Savings (dollars)

Pf \ Pr	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0	1084000	2168000	3252000	4336000	5420000
0.10	669091	1654545	2640000	3625455	4610909	5596364
0.20	1226667	2130000	3033333	3936667	4840000	5743333
0.30	1698462	2532308	3366154	4200000	5033846	5867692
0.40	2102857	2877143	3651429	4425714	5200000	5974286
0.50	2453333	3176000	3898667	4621333	5344000	6066667
0.60	2760000	3437500	4115000	4792500	5470000	6147500
0.70	3030588	3668235	4305882	4943529	5581176	6218824
0.80	3271111	3873333	4475556	5077778	5680000	6282222
0.90	3486316	4056842	4627368	5197895	5768421	6338947
1.00	3680000	4222000	4764000	5306000	5848000	6390000

TABLE 2-4: ANNUAL MAINTENANCE COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME TO RESTORE

Annual Maintenance Cost Savings (dollars)

Pr \ Pf	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0	1226667	2102857	2760000	3271111	3680000
0.10	542000	1678333	2490000	3098750	3572222	3951000
0.20	1084000	2130000	2877143	3437500	3873333	4222000
0.30	1626000	2581667	3264286	3776250	4174444	4493000
0.40	2168000	3033333	3651429	4115000	4475556	4764000
0.50	2710000	3485000	4038571	4453750	4776667	5035000
0.60	3252000	3936667	4425714	4792500	5077778	5306000
0.70	3794000	4388333	4812857	5131250	5378889	5577000
0.80	4336000	4840000	5200000	5470000	5680000	5848000
0.90	4878000	5291667	5587143	5808750	5981111	6119000
1.00	5420000	5743333	5974286	6147500	6282222	6390000



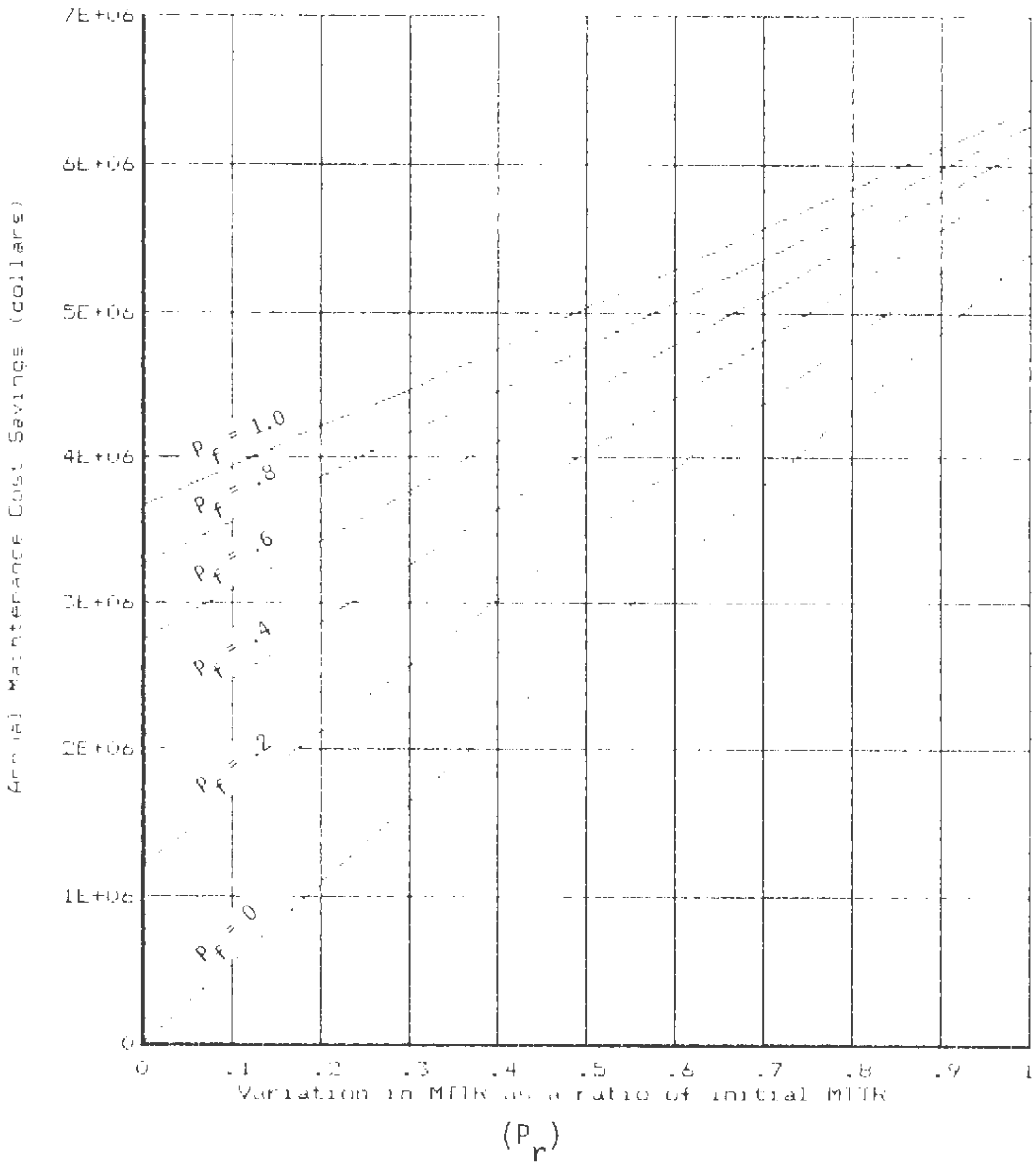
(P_f)

NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in mean time to repair}}{\text{initial mean time to repair}}$$

FIGURE 2-3: ANNUAL MAINTENANCE COST SAVINGS (FIXED MTTR)



NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in mean time to repair}}{\text{initial mean time to repair}}$$

FIGURE 2-4: ANNUAL MAINTENANCE COST SAVINGS (FIXED MTBF)

TABLE 2-5: ANNUALIZED CAPITAL COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME BETWEEN FAILURE

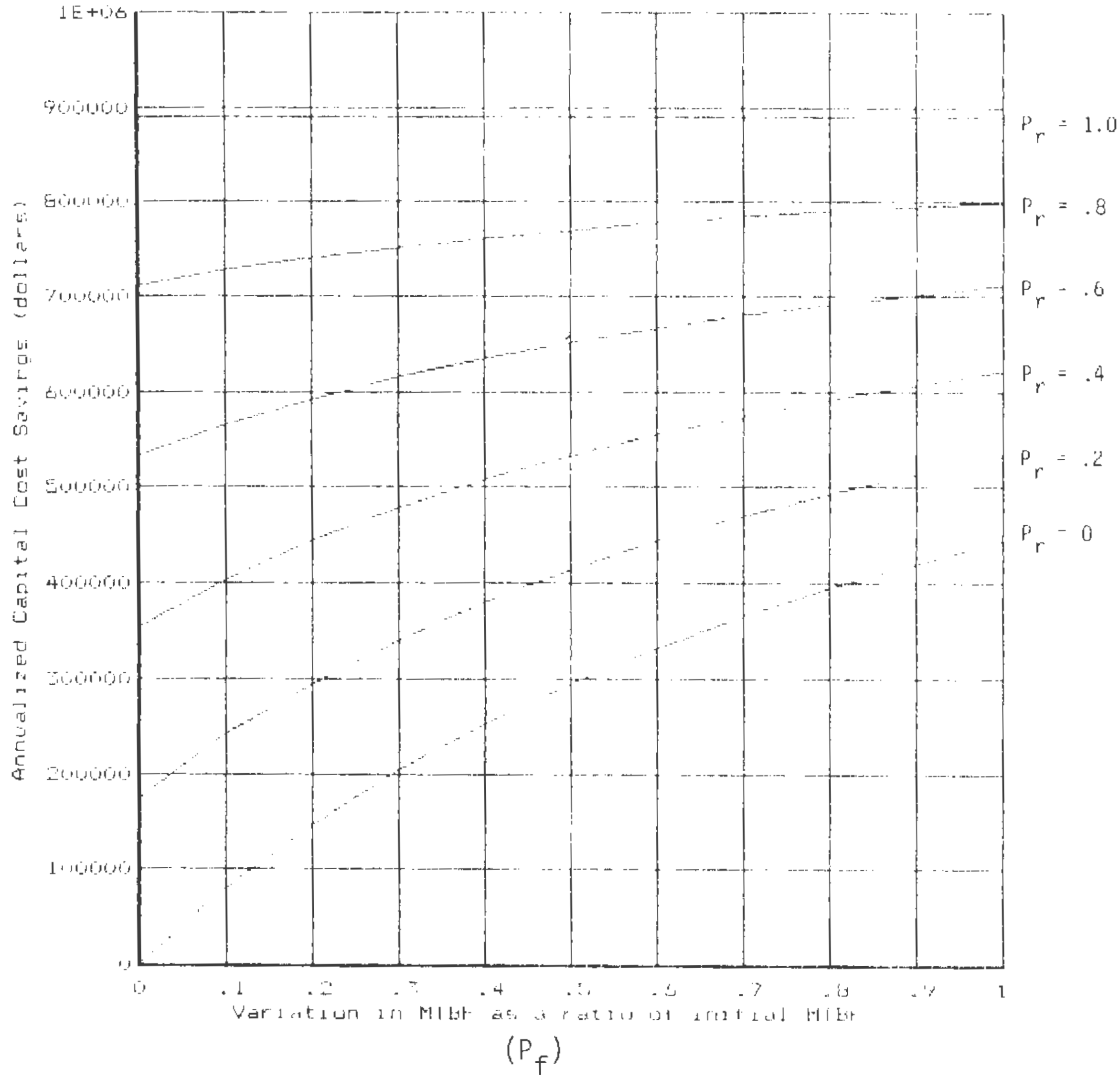
Annualized Capital Cost Savings (dollars)

Pf \ Pr	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0	178000	356000	534000	712000	890000
0.10	80909	242727	404545	566364	728182	890000
0.20	148333	296667	445000	593333	741667	890000
0.30	205385	342308	479231	616154	753077	890000
0.40	254286	381429	508571	635714	762857	890000
0.50	296667	415333	534000	652667	771333	890000
0.60	333750	445000	556250	667500	778750	890000
0.70	366471	471176	575882	680588	785294	890000
0.80	395556	494444	593333	692222	791111	890000
0.90	421579	515263	608947	702632	796316	890000
1.00	445000	534000	623000	712000	801000	890000

TABLE 2-6: ANNUALIZED CAPITAL COST SAVINGS FOR IMPROVEMENTS IN MEAN TIME TO RESTORE

Annualized Capital Cost Savings (dollars)

Pr \ Pf	0.00	0.20	0.40	0.60	0.80	1.00
0.00	0	148333	254286	333750	395556	445000
0.10	89000	222500	317857	389375	445000	489500
0.20	178000	296667	381429	445000	494444	534000
0.30	267000	370833	445000	500625	543889	578500
0.40	356000	445000	508571	556250	593333	623000
0.50	445000	519167	572143	611875	642778	667500
0.60	534000	593333	635714	667500	692222	712000
0.70	623000	667500	699286	723125	741667	756500
0.80	712000	741667	762857	778750	791111	801000
0.90	801000	815833	826429	834375	840556	845500
1.00	890000	890000	890000	890000	890000	890000

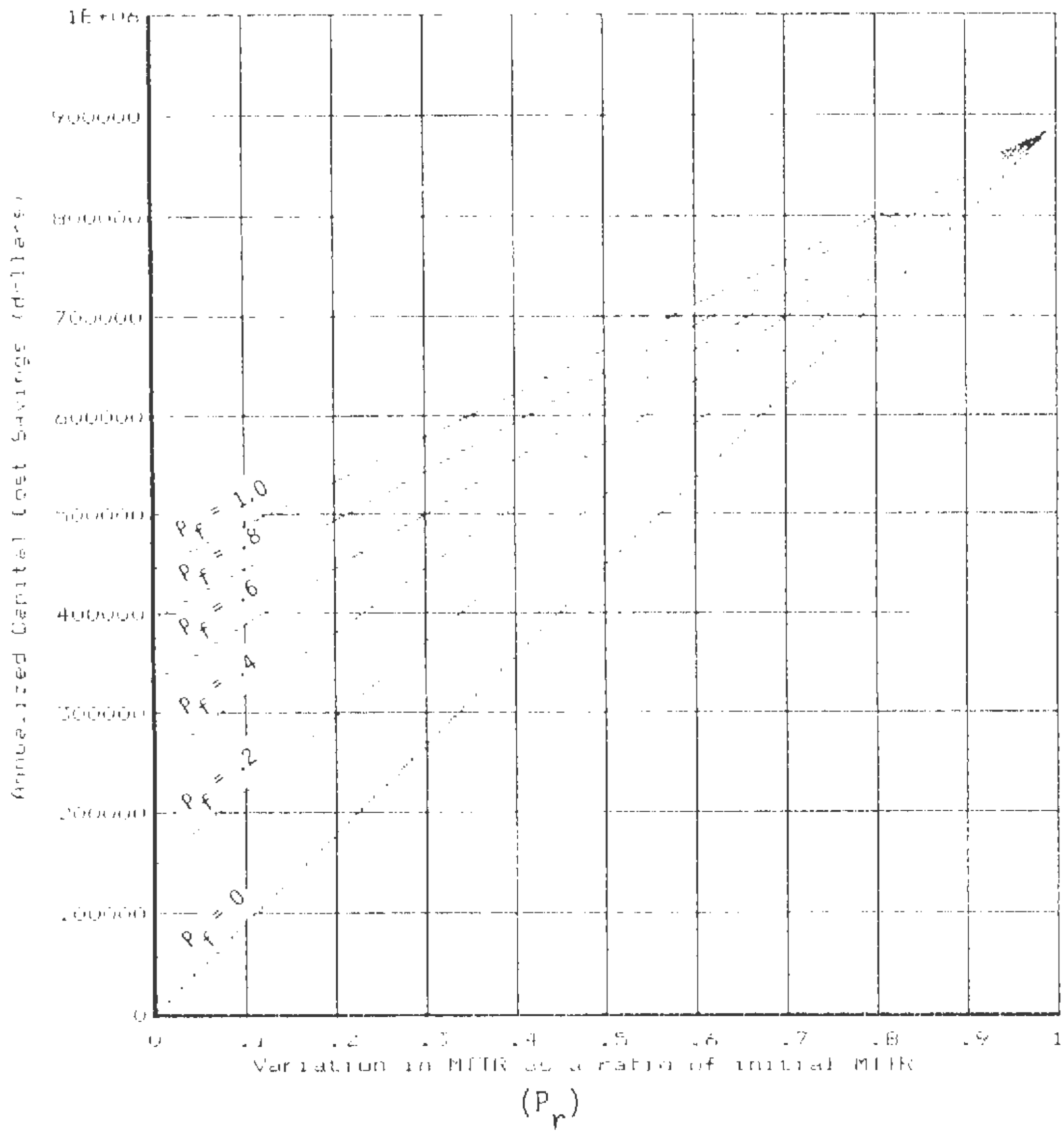


NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in MTTR}}{\text{initial MTTR}}$$

FIGURE 2-5: ANNUALIZED CAPITAL COST SAVINGS (FIXED MTTR)



NOTE:

$$P_f = \frac{\text{increase in MTBF}}{\text{initial MTBF}}$$

$$P_r = \frac{\text{reduction in MTTR}}{\text{initial MTTR}}$$

FIGURE 2-6: ANNUALIZED CAPITAL COST SAVINGS (FIXED MTBF)

2.2.4 Transit Facility Costs

Equipment performance also affects the sizes and costs of some transit facilities, including maintenance shops, yards, and storage areas. Generally, maintenance facilities are sized on the basis of the maximum percentage of cars that can be held out of service at anytime. This number of cars out of service, in turn, depends mostly on equipment reliability and maintainability. The cars held out of service consist of cars in storage and ready to be put in service, cars in the maintenance yard waiting to be repaired, and cars in the maintenance shop undergoing repair or service. By improving equipment performance the sizes of shops, yards, and storage areas can be reduced. The actual cost savings from facility size reduction may be estimated with a knowledge of the fleet size reduction realized, the effect of improvements on fleet failure rate, and the average cost per vehicle space for the respective facilities.

There are also interesting relationships between the sizes of various maintenance facilities. For instance, if the repair shop capacity is increased, this may result in a decrease in the yard capacity requirements and an increase in the "ready" car storage capacity. The relationships for the size of maintenance facilities are presented in Appendix C.

2.2.5 Transit Revenues

Improvements in transit performance may also have an effect on transit revenues. Improved equipment reliability may result in a higher level of service and, possibly, increased transit ridership. Increased ridership will, of course, generate increased revenues for the transit authority. However, because of the difficulty in predicting the actual effect of transit performance improvements on ridership, the subject of increased revenues was not addressed in this study.

2.3 STEP-BY-STEP PROCEDURE FOR CALIBRATING AND USING MODELS

This section presents a simplified step-by-step procedure for calibrating and using the estimating models developed in this report. A detailed calibration exercise using UMATA data is presented in Appendix B.

Operating Cost Savings

The operating cost savings model is given by

$$\Delta C_o = C_o \left(\frac{P_f + P_r}{1 + P_f}\right) \left\{\frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + \frac{n_1 (n_{c1} - n_o) R_c}{F_c}\right\} \tag{1}$$

With the exception of P_f and P_r, all parameters in the above expression can be determined for a given system and a given period under consideration. The procedure is as follows:

Step 1. Determine the operating cost, C_o, prior to initiation of any improvements.

Step 2. Obtain the average number of cars per train, n_o; average number of cars per line, n_{c1}; and number of lines affected by car failures, n_1.

Step 3. Obtain total number of service-related failures, n_{fs}, that occurred during period under investigation. Obtain the total on-line delay due to these service failures, D_1. Using the expression D_1/n_{fs}, determine the mean time to restore line service, R_1.

Step 4. Determine the total car-hours operated by the system during the period, H_o. Using the expression H_o/n_{fs}, compute the mean time between service failures, F_s.

Step 5. Based on the definitions of Case B and Case C failures, compute R_b and R_c, the mean times to restore service during Case B and

Case C failure scenarios respectively. If none of these types of failures occurred during the analysis period, ignore the relevant term in the cost savings expression. Similarly, compute F_b and F_c, if needed.

Step 6. Substitute the values of C_o, n_o, n_1, n_{c1}, R_1, F_s, R_b, F_b, R_c, and F_c in equation (1) to obtain the calibrated expression for operating cost savings in terms of the levels of improvement P_f and P_r. The resulting expression will be of the form

$$\Delta C_o = K_o \left(\frac{P_f + P_r}{1 + P_f} \right)$$

where K_o is a constant.

Step 7. To obtain the operating cost savings (dollars) for a desired level of improvement, substitute the values of P_f and P_r in the above equation. Note that P_f and P_r are the levels of improvement, where P_f represents the ratio of increase in MTBF to initial MTBF and P_r is the ratio of decrease in MTTR to initial MTTR.

Maintenance Cost Savings

Total corrective maintenance cost savings model is given by

$$\Delta C_{cm} = n_f \left\{ K_s R_s \left(\frac{P_f + P_{rs}}{1 + P_f} \right) + K_p \left(\frac{P_f}{1 + P_f} \right) \right\} \qquad (2)$$

Step 1. Estimate total "corrective maintenance infrastructure cost", C_{cm}, for a given period, say one year. This cost should include total personnel costs, related overhead, and any support activities associated with unscheduled maintenance.

Step 2. Determine the total repair time, D_s (for all incidents -- service and non-service related).

Step 3. Using the experssion C_{cm}/D_s, compute the corrective maintenance infrastructure cost constant, K_s.

Step 4. Obtain total number of failures, n_f (service and non-service) experienced during analysis period. Using the relationship D_s/n_f, compute the mean time to repair, R_s.

Step 5. Estimate the total cost of spare parts, C_{sp}, used during the period. Using C_{sp}/n_f, compute the spare parts constant, K_p.

Step 6. Substitute the values of n_f, K_s, R_s, and K_p in equation (2) to obtain the calibrated expression for maintenance cost savings in the form

$$\Delta C_{cm} = K_{ml} \left(\frac{P_f + P_{rs}}{1 + P_f} \right) + K_{mp} \left(\frac{P_f}{1 + P_f} \right)$$

where K_{ml} and K_{mp} are constants.

Step 7. To use the model, substitute the required level of improvement in MTBF, P_f, and the corresponding level of improvement in mean time to repair, P_{rs}; where P_f and P_{rs} are as defined above.

Fleet Capital Cost Savings

The annualized fleet capital cost savings is given by

$$\Delta E_c = \frac{C_v H_s}{h_s} (crf) \left\{ \frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + n_1 \left(n_{c1} - n_o \right) \frac{R_c}{F_c} + \frac{R_m}{F} \right\} \qquad (3)$$

Step 1. Obtain n_o, n_1, n_{c1}, R_1, F_s, R_b, F_b, R_c, and F_c as in Steps 2 through 5 of operating cost savings model.

Step 2. Obtain the cost per car, C_v; the hours scheduled per car, h_s; and the total car-hours scheduled, H_s, during the period under investigation.

Step 3. Assuming a given discount rate, i%, and vehicle service life, n years, look up the capital recovery factor from interest tables.

Step 4. Determine the total out-of-service delay components of all failures, D_m. This should include all retrieval time, shop and yard time (for service-related failures) and all shop and yard time (for non-service-related failures). Compute the mean time to restore, R_m from the relationship $R_m = D_m/n_f$, where n_f = total number of failures (service and non-service related).

Step 5. Using the expression, H_s/n_f, compute the mean time between failure (service and non-service related), F.

Step 6. Substitute the values of C_v, H_s, h_s, crf, n_o, n_1, n_{c1}, R_1, F_s, R_b, F_b, R_c, F_c, R_m, and F in equation (3) to obtain the calibrated expression for annual fleet capital cost savings in the form

$$\Delta E_c = K_c \left(\frac{P_f + P_r}{1 + P_f}\right)$$

where K_c is a constant.

Step 7. To use the model, substitute the desired values of P_f and P_r to obtain the annual fleet capital cost savings.

3. EXAMPLE APPLICATIONS OF THE MODELS

The various models for estimating potential cost savings that can be realized by improving fleet MTBF and MTTR were discussed in Section 2. In this section, three examples are presented to demonstrate some of the applications of the models.

3.1 COST SAVINGS FROM THE SUBSTITUTION OF AC PROPULSION FOR AN EXISTING DC PROPULSION SUBSYSTEM

In this example, the potential cost savings resulting from the introduction of an AC propulsion subsystem over an existing cam-controlled DC propulsion subsystem are estimated. The estimate results are then compared with separate estimates made in a study on AC inverter propulsion system costs.* The NYCTA R-44 rapid railcar is used for the cost modeling example. This is the same vehicle selected for use in demonstrating the AC propulsion system developed as part of the UMTA STARS program.

3.1.1 Data Base and Assumptions

The following presents the data base and assumptions used in this example. All data were obtained from the National Urban Mass Transportation Statistics, 1981 Section 15 Report, UMTA-MA-06-0107, November 1982, and the previously referenced UMTA STARS study.

- o Total number of cars in fleet: 6303
- o Number of R-44 cars: 352
- o Annual car-hours: 16,686,631
- o Annual car-miles: 256,688,930
- o Total annual operating expenses: $1,161,080,547
  (Rapid rail + apportioned joint motor bus expenses)
- o Percent operating expenses for vehicle maintenance: 18.1

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*Berger, K.W., "AC Inverter Propulsion System Operating Costs." Paper prepared as part of UMTA's Subsystem Technology Application to Rail System (STARS) program.

- Percent of operating expense for materials and services: 5.7
- Percent of vehicle maintenance attributable to propulsion subsystem = 30.7
- Average R-44 operating speed: 13.2 mph
- Estimated propulsion system MTBM (includes corrective and preventive maintenance)
  - R-44: 240 hours
  - AC: 385 hours
- Estimated propulsion system MTTM (includes corrective and preventive maintenance)
  - Shop time only
    - R-44: 12.6 hours
    - AC: 6.1 hours
  - Total clock time
    - R-44: 40.8 hours
    - AC: 40.9 hours

3.1.2 Maintenance Cost Savings

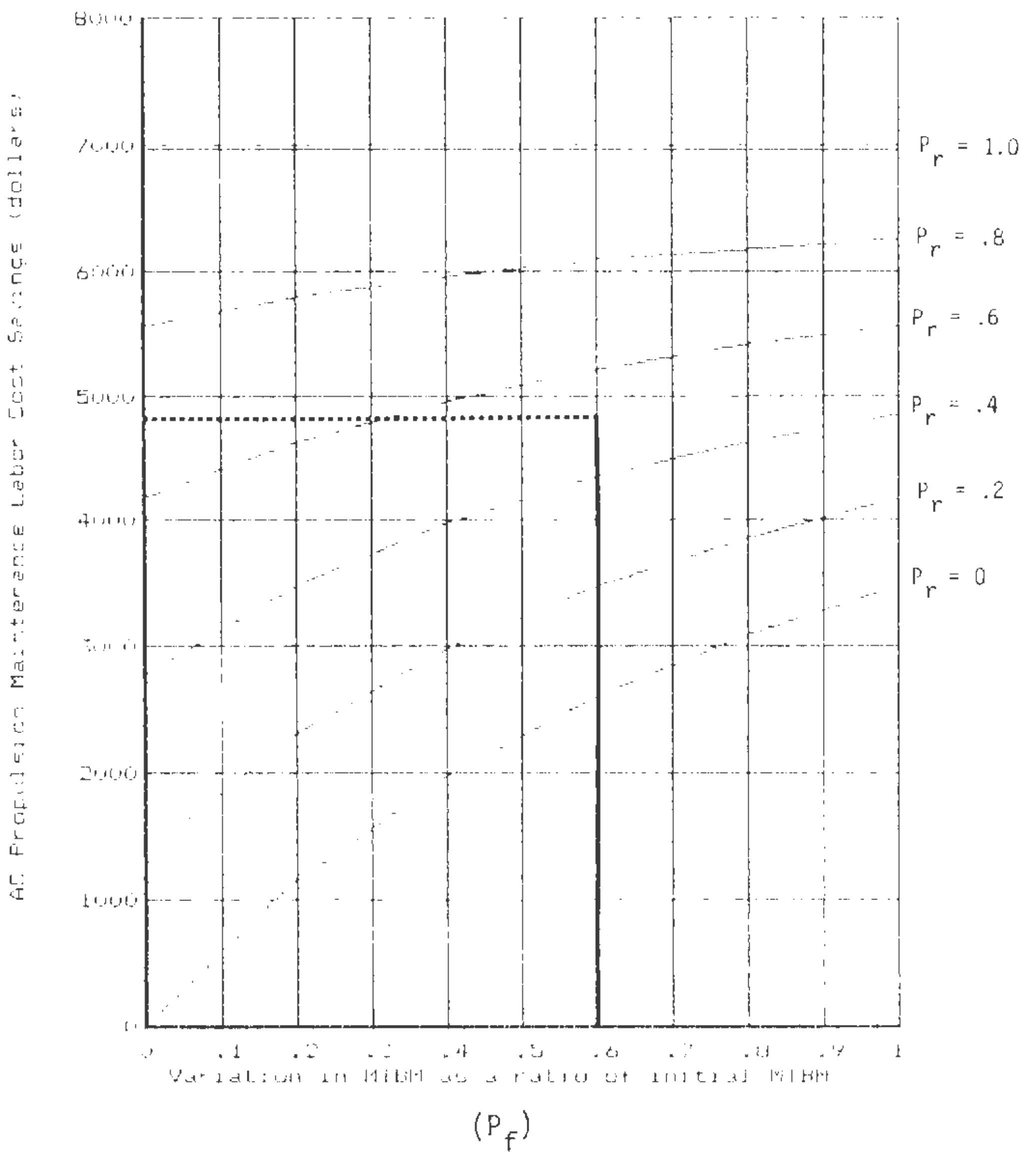
Applying the model to both corrective and preventive maintenance activities, the total savings in maintenance cost will be given by

$$\Delta C_m = n_f \left\{ K_s R_s \left(\frac{P_f + P_r}{1 + P_f} \right) + K_p \left(\frac{P_f}{1 + P_f} \right) \right\}$$

where the parameters now apply to all maintenance actions (preventive and corrective) during the period under investigation. Separating the labor and parts components and substituting the values of the parameters for the DC propulsion system, the savings in maintenance labor cost on a per car basis is given by

$$C_{ml} = 6962 \left(\frac{P_f + P_r}{1 + P_f} \right)$$

The above relationship is plotted in Figure 3-1 for various levels of



NOTE:

$$P_f = \frac{\text{increase in mean time between maintenance}}{\text{initial mean time between maintenance}}$$

$$P_r = \frac{\text{reduction in mean time to repair}}{\text{initial mean time to repair}}$$

FIGURE 3-1: MAINTENANCE LABOR COST SAVINGS

improvements in MTBF and MTTR. From these curves, it can be seen that for improvements of $P_f = 0.60$ and $P_r = 0.52$ which are obtained by substituting an AC propulsion subsystem in place of the DC subsystem, a maintenance labor cost savings of about $4900/car/year is achieved. The ratio of number of men per maintenance action for AC to that for DC propulsion subsystem is 0.92. Adjusting the cost savings obtained from the graph by this ratio, the effective maintenance labor cost savings becomes $4,500/car/year. Maintenance labor costs for DC propulsion subsystem is estimated at about $7,000/car/year. Hence the effective savings from using an AC propulsion subsystem is approximately 64 percent which compares with 67.2 percent savings estimated in the UMTA STARS Study.

Similarly the savings in maintenance parts costs is given by

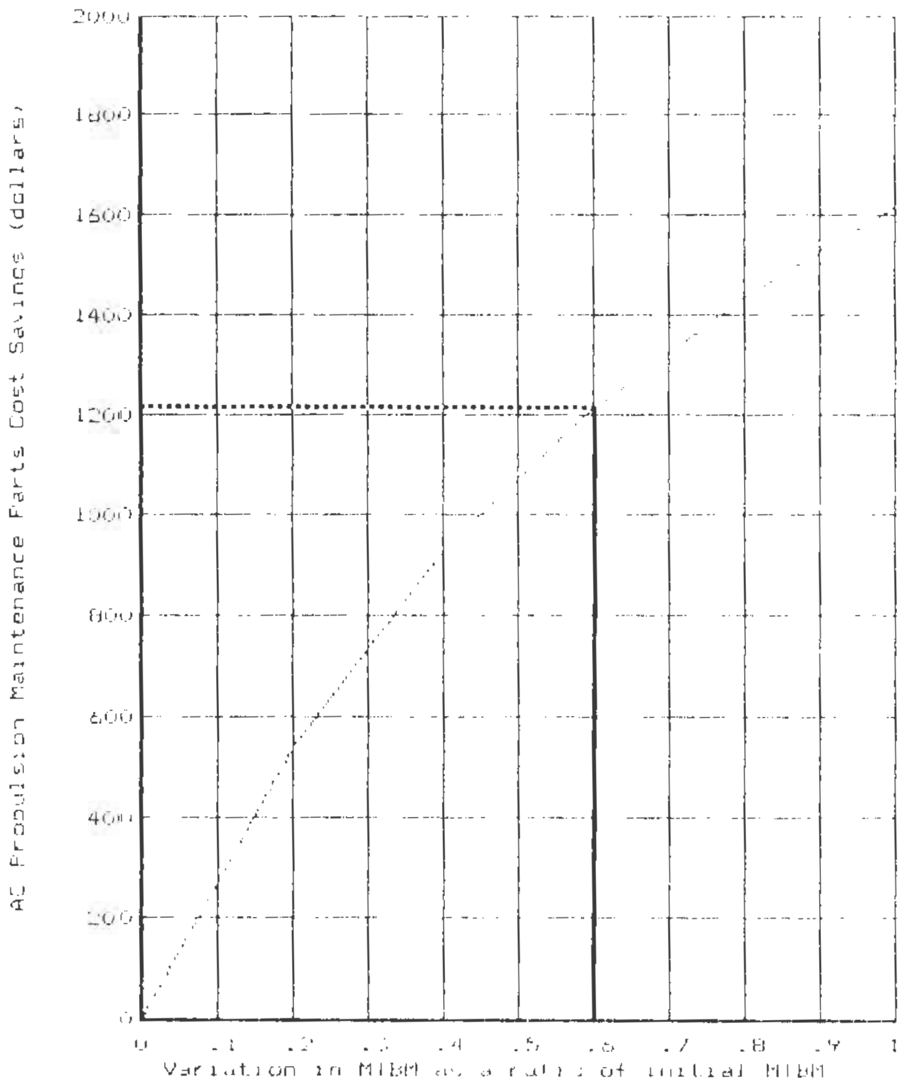
$$C_{mp} = 3232 \left(\frac{P_f}{1 + P_f} \right)$$

which is plotted in Figure 3-2 for various levels of MTBF improvements only since the relationship is independent of MTTR. For $P_f = 0.60$ obtained by using AC instead of DC propulsion subsystem, the savings in maintenance parts cost is about $1,220/car/year. Again, this is discounted by a factor of 0.75 to account for the fact that AC propulsion subsystem parts cost per maintenance action is higher than for the DC subsystem. Hence effective cost savings from using AC propulsion is about $900/car/year representing a 28 percent savings based on approximately $3,200/car/year estimated for maintenance parts for DC subsystem. This percent savings compares favorably with 22.7 percent savings cited in the UMTA STARS study.

3.1.3 Fleet Capital Cost Savings

The potential fleet cost savings resulting from the introduction of AC propulsion subsystem over cam controlled DC propulsion can be approximated as follows

$$\Delta C_v = \frac{R_{cam}}{F_{cam}} N_v C_v \left(\frac{P_f + P_r}{1 + P_f} \right)$$



(P_f)

NOTE:

$$P_f = \frac{\text{increase in mean time between maintenance}}{\text{initial mean time between maintenance}}$$

FIGURE 3-2: MAINTENANCE PARTS COST SAVINGS

where

R_{cam} = mean time to restore for DC propulsion (based on total clock time)

F_{cam} = mean time between maintenance for DC propulsion

N_v = fleet size (R-44 cars)

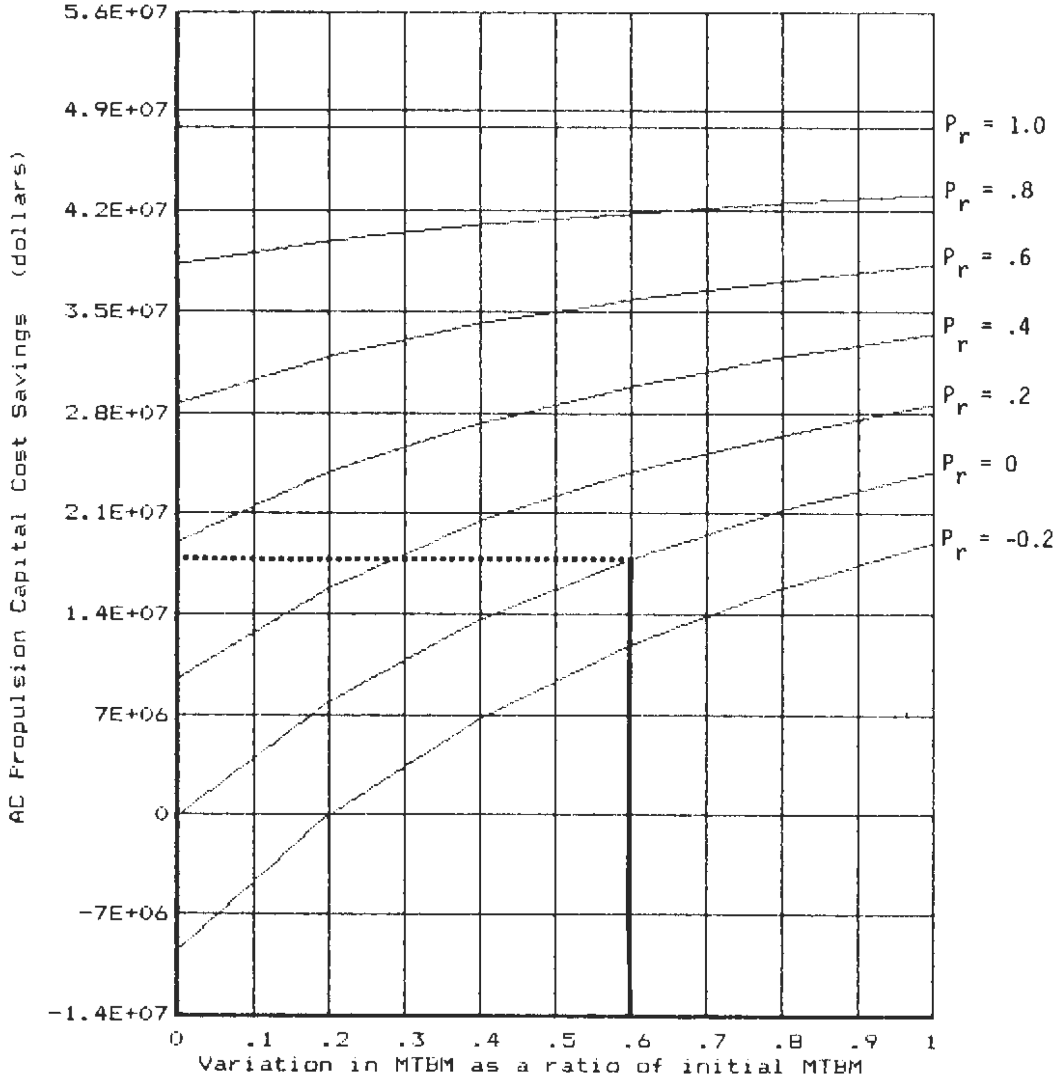
C_v = cost per car (assumed to be equal to $800,000)

P_f, P_r = improvements in MTBM and MTTR respectively

Substituting the values for the different parameters, the capital cost savings becomes

$$C_v = 47.9 \times 10^6 \left(\frac{P_f + P_r}{1 + P_f} \right)$$

This is plotted in Figure 3-3 for variations in P_f and P_r. For $P_f = 0.6$ and $P_r = -0.0025$ obtained by substituting AC for DC propulsion subsystem, the savings in capital cost amounts to about $17,888,000 or 22 cars. This represents approximately 6 percent of the total fleet size, which compares with an estimated savings in spare cars of 5.5 percent obtained in the UMTA STARS study. Note that in this case P_r is negative since total restore time is higher for AC than for DC propulsion systems.



(P_f)

NOTE:

$$P_f = \frac{\text{increase in mean time between maintenance}}{\text{initial mean time between maintenance}}$$

$$P_r = \frac{\text{reduction in mean time to restore}}{\text{initial mean time to restore}}$$

FIGURE 3-3: FLEET CAPITAL COST SAVINGS

3.2 COST SAVINGS FROM AIR COMFORT SYSTEM IMPROVEMENTS

This second example estimates the potential maintenance and capital cost savings that may be realized by improving the MTBF and MTTR of air comfort systems. The results from this model are compared with estimates of cost savings obtained by using a different more detailed estimating approach that was carried out in another study.*

3.2.1 Data Base and Assumptions

The data items of primary interest follow:

- o average daily operating fleet: 148
- o annual A/C repair labor hours per car: 41
- o A/C maintenance actions constitute 6.8 percent of total vehicle maintenance.

All data items are obtained from the report cited above.

3.2.2 Maintenance Cost Savings

The model is assumed to be true for both preventive and corrective maintenance. Only maintenance labor cost savings obtained from the model are compared with estimates from the Air Comfort System Study. The equation for this labor cost savings component is

$$\Delta C_m = N_f K_s R_s \left(\frac{P_f + P_r}{1 + P_f} \right)$$

Noting that 6.8 percent of all maintenance actions are attributable to air-condition malfunction, the resulting equation becomes

$$\Delta C_m = 369{,}000 \left(\frac{P_f + P_r}{1 + P_f} \right)$$

---

* N.D. Lea & Associates, Inc., "Task 2b Technical Report-Estimation of Costs and Benefits of Transit Railcar Air Comfort System Improvements."

Figure 3-4 compares results obtained from the above relationship and estimates made in the Air Comfort System Study. In general, results from the model are higher than those estimated in the Air Comfort System Study. Better correlation between the two results is obtained as both P_f and P_r increase.

3.2.3 Capital Cost Savings

The annual capital cost savings from A/C improvements is given by

$$\Delta E_{ac} = \frac{C_v H_s R_a}{h_s F_a} \; (crf) \left(\frac{P_f + P_r}{1 + P_f} \right)$$

where R_a, F_a are the MTTR and MTBF for the air comfort system. Substituting the values for the parameters, the resulting equation is

$$\Delta E_{ac} = 5.47 \times 10^4 \left(\frac{P_f + P_r}{1 + P_f} \right)$$

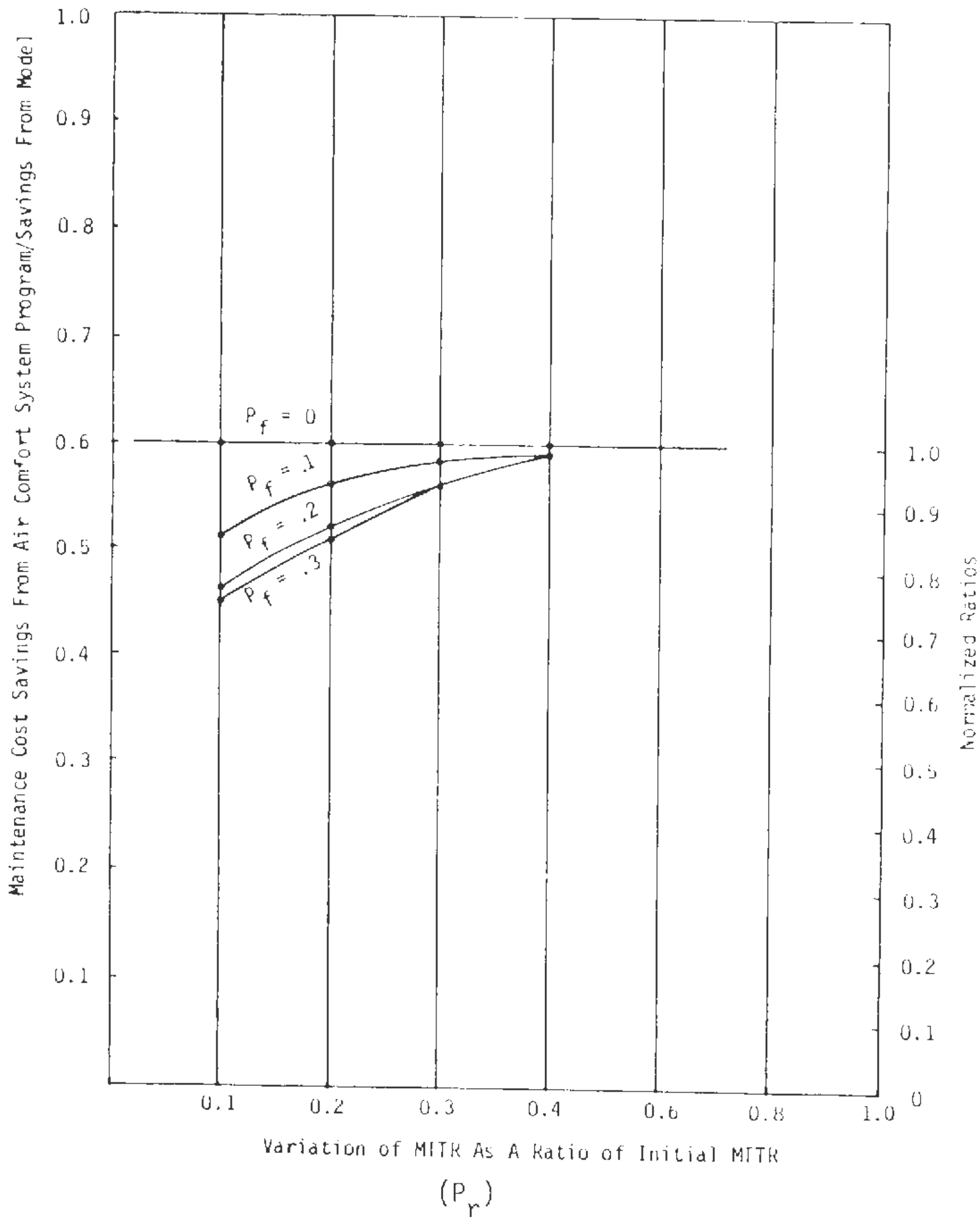
The results from the model are compared with results from the Air Comfort System Study in Figure 3-5. In this case also, the results from the model are higher than that from the Air Comfort System Study.

3.2.4 Discussion of Results

The following observations can be made in connection with the results obtained in this example:

- Because the model overestimates cost savings from system improvements, it is conservative as a first estimating tool since the results point toward improvement projects with good potential for cost savings.

- The detailed estimate in the Air Comfort System Program Study is conservative if it underestimates the savings, since it becomes a part of the justification for a development program.

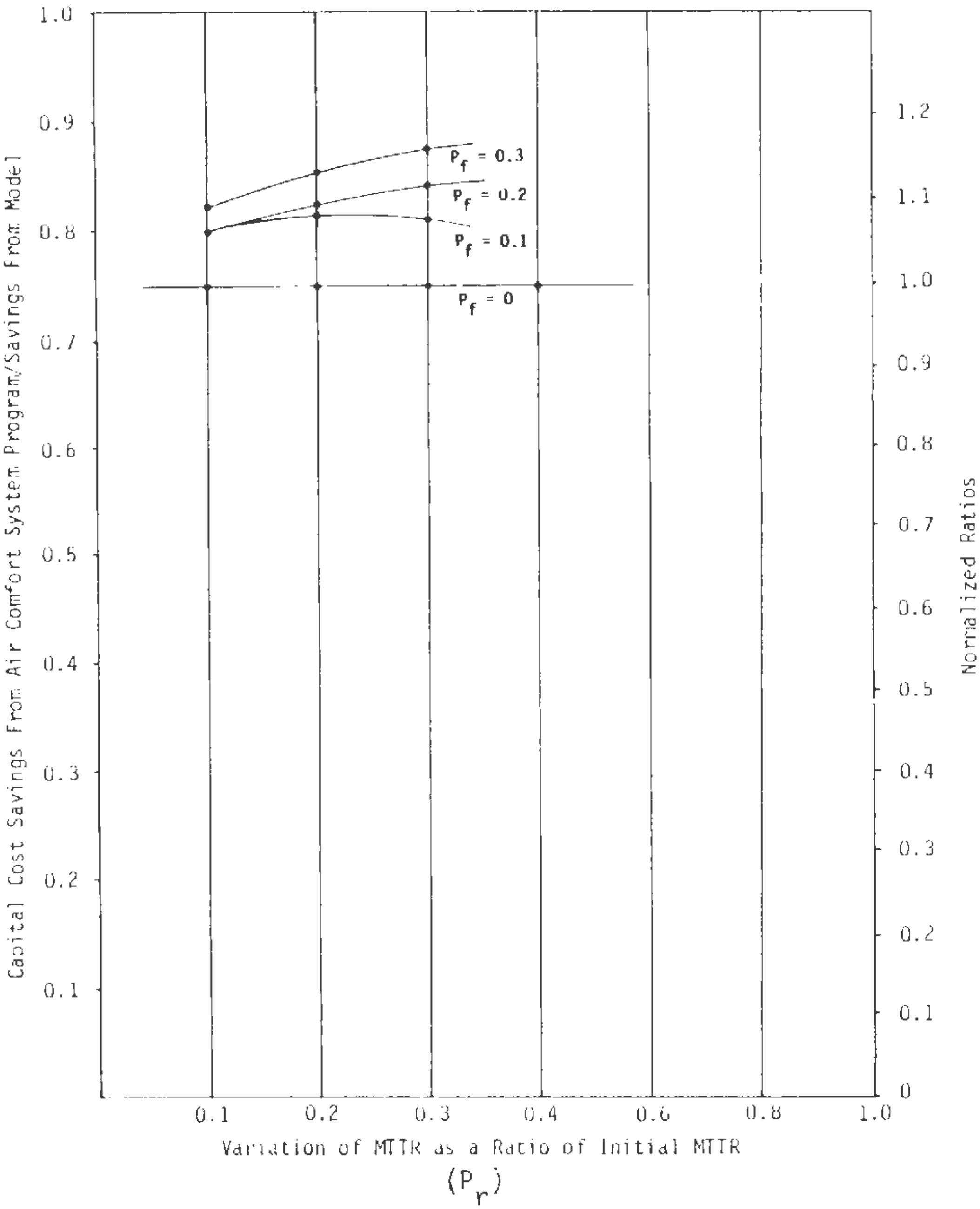


NOTE:

$$P_f = \frac{\text{increase in mean time between maintenance}}{\text{initial mean time between maintenance}}$$

$$P_r = \frac{\text{reduction in mean time to restore}}{\text{initial mean time to restore}}$$

FIGURE 3-4: COMPARISON OF MAINTENANCE COST SAVINGS OBTAINED FROM MODEL AND FROM AIR COMFORT SYSTEM PROGRAM



NOTE:

$$P_f = \frac{\text{increase in mean time between maintenance}}{\text{initial mean time between maintenance}}$$

$$P_r = \frac{\text{reduction in mean time to restore}}{\text{initial mean time to restore}}$$

FIGURE 3-5: COMPARISON OF CAPITAL COST SAVINGS OBTAINED FROM MODEL AND FROM AIR COMFORT SYSTEM PROGRAM

- The labor cost factor for the model is less than that from the Air Comfort System Study. This difference results because the study developed labor costs on a per man-hour basis, whereas, the model uses the labor portion of car maintenance costs.

The ratio of the cost savings from the two estimating methods can be normalized on the basis of the actual ratio for $P_f = 0$. These normalized scales are shown on the right vertical axis of Figures 3-4 and 3-5 for maintenance and capital cost savings respectively. It may be observed that the maintenance cost savings ratio between the two estimating procedures remains within 25 percent for $0 < P_f < 0.3$, whereas the ratio of capital cost savings remains within 20 percent, for $0 < P_f < 0.3$.

3.3 LIFE CYCLE COST COMPARISON FOR MAKING DECISIONS TO REBUILD OR BUY NEW CARS

Transit authorities are often faced with the problem of deciding between a purchase of new cars or rebuilding existing cars. The following example illustrates how the models can be used as part of a life cycle cost analysis to assist in making such decisions. The process involves the comparison of the potential net benefits that can be realized by extending the life and improving the performance of an existing car against the net benefits from buying new and possibly more reliable equipment.

3.3.1 Adaptation of the Models

Consider a set of existing cars whose mean time between maintenance (MTBM), and mean time to maintain (MTTM) are known and have degraded due to age and wear or neglect. A decision must be made to either replace or rebuild the cars so that acceptable performance in MTBM and MTTM is returned. The maintenance costs, MTBM, MTTM and MTTR for the current state of the cars is used to generate the general models for maintenance and capital cost savings noting that both preventive and corrective maintenance costs are included.

Reformatting Eq. (A-30) from Appendix A, one obtains the following model for total maintenance cost savings.

$$\Delta C_m = \frac{H_o}{L} \left\{ K_s M \left(\frac{P_f + P_m}{1 + P_f} \right) + K_p \left(\frac{P_f}{1 + P_f} \right) \right\}$$

where ΔC_m = maintenance cost savings in dollars

H_o = car-hours operated by the fleet in question

L = MTBM per car in hours

K_s = Maintenance Infrastructure Cost (MIC) Factor in dollars per car-hour of maintenance

M = MTTM per car in hours

P_f = change in L per L; $P_f > 0$

P_m = change in M per M; $0 \leq P_m < 1$
K_p = parts cost factor

Replacing R_m/F in Eq. (A-37, p. 61) by R_m/L to account for all maintenance actions, ΔC_v can be simplified because the factor R_m/L dominates the expression. The mean time to restore a car to service condition (R_m = MTTR) includes all storage and repair time and is much greater than the delays in service. Also the mean time between maintenance (L = MTBM) is usually less than one half the mean time between all classes of failures in service. Therefore, the expression for the number of cars saved (Eq. (A-31)) is simplified as follows:

$$\Delta N_c = N_o \left(\frac{P_f + P_r}{1 + P_f} \right) \frac{R_m}{L}$$

where

ΔN_c = Number of spare cars saved
N_o = Average number of the cars required for service over the operating days $= \frac{H_s}{h_s}$
P_r = change in R_m per R_m; $0 \leq P_r < 1$
R_m = MTTR in hours for current condition

The main differences to be compared between rebuilding or purchasing new cars are the life cycle costs. The annual operating costs and the performance, except MTBF and MTTM, are assumed to be the same for both options. The life cycle cost is then expressed as:

$$C = C_v(N_c - \Delta N_c) + (C_m - \Delta C_m) \text{ pwf} + C_j$$

where

C = life cycle cost
C_v = capital cost per car to rebuild or buy new
N_c = total current number of cars under consideration, including spares
ΔN_c = number of cars to be saved
pwf = present worth factor for interest i percent and expected lifetime of n years

C_m = current annual cost to maintain fleet in question

ΔC_m = savings in maintenance cost due to improvements in reliability and maintainability

C_j = present value of any other important costs

3.3.2 Data Base and Assumptions

A hypothetical example has been developed based upon data from two transit authorities to illustrate the comparison. The assumptions are as follows:

a. Current Status

N_c = 40 cars, each 25 years old

L = 3000 miles between maintenance at average of 20 mph. This translates to 150 hours for current condition

M = 8 hours

R_m = 24 hours

H_o = 130,000 hours

N_o = 20 cars

C_m = \$75,000 per car; \$3,000,000 total

K_s = \$325/car-hour of maintenance

K_p = \$865/maintenance incident

b. Rebuilding Cars

The cars are assumed to be rebuilt to a condition where reliability is doubled and remains constant for 10 years. In the 11th and 12th year reliability is assumed to again degrade to the current condition. This is essentially the same as restoring reliability to what it was during the prime life of the cars followed by a slow decline back to the current conditon in 10 years. Since subsystems are not being replaced the MTTM and MTTR are assumed constant.

$P_f = 1$, i.e., L after rebuilding = 6,000 miles or 300 hours
$P_m = 0$
$P_r = 0$
Assume C_v = \$400,000/car
Life of Rebuilt = 10 years
Salvage value of unrebuilt car = \$10,000

c. New Cars

After initial burn-in the new cars are assumed to be more reliable and maintainable than the rebuilt cars because of attention to this issue during the procurement. Two major overhauls are assumed, at 10 and 20 years, for the reliability to remain constant over the car's 30 year lifetime.

$P_f = 2$, i.e., L for new car = 9,000 miles or 450 hours
$P_m = 0.25$, i.e., M for new car = 6 hours
$P_r = 0.083$, i.e., R_m for new car = 22 hours
C_v = \$950,000/car
Life = 30 years, with major overhauls at 10th and 20th years
Cost of Major Overhaul = \$200,000

3.3.3 Application of Models to Evaluate Two Alternatives

For comparison, two alternatives are assumed. Alternative A assumes that new cars are purchased and then subjected to major overhauls after 10 and 20 years of service. Alternative B assumes the rebuilt cars are used only for 10 years and then replaced with the same new cars as Alternative A, with major overhaul of the new cars after 10 years of service. The total comparison is then made for a 30-year period so that Alternative B is credited with 10 years of the remaining value of the 20-year-old new cars. Salvage values for the 10-year-old rebuilt cars are included. However, the present worth of the salvage value when new cars are 30 years old is negligible. Present worth factors assume no inflation and a 10% discount rate per the OMB.

Alternative A: New Cars

Savings in total maintenance costs are calculated to be

$$\Delta C_{ma} = 2.25 \times 10^6 \left(\frac{2 + 0.25}{1 + 2}\right) + 0.75 \times 10^6 \left(\frac{2}{1 + 2}\right)$$
$$= \$2,187,500$$

Also, number of cars saved

$$\Delta\ N_{ca} = 20 \left(\frac{2 + 0.083}{1 + 2}\right) \left(\frac{24}{150}\right)$$

$$= 2.22 \text{ or } 2 \text{ cars}$$

The old cars are assumed to be sold for their salvage value and this amount credited against the purchase of the new fleet. The life cycle cost for Alternative A is as follows.

$$C_A = \underbrace{0.95 \times 10^6\ (40-2)}_{\text{Initial cost of new fleet}} + \underbrace{(3.0-2.19)10^6(9.43)}_{\text{Present value of 30 years of maintenance}} + \underbrace{0.2 \times 10^6(0.386+0.149)}_{\text{Present value of 2 overhauls, one at 10 years and one at 20 years.}}$$

$$\ldots \underbrace{-\ 0.01 \times 10^6\ (40)}_{\text{salvage value of old fleet}}$$

$$C_A = 36.10 \times 10^6 + 7.64 \times 10^6 + 0.11 \times 10^6 - 0.40 \times 10^6$$

$$C_A = \$43,450,000$$

Alternative B: Rebuilding and Postponing the New Purchase

Savings in maintenance cost and spare vehicles are calculated to be

$$\Delta C_{mb} = 2.25 \times 10^6 \left(\frac{1 + 0}{1 + 1}\right) + 0.75 \left(\frac{1}{1 + 1}\right)$$

$$= \$1,500,000$$

$$\Delta N_{cb} = 20 \left(\frac{1 + 0}{1 + 1}\right) \left(\frac{24}{150}\right)$$

$$= 1.6 \text{ or } 1 \text{ car}$$

The life cycle cost for Alternative B is as follows:

$$C_B = \underbrace{0.4 \times 10^6 \ (40-1)}_{\substack{\text{Initial cost to} \\ \text{rebuild fleet}}} + \underbrace{(3.0-1.5) \ 10^6 \ (6.14)}_{\substack{\text{Present value of 10 years of maintenance} \\ \text{for rebuilt cars}}}$$

$$\underbrace{+ \ 0.95 \times 10^6 \ (40-2) \ (0.386)}_{\substack{\text{Present value of buying} \\ \text{new fleet in 10 years}}} + \underbrace{(3.0-2.19) \times 10^6 \ (8.51)(0.386)}_{\substack{\text{Present value of maintenance of} \\ \text{new cars over years 10 through 30.}}}$$

$$\underbrace{+ \ 0.2 \times 10^6 \ (0.149)}_{\substack{\text{Present value of} \\ \text{overhauling new} \\ \text{cars at year 20}}} - \underbrace{\frac{0.95}{3} \ 10^6 \ (40-2)(0.0573)}_{\substack{\text{Present value of remaining} \\ \text{life of 20 year old new cars} \\ \text{at year 30}}}$$

$$\underbrace{- \ 0.01 \times 10^6}_{\substack{\text{Salvage value} \\ \text{of one car} \\ \text{not rebuilt}}} - \underbrace{0.01 \times 10^6 \ (40-1)(0.386)}_{\substack{\text{Present worth of the salvage value} \\ \text{of the rebuilt cars after 10 years}}}$$

$$C_B = 15.6 \times 10^6 + 9.21 \times 10^6 + 13.93 \times 10^6 + 2.66 \times 10^6$$

$$\ldots + 0.03 \times 10^6 - 0.69 \times 10^6 - 0.01 \times 10^6 - 0.15 \times 10^6$$

$$C_B = \$40{,}580{,}000$$

For the above example the difference between Alternatives A and B is \$2,870,000 which is 7% of the cost for Alternative B and probably less than the accuracy of the model. Therefore, one could conclude that the choice between buying new or rebuilding should be made on the basis of additional considerations. However, the difference is highly sensitive to the discount factor that was used. For an interest rate of 10% and annual inflation of 6%, the net time value of money would be 4%. Applying a 4% discount factor produces significantly different results, almost doubling the present value of future costs as follows:

<u>Alternative A (Discount Factor = 4%): Buying New Cars</u>

$$C_A = 0.95 \times 10^6\ (40-2) + (3.0-2.19)10^6(17.29) + 0.2 \times 10^6\ (0.676+0.456)$$
$$- 0.40 \times 10^6$$

$$C_A = 36.1 \times 10^6 + 14.00 \times 10^6 + 0.23 \times 10^6 - 0.40 \times 10^6$$

$$C_A = \$49{,}930{,}000$$

<u>Alternative B (Discount Factor = 4%): Rebuilding Old Cars First</u>

$$C_B = 0.4 \times 10^6(40-1) + (3.0-1.5)10^6(8.11) + 0.95 \times 10^6(40-2)(0.676)$$
$$+ (3.0-2.19)10^6(13.59)(0.676) + 0.2 \times 10^6(0.456)$$
$$- \frac{0.95}{3}\ 10^6(40-2)(0.308) - 0.01 \times 10^6 - 0.01 \times 10^6(40-1)(0.676)$$

$$C_B = 15.60 \times 10^6 + 12.17 \times 10^6 + 24.40 \times 10^6 + 7.44 \times 10^6$$
$$+ 0.09 \times 10^6 - 3.71 \times 10^6 - 0.01 \times 10^6 - 0.26 \times 10^6$$

$$C_B = \$55{,}720{,}000$$

One can observe that a difference of nearly $6 million results in favor of Alternative A, buying new cars, if the net time value of money is 4%. The differences in the life cycle costs are also sensitive to the relative differences in reliability and maintainability between rebuilt and new cars. Table 3-1 gives these differences for three discount rates (10%, 4% and 2%) for two cases where reliability/maintainability of rebuilt cars is less than for new cars and also for reliability/maintainability of rebuilt cars equal to new cars. Figure 3-6 plots the data from Table 3-1. The horizontal scale shows the time value of money which represents the net effect of discount rate and the prevailing rate of inflation. The vertical scale shows the life cycle cost savings from either alternative.

The "performance ratio", R, is defined as

$$\frac{q_f + q_m}{1 + q_f}$$

where $q_f = \dfrac{\text{improvement in reliability of new car over rebuilt car}}{\text{reliability of rebuilt car}}$

$q_m = \dfrac{\text{improvement in maintainability of new car over rebuilt car}}{\text{maintainability of rebuilt car}}$

Two values of performance ratios are indicated: R = 0 represents a case where the reliability/maintainability of both the new and rebuilt cars are the same; R = 0.5 is where the relative reliability of the new car is assumed to be 50% better than for rebuilt and maintainability of the new car is 25% better than for rebuilt car.

The plot shows the boundary where there is no difference in life cycle costs between Alternatives A and B as a function of the discount rate and ratio of the differences in performance. In this example the region above the boundary is where the life cycle costs favor the option to buy new cars. In the region below the boundary the life cycle costs for rebuilding the cars are less.

TABLE 3-1
LIFE CYCLE COSTS OF TWO ALTERNATIVES:
BUYING NEW CARS VS. REBUILDING CARS FIRST
AND POSTPONING NEW CAR PURCHASE FOR 10 YEARS

Discount Rate	Relative Reliability & Maintainability	Alternative A Buy New Cars Now	Alternative B Rebuild then Buy New Cars	In Favor of Choice
10%	NEW > REBUILT*	$43,450,000	$40,580,000	$ 2,870,000 B
	NEW EQUAL TO REBUILT	$43,450,000	$35,950,000	$ 7,500,000 B
4%	NEW > REBUILT*	$49,930,000	$55,720,000	$ 5,790,000 A
	NEW EQUAL TO REBUILT	$49,930,000	$49,730,000	$ 200,000 B or NIL
2%	NEW > REBUILT*	$54,040,000	$62,830,000	$ 8,790,000 A
	NEW EQUAL TO REBUILT	$54,040,000	$56,240,000	$ 2,200,000 A

* Reliability for new cars is assumed to be 50% better than for rebuilt cars; maintainability of new cars is assumed to be 25% better than for rebuilt cars.

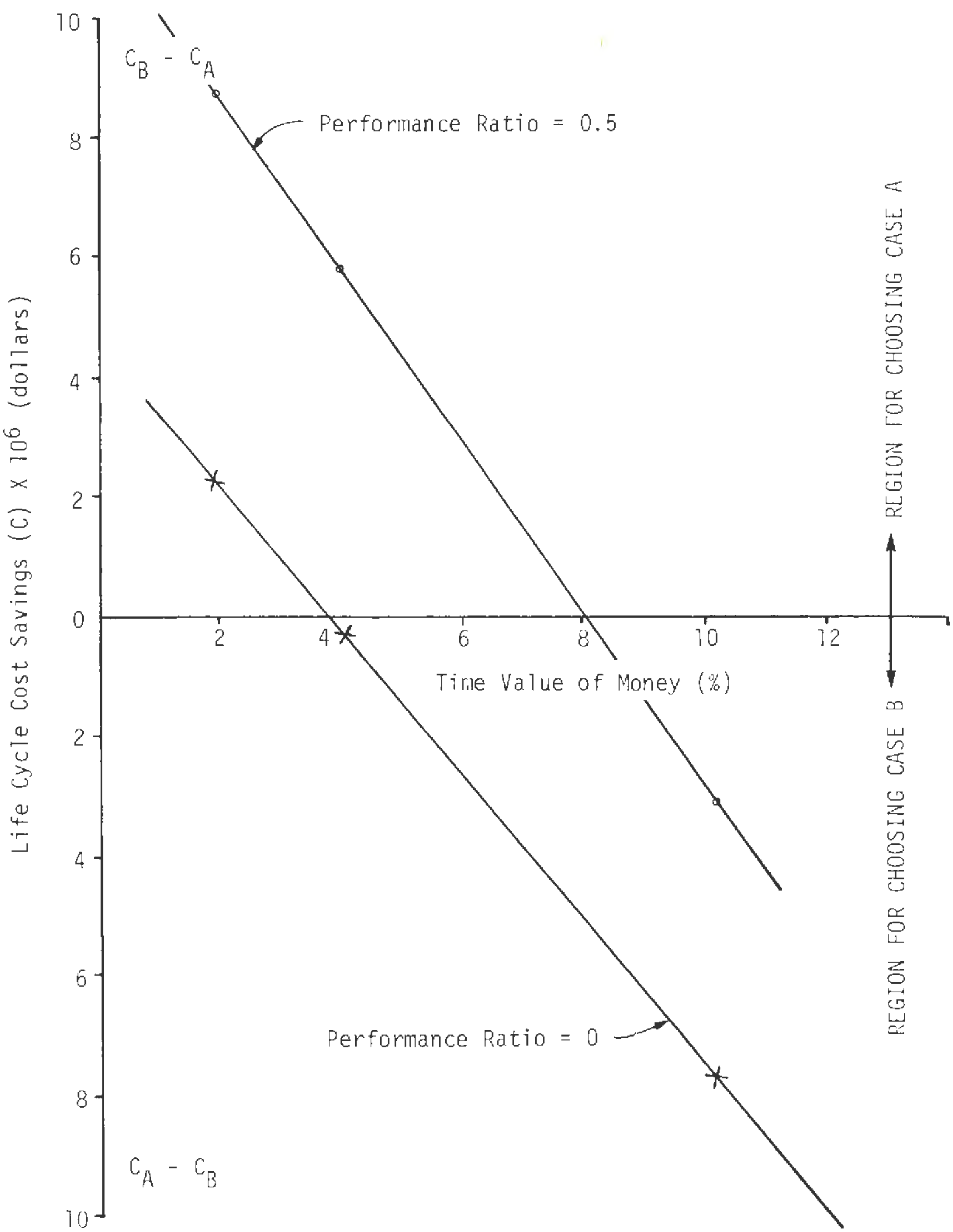


FIGURE 3-6: LIFE CYCLE COST BOUNDARY BETWEEN EXAMPLE ALTERNATIVES

The graphical presentation of Figure 3-6 can be very useful to provide insight regarding the differences in life cycle costs. Data regarding current reliability and maintainability, O&M costs, new car costs and rebuild costs can be determined to reasonable accuracy for the specific case under consideration. This leaves the greatest uncertainty in regard to the future time value of money and relative reliability and maintainability of the two cases.

In general, two major conclusions can be drawn from Figure 3-6.

- o As the reliability/maintainability of rebuilt cars becomes worse than that for new cars ($R > 0$), then the time value of money must decrease to favor the choice to buy new cars.

- o As the reliability/maintainability of rebuilt cars approach that for new cars, then the time value of money must increase to favor rebuilding cars.

Again, it should be pointed out that the foregoing is a hypothetical example. Therefore, the above conclusions cannot be interpreted to apply to such decisions in general. Since the data of the example were taken from an existing rail transit system, the results imply that the methodology provides important insight regarding the cost effectiveness of rebuilding vs. buying new cars.

APPENDICES

APPENDIX A

A. DEVELOPMENT OF MODELS

The development of the various cost savings models is presented in this appendix. These estimating models have been generated so that they are applicable to any rail transit operation.

A.1 OPERATING COST MODEL

Three possible scenarios of failure that can result in equipment downtime were identified in Section 2.1. The classification of these service failures was made on the basis of the effect that the resulting delay may have on system operation. In general, system unavailability due to these failures can be minimized by providing spare vehicles to compensate for car downtime. The operating cost model estimates the potential cost savings that can be realized by reducing car-hours lost before restoration of line service. Only service-related failures are, therefore, considered in developing this model. It is assumed that delays in excess of the operating headway would result in Case C scenario. In addition, during Case C failures, all trains upstream of the failed train are assumed to experience delay equal to the difference between the on-line delay of the failed train and the operating headway.

For any period under consideration, lost car-hours may consist of

- o car-hours lost due to failed cars and other cars within trains that contain the failed cars;
- o car-hours lost by locking out cars during Case B failures; and
- o car-hours lost by following trains when Case C failures occur.

Consider the definition of fleet availability,

$$A_f = \frac{F_s}{F_s + R_l} \tag{A1}$$

Where F_s = mean time between service failures = $\frac{H_o}{n_{fs}}$ (A2)

R_1 = mean time to restore line service = $\frac{D_1}{n_{fs}}$ (A3)

and H_o = car-hours operated by fleet prior to any improvement

n_{fs} = total number of service failures experienced by fleet during a specified period

D_1 = total line delay due to all service failures

$$= \sum (D_a + D_b + D_c) \tag{A4}$$

The subscripts a, b, c, denote types A, B, or C failures, respectively.

Fleet unavailability, $\bar{A}_f = 1 - A_f$

$$= \frac{R_1}{F_s + R_1} \tag{A5}$$

If H_s = car-hours scheduled for fleet,

Car-hours lost from failed cars, $h_f' = H_s \left(\frac{R_1}{F_s + R_1} \right)$ (A6)

Hence car-hours lost from failed cars and other cars in failed trains is given by

$$h_f = n_o H_s \left(\frac{R_1}{F_s + R_1} \right) \tag{A7}$$

Consider the car-hours lost from locked-out cars as a result of Case B failures;

$$\text{Unavailability of locked-out cars, } \bar{A}_k = \frac{R_b}{F_s + R_b} \tag{A8}$$

where R_b = MTTR for Case B failures

$$= \frac{\sum t_l}{n_{fb}} \tag{A9}$$

t_l = time car is locked-out while it remains in train on-line

n_{fb} = number of Case B failures experienced during period under consideration.

F_b = mean time between Case B failures

$$= \frac{H_o}{n_{fb}} \tag{A10}$$

Hence car-hours lost from locked-out cars,

$$h_k = H_s \left(\frac{R_b}{F_b + R_b} \right) \tag{A11}$$

Finally, car-hours lost from following trains as a result of Case C failures is given by

$$h_u = n_l \, (n_{cl} - n_o) \left(\frac{R_c}{F_c + R_c} \right) H_s \tag{A12}$$

where R_c = mean delay for following trains during Case C failures

$$= \frac{\sum \left(D_c - H_{min} \right)}{n_{fc}} \tag{A13}$$

D_c = on-line delay per failure due to Case C failures

H_{min} = Minimum operating headway at the time Case C failure occurs. It is assumed that each train upstream of a failed train experiences the same amount of delay.

n_{fc} = number of Case C failures

n_1 = number of lines affected by failures

n_{c1} = average number of cars per line

n_o = average number of cars per train

$$F_c = \frac{H_o}{n_{fc}} \tag{A14}$$

= mean time between Case C failures

Total car-hours lost prior to any improvements is therefore given by

$$h_1 = h_f + h_k + h_u \tag{A15}$$

$$= n_o H_s \left(\frac{R_1}{F_s + R_1} \right) + H_s \left(\frac{R_b}{F_b + R_b} \right) + n_1 \; (n_{c1} - n_o) \; H_s \left(\frac{R_c}{F_c + R_c} \right)$$

From the above, it can be seen that to reduce these lost car-hours, MTBF must be increased and/or MTTR must be reduced. If ΔF, ΔR are the respective improvements, the total car-hours saved from service-related failures will be given by

$$\Delta h_s = n_o H_s \left\{ \frac{R_1}{F_s + R_1} - \frac{R_1 - \Delta R_1}{(F_s + \Delta F_s) + (R_1 - \Delta R_1)} \right\}$$

$$+ H_s \left\{ \frac{R_b}{F_b + R_b} - \frac{R_b - \Delta R_b}{(F_b + \Delta F_b) + (R_b - \Delta R_b)} \right\}$$

$$+ n_1 (n_{c1} - n_o) \; H_s \left\{ \frac{R_c}{F_c + R_c} - \frac{R_c - R_c}{(F_c + \Delta F_c) + (R_c - \Delta R_c)} \right\} \tag{A16}$$

If C_o = operating cost (exclusive of maintenance) prior to any improvement, then total savings in operating cost due to the improvements are given by

$$\Delta C_o = \frac{C_o}{H_o} (\Delta h_s) \tag{A17}$$

For simplicity, assume the following

(i) $F >> R$

(ii) $H_o \sim H_s$

Hence

$$\Delta C_o = C_o \left\{ n_o \left(\frac{R_1}{F_s} - \frac{R_1 - \Delta R_1}{F_s + \Delta F_s} \right) + \left(\frac{R_b}{F_b} - \frac{R_b - \Delta R_b}{F_b + \Delta F_b} \right) + n_1 (n_{c1} - n_o) \left(\frac{R_c}{F_c} - \frac{R_c - \Delta R_c}{F_c + \Delta F_c} \right) \right\}$$

Let changes in F and R be represented by

$$P_{r1} = \frac{\Delta R_1}{R_1} \ ; \quad P_{rb} = \frac{\Delta R_b}{R_b} \ ; \quad P_{rc} = \frac{\Delta R_c}{R_c}$$

$$P_{fs} = \frac{\Delta F_s}{F_s} \ ; \quad P_{fb} = \frac{\Delta F_b}{F_b} \ ; \quad P_{fc} = \frac{\Delta F_c}{F_c}$$

$$\Delta C_o = C_o \left\{ n_o \left(\frac{R_1}{F_s} - \frac{R_1 - P_{r1} R_1}{F_s + P_{fs} F_s} \right) + \left(\frac{R_b}{F_b} - \frac{R_b - P_{rb} R_b}{F_b + P_{fc} F_b} \right) + n_1 (n_{c1} - n_o) \left(\frac{R_c}{F_c} - \frac{R_c - P_{rc} R_c}{F_c + P_{fc} F_c} \right) \right\}$$

Simplifying,

$$C_o = C_o \left\{ \frac{n_o R_1}{F_s} \left(\frac{P_f + P_{r1}}{1 + P_{fs}} \right) + \frac{R_b}{F_b} \left(\frac{P_{fb} + P_{rb}}{1 + P_{fb}} \right) + \frac{n_1 (n_{c1} - n_o) R_c}{F_c} \left(\frac{P_{fc} + P_{rc}}{1 + P_{fc}} \right) \right\} \tag{A18}$$

Assuming that changes in F are the same for all types of failure and that changes in R are also the same for the different failures, Eq. (A18) takes the following form:

$$\Delta C_o = C_o \left(\frac{P_f + P_r}{1 + P_f} \right) \left\{ \frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + \frac{n_1 (n_{c1} - n_o) R_c}{F_c} \right\} \tag{A19}$$

Eq. (A19) gives the savings in operating cost obtained from improvements in MTBF and MTTR.

Note that in Eq. (A19) the relationship for savings in operating cost consists of these parts:

(i) First part of the equation gives the cost savings due to reduction in car-hours lost by failed cars and other cars within failed trains.

(ii) Second part of the equation gives the savings due to reduction in car-hours lost by locked-out cars as a result of Case B failures.

(iii) Third component of the relationship represents cost savings due to reduction of car-hours lost by following trains when Case C failures occur.

Note also that because operating cost is affected only by service-related failures, F and R values in Eq. (A19) are based on service-related incidents only.

A.2 MAINTENANCE COST MODEL

Maintenance cost includes all cost (labor and materials) incurred in maintaining the railcars. It is a composite of the Maintenance Infrastructure Cost (MIC) and spare parts cost. The effect of performance improvement on operating cost discussed in the previous section considered only those failures which result in service delays. In analyzing the effect on maintenance cost, however, those failures which do not affect service should also be taken into consideration. The following presents the development of the maintenance cost model.

A.2.1 Maintenance Infrastructure Cost Savings

Maintenance Infrastructure Cost (MIC) consists of all labor cost, related overhead, and any cost for support activities associated with the accomplishment of scheduled and unscheduled maintenance. Only the MIC as related to unscheduled maintenance is modeled in this study. However, the resultant model can be reformatted to include both preventive and unscheduled maintenance. To do this, mean time between failure, F, would have to be replaced by mean time between maintenance, L. Also, mean time to repair, R_s, would be replaced by mean time to maintain, M.

Assume that unscheduled maintenance infrastructure costs are directly proportional to the length of time cars are shopped.

If D_s = shop delay (or time cars are actually worked on)

then $$C_{cm} = K_s D_s \tag{A20}$$

where K_s = corrective maintenance infrastructure cost constant and represents the cost per car-hour in the shop, and

C_{cm} = corrective maintenance infrastructure cost

Now Mean time to repair,

$$R_s = \frac{D_s}{n_f} \tag{A21}$$

or $$D_s = n_f R_s \tag{A22}$$

where n_f = total number of failures including service and non-service related failures.

Also mean time between failure, F, is

$$F = \frac{H_o}{n_f} \tag{A23}$$

or

$$n_f = \frac{H_o}{F} \tag{A24}$$

where H_o = car-hours operated

Note that F gives the mean time between all failures (service and non-service).

Substituting equations (A22) and (A24) in equation (A20), we find,

$$C_{cm} = \frac{K_s H_o R_s}{F} \tag{A25}$$

Eq. (A25) gives the general relationship for corrective maintenance infrastructure cost in terms of mean time to repair (R_s) failed cars and mean time between failure (F). If ΔR_s, ΔF are improvements in MTTR and MTBF respectively, the savings in corrective maintenance infrastructure cost will be given by

$$\Delta C_{cm} = K_s H_o \left\{ \frac{R_s}{F} - \frac{R_s - \Delta R_s}{F + \Delta F} \right\} \tag{A26}$$

A.2.2 Spare Parts Cost Savings

Spare parts are also used for both scheduled and unscheduled maintenance. The model for spare parts cost savings also focuses on unscheduled maintenance only. Spare parts usage is dependent on the number of failures experienced in a given period. The cost for spare parts can, therefore, be represented by

$$C_{sp} = K_p n_f \tag{A27}$$

Hence $$C_{sp} = K_p \frac{H_o}{F}$$

where K_p = constant of proportionality for spare parts and represents the average cost per failure. If ΔF represents the improvement in MTBF, the spare parts costs savings becomes

$$\Delta C_{sp} = K_p H_o \left(\frac{1}{F} - \frac{1}{F+\Delta F}\right) \tag{A28}$$

A.2.3 Total Maintenance Cost Savings

Total savings in maintenance cost, ΔC_m is the sum of corrective MIC savings and spare parts cost savings.

Hence, $$\Delta C_m = H_o \left\{ K_s \left(\frac{R_s}{F} - \frac{R_s - \Delta R_s}{F + \Delta F}\right) + K_p \left(\frac{1}{F} - \frac{1}{F + \Delta F}\right) \right\} \tag{A29}$$

If $$P_{rs} = \frac{\Delta R_s}{R_s} \; ; \quad P_f = \frac{\Delta F}{F}$$

$$\Delta C_m = H_o \left\{ K_s \left(\frac{R_s}{F} - \frac{R_s - P_{rs} R_s}{F + P_f F}\right) + \left(K_p \;\frac{1}{F} - \frac{1}{F + P_f F}\right) \right\}$$

$$= \frac{H_o}{F} \left\{ K_s R_s \left(\frac{P_f + P_{rs}}{1 + P_f}\right) + \left(K_p \frac{P_f}{1 + P_f}\right) \right\} \tag{A30}$$

Note that H_o/F is equal to the number of failures in the period.

A.3 FLEET CAPITAL COST MODEL

Savings in fleet cost is reflected in the reduction in spare vehicle requirement realized as a result of car-hours saved by increasing MTBF or reducing MTTR. Car-hours are lost from failures occurring in service as well as failures detected when the car is in the shop for other maintenance. All these failures and their resulting downtime dictate the need for the provision of spare vehicles. Hence, in estimating fleet cost savings, both service and non-service related incidents should be considered.

If Δh = total car-hours saved from both service and non-service related failures, then the number of cars saved, is as follows:

$$\Delta N_c = \frac{\Delta h}{h_s} \tag{A31}$$

where h_s = average hours scheduled per car during the same period Δh is accumulated

$$\Delta h = \Delta h_s + \Delta h_{ns} \tag{A32}$$

where Δh_s, the in-service car-hours saved is given by Eq. (A16)

Δh_{ns}, the out-of-service car-hours saved is given by

$$\Delta h_{ns} = H_s\left(\frac{R_m}{F} - \frac{R_m - \Delta R_m}{F + \Delta F}\right) \tag{A33}$$

where R_m = mean time to restore (for all failures) considering only the out-of-service delay components of all failures which occur in the shop and yard and in getting failed cars to the yard or shop. If preventive maintenance is considered, R_m will include preventive maintenance activities.

F = mean time between all failures. F would be replaced by L if preventive maintenance activities are considered.

If C_v = cost per car, then the savings in capital cost is as follows

$$\Delta C_v = \frac{\Delta h}{h_s} C_v \tag{A34}$$

Substituting for Δh, the savings in capital cost is given by

$$\Delta C_v = \frac{C_v H_s}{h_s} \left\{ n_o \left(\frac{R_1}{F_s} - \frac{R_1 - \Delta h_1}{F_s + \Delta F_s} \right) + \left(\frac{R_b}{F_b} - \frac{R_b - \Delta R_b}{F_b + \Delta F_b} \right) \right.$$

$$\left. + n_1 (n_{c1} - n_o) \left(\frac{R_c}{F_c} - \frac{R_c - \Delta R_c}{F_c + \Delta F_c} \right) + \left(\frac{R_m}{F} - \frac{R_m - \Delta R_m}{F + \Delta F} \right) \right\} \tag{A35}$$

This savings in fleet cost can be combined with the annual O&M cost savings determined above by calculating the present worth of the latter. Alternatively, the capital cost savings can be annualized into an equivalent series amount using a capital recovery factor (crf) for a given vehicle service life, n years, and discount rate, i%. The annualized capital cost savings is given by

$$E_c = \Delta C_v (crf) \tag{A36}$$

Let $P_{r1} = \frac{\Delta R_1}{R_1}$; $P_{rb} = \frac{\Delta R_b}{R_b}$; $P_{rc} = \frac{\Delta R_c}{R_c}$; $P_{rm} = \frac{\Delta R_m}{R_m}$

$P_{fs} = \frac{\Delta F_s}{F_s}$; $P_{fb} = \frac{\Delta F_b}{F_b}$; $P_{fc} = \frac{\Delta F_c}{F_c}$; $P_f = \frac{\Delta F}{F}$

Hence

$$\Delta C_v = \frac{C_v H_s}{h_s} \left(\frac{P_f + P_r}{1 + P_f} \right) \left\{ \frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + n_1 (n_{c1} - n_o) \frac{R_c}{F_c} + \frac{R_m}{F} \right\} \tag{A37}$$

assuming $P_f = P_{fs} = P_{fb} = P_{fc}$

and $P_r = P_{r1} = P_{rb} = P_{rm}$

APPENDIX B

B. CALIBRATION OF MODELS

This appendix presents the calibration of the operating, maintenance, and fleet cost models developed in Appendix A. The results obtained from this calibration are only applicable to the system on which they are based and are not transferable to other transit systems.

B.1 DATA USED FOR CALIBRATION

Reliability information used in calibrating the models are based on data obtained from WMATA for the month of February 1983. These data are then extrapolated to reflect an entire year. It is recognized that February data may not be representative of the year's experience. Hence calibration on the basis of such data is only intended to demonstrate the use of the model. Operating and maintenance costs used are estimates made on the basis of data obtained from "WMATA Approved 1983 Fiscal Year Budget" as well as discussions with WMATA officials. The data base are shown below and summarized in Tables B-1, B-2, and B-3. Table B-1 shows calculated reliability data for the month of February 1983. Table B-2 shows estimates of distribution of operating cost based on data from WMATA 1983 Budget for Rail Transportation Branch. Estimates of maintenance cost distribution are shown in Table B-3 based on data from WMATA Approved 1983 Fiscal Year Budget (Rail Car Maintenance Branch)

B.1.1 System Operating Data

Number of lines affected by failures, $n_l = 3$

Average number of cars per train, $n_o = 4$

Number of cars operated at peak period = 222

Number of cars operated at non-peak period = 118

System operating hours = 18 hours/day

Weighted average number of cars operated per day = 148

Average number of trains operated per day = $\frac{148}{4} = 37$

Average number of trains per line = 12

Average number of cars per line, $n_{cl} = 48$

TABLE B-1: RELIABILITY DATA FOR FEBRUARY 1983
(WMATA Metro-rail System)

	SERVICE RELATED	NONSERVICE RELATED	ALL INCIDENTS
No. of Failures, N_f	80	370	450
Repair Time, D_s (car-hours)	149	546	695
Restore Time, D(car-hours)	844	2,973	3,817
Maint. Man-hours, MH	297	908	1,205
MTBF (car-hours)	932	-	166
MTBF (system-hours)	6.3	-	1.12
MTT Restore line service, R_1	0.12	-	-
Composite MTTR, R	-	-	8.5
MTT Repair, R_s	1.86	1.47	1.54
Man-hours/Maint. Action	3.71	2.45	2.68

TABLE B-2: ESTIMATE OF RAIL TRANSPORTATION OPERATING COST DISTRIBUTION FOR WMATA

PERSONNEL	NUMBER (1)	ESTIMATED AVERAGE SALARY (2)	ESTIMATED COST
Administration	2	65,000	$ 130,000
Operations & Analysis Support			
Management & Clerical	11	29,000	319,000
Depot Clerks	14	19,000	266,000
Operations Control Center (3)	22	28,000	616,000
Train Operations (3)			
Administration	6	42,000	252,000
Supervisors	40	40,000	1,600,000
Train Operators	212	32,000	6,784,000
Station Operators			
Administration	4	42,000	168,000
Station Supervisors	13	40,000	520,000
Station Attendants	230	21,000	4,830,000
Start-up (3)			
Supervisors	17	40,000	680,000
Train Operators	24	32,000	768,000
			$16,933,000

Notes:

(1) Personnel distribution obtained from WMATA 1983 Budget for Rail Transportation Branch
(2) Includes overhead, fringes, etc. in dollars.
(3) Categories directly affected by service delays. These categories are used in estimating operating cost for use in the model.

TABLE B-3: ESTMIATE OF MAINTENANCE COST DISTRIBUTION FOR WMATA

ITEM DESCRIPTION	ALL ACTIVITIES	UNSCHEDULED ACTIVITIES	SCHEDULED ACTIVITIES
Direct (in house) Labor (1)	11,795,000	4,800,565	6,994,435
Indirect Costs (1)			
Consultants	6,000	2,442	3,558
Training	35,000	14,245	20,755
Temporaries	3,000	1,221	1,779
Contract Maint. (office machines, etc.)	800	326	474
Contract Maint. (vehicles)			
Traction Motor Overhauls	375,000	-	375,000
Traction Motor Repair	480,000	480,000	-
A/C Compressor Armature	81,000	81,000	-
Other Repairs	70,000	28,490	41,510
Contract Maint. (garage & shop equipment)	25,000	10,175	14,825
Duplication & Reproduction	16,000	6,512	9,488
Equipment Leases	5,000	2,035	2,965
Dues & Subscriptions	800	326	474
Other Periodicals	500	204	296
Business Travel	2,200	895	1,305
Freight & Delivery Charges	600	244	356
Total Maint. Infra-structure Cost (2)	12,895,900	5,428,680	7,467,220
Materials and Supplies			
Special Purpose Materials (furniture & tools)	59,400	-	-
Revenue Vehicle Parts (3)	3,838,300	1,919,150	1,919,150
Fuels & Lubrication (3)	58,400	29,200	29,200
Other Material (4)	938,200	-	-
Total Materials Cost (5)	4,894,300	1,948,350	1,948,350
Total Maint. Cost	17,790,200		

Notes:

(1) Except where the category is known, item costs are split according to personnel distribution as follows: Unscheduled - 40.7%, Scheduled - 59.3%.

(2) Sum of all labor cost, related overhead, and any support activities associated with maintenance.

(3) Distributed on the basis of 50-50 split.

(4) Assumed not related to vehicle maintenance.

(5) Sum of costs for unscheduled and scheduled does not equal subtotal because only MTBF-related costs are distributed.

Source: WMATA Approved 1983 Fiscal Year Budget (Rail Car Maintenance Branch)

Average number of car-hours operated,

H_o = 148 cars x 18 hrs/day x 28 days

H_o = 74,592 car-hours/mo

H_o = 972,360 car-hours/yr

Hours scheduled per car (using average 148 cars), h_s = 18 hrs/day x 28 days = 504 hrs/mo or 6,570 hrs/year

B.1.2 Reliability Data

B.1.2.1 Service-Related Incidents

Number of failures experienced, n_{fs} = 80 per mo or 1,043 failures/yr

Number of Case B failures, n_{fb} = 0

Number of Case C failures, n_{fc} = 18 per mo or 235 failures/yr

Total on-line service delay, D_l = 9.27 hrs per mo or 120.8 hrs/yr

Total on-line service delay for upstream cars during Case C failures,

$D_c - H_{min}$ = 2.83 hrs/mo or 36.9 hrs/yr

Mean Time Between Service Failure, $F_s = \frac{972,360}{1,043}$ = 932 car-hrs

Mean Time Between Case C Failure, $F_c = \frac{972,360}{235}$ = 4,138 car-hrs

Mean Time To Restore line service, $R_l = \frac{120.8}{1,043}$ = 0.12 hrs

Mean Time to Restore Service for upstream cars during Case C failures,

$R_c = \frac{36.9}{235}$ = 0.16 hrs

B.1.2.2 Non-Service-Related Incidents

Number of incidents = 370 per mo or 4,823 failures/yr

Total restore time = 2,973 car-hrs/mo or 38,755 car-hrs/yr

Actual repair time = 546 car-hrs/mo or 7,118 car-hrs/yr

B.1.2.3 All Incidents

Number of failures experienced,

n_f = 450 per mo or 5,866 failures per yr

Total restore time, D = 3,817 hrs per mo or 49,757 hrs/yr

Total time to restore (excluding line delay),

D_m = 49,757-120.8 = 49,636 hrs/yr

Total repair time, D_s = 695 car-hrs or 9,060 car-hrs/yr

Mean Time between failures, $F = \frac{972,360}{5,866} = 166$ car-hrs

Mean time to restore $= \frac{49,757}{5,866} = 8.5$ hours

Mean time to restore (excluding line delay), $R_m = \frac{49,636}{5,866} = 8.5$ hrs

Mean time to repair, $R_s = \frac{9,060}{5,865} = 1.54$ hrs

B.1.3 Cost Data

B.1.3.1 Operating Cost

Total operating budget for 1983 for Rail Transportation Branch is $16,935,000 to cover personnel costs. An estimate of the distribution of this cost is shown on Table B-2 based on estimated annual salaries for personnel. Since operating cost is affected by service delays, an adjusted annual operations cost that reflects the services of personnel directly involved with train operations has been estimated as $10,800,000.

B.1.3.2 Maintenance Cost

An estimate of maintenance costs obtained from WMATA 1983 budget report is presented in Table B-3. Except where labor categories are known, the distribution between scheduled and unscheduled activities is based on discussions with WMATA officials on the personnel split for this system functions. Total annual unscheduled maintenance infrastructure cost is estimated at about $5,429,000 and the annual spare parts cost for revenue vehicles is about $1,948,000.

B.2 CALIBRATION PROCEDURE

B.2.1 Operating Cost Model

The general relationship for operating cost savings was given as

$$\Delta C_o = C_o\left(\frac{P_f + P_r}{1 + P_f}\right)\left\{\frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + \frac{n_1(n_{c1} - n_o)R_c}{F_c}\right\} \qquad \text{(B1)}$$

Using WMATA data presented in the previous section, the above relationship reduces to the following:

$$\Delta C_o = 10.8 \times 10^6 \left\{\frac{4 \times 0.12}{932} + \frac{3(44)(0.16)}{4,138}\right\}\left(\frac{P_f + P_r}{1 + P_f}\right)$$

$$= 60,685\left(\frac{P_f + P_r}{1 + P_f}\right) \qquad \text{(B2)}$$

where P_f, P_r represent the improvements in MTBF and MTTR respectively. For a given value of P_f, P_r can be varied to investigate the impact of MTTR on operating cost. Similarly, by holding P_r constant at different levels, P_f can be varied to test the effect of MTBF on operating cost. Families of curves obtained by performing these sensitivity analyses are shown in Figures 2-1 and 2-2.

B.2.2 Maintenance Cost Model

Total corrective maintenance cost savings is given by

$$\Delta C_{cm} = n_f \left\{K_s R_s \left(\frac{P_f + P_{rs}}{1 + P_f}\right) + K_p \left(\frac{P_f}{1 + P_f}\right)\right\} \qquad \text{(B3)}$$

Substituting WMATA data,

$$K_s = \frac{C_{cm}}{D_s} = \frac{5,429,000}{9,060} = \$599 \text{ per car-hour}$$

Say \$600 per car-hour.

$$K_p = \frac{C_{sp}}{n_f} = \frac{1,948,000}{5,866} = \$332 \text{ per failure}$$

Hence,

$$\Delta C_{cm} = 5866 \left\{(600)(1.54)\left(\frac{P_f + P_{rs}}{1 + P_f}\right) + 332\left(\frac{P_f}{1 + P_f}\right)\right\}$$

$$= 5,420,000\left(\frac{P_f + P_{rs}}{1 + P_f}\right) + 1,948,000\left(\frac{P_f}{1 + P_f}\right) \quad \text{(B4)}$$

The results of the sensitivity analyses are shown in Figures 2-3 and 2-4.

B.2.3 Fleet Capital Cost Model

The annualized fleet capital cost savings is given by

$$\Delta E_c = \frac{C_v H_s}{h_s} \text{ (crf) } \left\{\frac{n_o R_1}{F_s} + \frac{R_b}{F_b} + n_1 (n_{c1} - n_o) \frac{R_c}{F_c} + \frac{R_m}{F}\right\} \quad \text{(B5)}$$

Using WMATA data and assuming the following

- o Cost per car, C_v = \$1,000,000
- o Discount rate, i = 10% (per OMB)
- o Vehicle service life, n = 30 yrs

$$\Delta E_c = \frac{10^6 \times 972,360 \times 0.10608}{6,570} \left(\frac{4 \times 0.12}{932} + \frac{3 \times 44 \times 0.16}{4,138} + \frac{8.46}{166}\right)\left(\frac{P_f + P_r}{1 + P_f}\right)$$

$$= 890,000\left(\frac{P_f + P_r}{1 + P_f}\right) \quad \text{(B6)}$$

Figures 2-5 and 2-6 show the results of the sensitivity analyses.

APPENDIX C

C. DEVELOPMENT OF RELATIONSHIPS FOR SIZES OF MAINTENANCE FACILITIES

Relationships for sizes of maintenance facilities are developed in this section. The size of a facility is expressed in terms of the maximum number of cars it can hold.

At any particular time during a transit system operating period, the total number of cars in the fleet consist of

- o Cars in service, N_p or N_o depending on whether peak or non-peak period is being considered
- o Failed cars in sidings or being taken to the yard, N_t
- o Failed cars in the "dead" yard awaiting repair, N_{dy}
- o Cars in the maintenance shop undergoing repair, N_s
- o Cars in "ready" yard waiting to be put in service, N_{ry}

Hence fleet size, $N = N_{p/o} + N_t + N_{dy} + N_s + N_{ry}$ (C1)

C.1 MINIMUM REQUIREMENT FOR MAINTENANCE SHOP SIZE

During peak period, the number of cars that fail is given by

$$\frac{N_p T_p}{F} \tag{C2}$$

where F = mean time between failure

T_p = peak hours

During this same time, the shop can repair cars at a rate given by

$$\frac{N_s T_p}{R} \tag{C3}$$

where R = mean time to repair

Hence, additional spares (i.e., deficiency in shop capacity) required to meet peak period

$$= T_p\left(\frac{N_p}{F} - \frac{N_s}{R}\right) \tag{C4}$$

During off-peak, the shop can repair faster than the rate at which they fail.

Excess spare cars generated during this period

$$= T_o\left(\frac{N_s}{R} - \frac{N_o}{F}\right) \tag{C5}$$

where T_o = non-peak hours
R = mean time to repair

For equilibrium, the excess cars generated during off-peak must compensate for the shop deficiency during peak period.

Thus

$$T_o\left(\frac{N_s}{R} - \frac{N_o}{F}\right) = T_p\left(\frac{N_p}{F} - \frac{N_s}{R}\right)$$

Hence, shop size, $N_s = \frac{R}{F}\left(\frac{T_pN_p + T_oN_o}{T_o + T_p}\right)$ (C6)

If k is a shop capacity design factor, necessary to meet failure rates, greater than the mean, then the shop design capacity is given by

$$\hat{N}_s = \frac{kR}{F}\left(\frac{T_pN_p + T_oN_o}{T_o + T_p}\right) \tag{C7}$$

C.2 NUMBER OF VEHICLES ON SIDINGS AND IN TRANSIT TO YARD

Let T_t = time on sidings and in transit to the yard

$$N_t = \frac{N_p T_p}{F} + \frac{N_o}{F}(T_t - T_p) \quad \text{for } T_p \leq T_t < (T_o + T_p) \tag{C8}$$

or

$$N_t = \frac{N_p T_t}{F} \quad \text{for } T_t \leq T_p$$

C.3 SIZE OF DEAD VEHICLE YARD

The dead yard is used to hold failed cars until they can be moved into the shop for repairs. It excludes the space needed to store cars not required for service during off-peak period. The yard should be sized on the basis of the rate at which dead cars are received from sidings and the rate at which the shop accepts these cars for repair. The "dead" yard will receive cars at a faster rate for a period T_p as a result of the difference between peak period failure rate and the ability of the shop to repair them. The minimum size of the dead yard for minimum shop capacity, N_s, is given by

$$N_{dy} = \frac{N_p}{F} T_p - \frac{N_s}{R} T_p$$

$$= \frac{T_p T_o}{F}\left(\frac{N_p - N_o}{T_o + T_p}\right) \tag{C9}$$

Dead yard capacity required to match factored shop design capacity ($\hat{N}_s$) is given by

$$\hat{N}_{dy} = \frac{T_p}{F(T_o + T_p)}\left\{T_o(N_p - kN_o) - T_p N_p (K - 1)\right\}$$