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METHODOLOGY FOR URBAN RAIL AND CONSTRUCTION TECHNOLOGY RESEARCH AND DEVELOPMENT PLANNING

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FINAL REPORT

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16. Abstract

To develop an improved return on the investment in rail and construction technology research and development, the Urban Mass Transportation Administration (UMTA) sponsored this R&D planning project. The UMTA objective is to apply existing industrial technology toward reducing the operating and capital costs of rail transit systems.

A series of transit system visits, organized by the American Public Transit Association (APTA), were conducted in which the system operators identified the most pressing development needs. These varied by property and were reformulated by JPL into a series of potential R&D projects. To assist in the evaluation, a data base useful for estimating the present capital and operating costs of various transit system elements was generated primarily from published data. An evaluation model was developed which considered the rate of deployment of the research and development project, potential benefits, development time and cost. An outline of an evaluation methodology that considered benefits other than capital and operating cost savings was also presented.

During the course of the study, five candidate R&D projects were selected by UMTA for detailed investigation: (1) air comfort systems, (2) solid state auxiliary power conditioners, (3) door systems, (4) escalators, and (5) fare collection systems. Application of the evaluation model to these five examples showed the usefulness of modeling deployment rates and indicated a need to increase the scope of the model to quantitatively consider reliability impacts.

17. Key Words

Rail Rapid Transit, Research and Development, Research and Development Management, Program Planning

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PREFACE

The results from this overall Research and Development Planning Project appear in several reports. This one pertains primarily to an R&D planning methodology. Other reports concentrate on escalators and fare collection technology.

The conclusions presented in this report were developed by the Jet Propulsion Laboratory (JPL) in support of the UMTA Office of Rail Technology. The primary objective of this effort was to present the necessary information to UMTA to define a more effective five-year R&D program in Rail and Construction Technology. The effort reported herein consists of the development of a rationale for program elements, mechanisms for implementing the promising results of the R&D efforts, and a means for continually evaluating the effectiveness of the R&D program.

Sources of information on the various aspects of rail transit systems were developed by talking to various transit agencies in the United States and Canada. JPL participated in several of the UMTA-sponsored meetings with the American Public Transit Association (APTA) and agencies as a part of the UMTA Subsystem Technology Applications to Rail Systems (STARS) program. The New York City Transit Authority (NYCTA) and the Bay Area Rapid Transit District (BART) provided extensive information on operating and maintenance costs. Other data reported here was derived from existing literature. Efforts were also made to contact suppliers of equipment and consultants in the area of rail transit systems.

In addition to the authors, many persons contributed to this task. A partial listing of contributors at JPL and sponsoring or coordinating agencies include: UMTA, Stephen Teel, Russell McFarland, Ray Orren, Lee Tucker, and Paul Spencer; Transportation Systems Center, Joe Koziol, George Neat and Louis Frasco; American Public Transit Association, Frank Cihak and Ted Gordon, and JPL, David Humphreys, Dean Westerfield, Barry Harrow, Tad Macie, Richard O'Toole, John Cucchissi, Keith Hardy, and Jane Okano.

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	6.6	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

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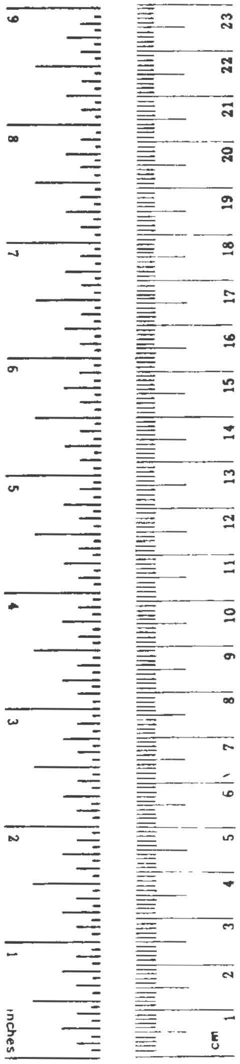
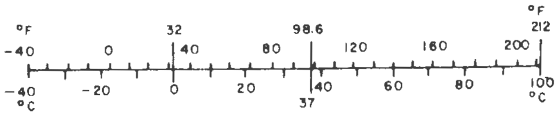
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



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



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1. EXECUTIVE SUMMARY

Anticipated major expenditures for rehabilitation and new or extended rail transit systems will place a large demand on UMTA's funding capabilities over the next several decades. A research and development planning methodology can aid UMTA in developing R&D programs that more effectively utilize federal investment in the nation's public transit systems and aid the transit operators in providing improved and more cost-effective service. This report develops a systematic method for identifying, evaluating, and developing an R&D program.

UMTA's R&D interests are primarily guideway construction and equipment and operating costs of transit systems. The cost of new systems is mostly in guideway construction which offers the potential for large savings from R&D projects implemented in construction technology. Improved equipment offers the possibility of more reliable and effective service with lowered capital and operating costs. Other UMTA interests in R&D are supporting national goals of revitalizing urban centers, protecting the environment, increasing the mobility of the elderly and handicapped, conserving energy, and supporting high risk, high potential payoff projects. However, as noted in Section 5.6 of this report, a review of congressional testimony indicates that UMTA's highest R&D policy objective is cost reduction.

Large deficits and the demands of providing daily service make it extremely difficult for transit operators to provide the funds or staff time to conduct an R&D program. Only a few hundred transit vehicles are purchased in any one year. This small market makes it unlikely that the supply industry can recoup any major private R&D investment by increased sales of improved products. This leaves the Federal government, with its ability to spread the risk of R&D among all taxpayers, as a prime source of R&D funding.

Cost reduction was selected as the prime policy objective in developing an R&D planning methodology. This tends to favor the selection of projects with high short-term benefits that can be quantified and have minimal risk.

The long lead times required from initiation of an R&D project to its first regular field deployment, the time required for the improved product to be widely deployed throughout the industry, the chances of a later, alternate product reducing the technological life of the initial R&D investment, and the time value of money discounting the annual operating cost and capital costs savings all work against long-term R&D efforts. These issues are described more fully in Sections 5.1, 5.2, and 5.3 where two methodologies are developed for determining the present value, potential savings and costs of an R&D project that is deployed incrementally. The first methodology utilizes an analytic expression which is amenable to computer manipulation. The second methodology uses engineering economic analysis tables for the present value of a gradient series of payments modified to include a relative escalation rate.

Under cost reduction optimization guidelines, there is a danger of excluding worthwhile projects. Methodologies to consider projects with non-quantifiable benefits and high risks are described in Sections 5.4 and 5.7. Further study is required to refine the methods and to develop the supporting data base. Those types of projects which offer a low expectation for major advances in technology deployment or provide for system goals such as safety can be supported by setting aside a small, appropriate portion of R&D resources. Related developments in areas such as airport ground circulation, which can support private R&D due to less sensitivity to high per vehicle capital costs, may also serve as an impetus for rail transit technology advancement.

Knowing the present value of the cost savings for an R&D project is only one element of a program. Section 5.5 develops a method for combining individual projects into a multiyear program. With the present value of the project benefits and the project funding requirements over a period of years, this methodology can be used to select the combination of projects that optimizes benefits under a given set of program budget limitations.

To utilize the project evaluation methodology, a candidate set of projects and a data base have been developed. Chapter 4 presents a set of potential rail and construction technology research and development projects. These were developed via a series of meetings with the staffs of several transit operators, coordinated through the American Public Transit

Association, and a review of recent literature on rail transit R&D needs. Recent research on the implementation of innovative projects indicates that those developed with direct input on users' needs have a high probability of implementation. The needs as expressed by the different operators were reformulated into a set of projects in several programmatic areas, having wide applicability.

Chapter 3 develops a data base which can be used to estimate the potential savings of various R&D projects. Data from literature and data supplied by BART and NYCTA were used to estimate the construction, power, and maintenance costs of various subsystems of a transit guideway (or transit equipment).

The methodology and data base were used to examine in detail five potential R&D projects: (1) air comfort systems, (2) solid state auxiliary power conditioners, (3) door systems, (4) escalators, and (5) fare collection systems (Section 5.8). UMTA classified these projects as high interest. Additional data was developed as required. Each of the projects was examined under a set of optimistic, nominal, and pessimistic conditions. Projects showed high potential benefits under the optimistic case, less benefits under the nominal case, and, under the pessimistic case, no justification existed for some projects.

The prime benefit identified from the air comfort project was the reduction in car construction costs due to systems requiring less special duct work in the car walls. The power of the methodology was illustrated in the analysis of the solid state power conditioner. This project could not be justified, considered by itself. However, use of this project would result in a more rapid deployment of AC powered air comfort systems. Taken as a package, the two projects had a high cost savings potential. Estimated benefits of the door system were positive but small. This was due to the evaluation methodology not quantifying the impact of reliability improvements. The escalator project showed potential for significant cost savings in the capital costs of escalators. The fare collection system showed a much larger potential savings in operating cost than in capital cost.

This report is a first step toward an improved process of R&D planning for rail and construction technology. Several recommendations are worthy of further consideration. They are: (1) a systematic approach to R&D planning is essential if new technology is to be made available to the rail transit industry in a reasonable time frame. The systematic approach involves the development of accepted industry-wide guidelines and criteria for R&D project implementation approaches and a standard implementation approach that involves the government, industrial suppliers and operators in their appropriate roles, (2) there is a general lack of information necessary to make decisions regarding R&D projects. This can only be overcome by developing standardized data formats and the willingness of transit operators to devote time and money to the development and maintenance of data on their property; then making that data available to R&D planners. Until such time, too many hasty decisions must be made on the merits of individual R&D projects.

The most important recommendation is that an industry-wide approach to R&D be developed which is acceptable to the operators, the supply industry, and UMTA. This approach should encourage the entry of new ideas into transit.

2. APPROACH

Research and development program planning is a formidable task. Although difficult in private corporations, a measure of R&D is the degree of acceptance of the R&D products in the marketplace as measured by the profit and loss statement. However, in government-sponsored projects, success is far more nebulous. Perhaps the most important and well known contributor to the problem is the non-existence of a precise measure of the actual benefits derived from government-sponsored R&D - i.e., there is no profit and loss statement.

Two other contributors to the problem have become visible in recent times. First, the benefits actually realized from R&D have often been less than those promulgated by the R&D advocates. The cause of this disparity is still unclear, but it is now recognized that R&D must address social and institutional barriers in the introduction of a technology. Second, introduction of a technology into complex societal and institutional systems requires cooperation, commitment and expenditure of resources, direct or indirect, by many parties including federal, state, regional and local governments, operating agencies, public interest groups, and suppliers of industrial products and services. Although government spending in R&D can encourage or provide leadership to these parties, it cannot supplant their indispensable roles.

The approach to the analysis presented here attempts to address the needs for R&D in urban rail and construction technology in light of the above requirements. In particular, it was attempted from the outset to develop an understanding of prevailing policy, needs of the national urban transportation system, the current state of in-use technology, the status of available or developing technology and the infrastructure which must bear the ultimate responsibility for placing new technology into service.

The approach to the analysis has been to concentrate efforts in three areas: (1) develop a good data base upon which projects can be subjectively evaluated, (2) develop a comprehensive list of projects from extensive sources of information and (3) develop a methodology which will serve as a framework and forum to evaluate the merits and deficiencies of project candidates.

2.1 Acquiring the Data Base

Paramount to the evaluation of R&D projects is the development of a good data base on the characteristics of existing systems, costs of operation of these systems, costs of capital improvements, extensions and new systems, and the characteristics of existing or potential technology which could be made available for urban rail application through R&D. Thus, much of the study effort was concentrated in this area.

There is much data available in the literature concerning existing and developing systems. However, the data is scattered and often not reported in a consistent format. Therefore, a data base was compiled in a consistent format. Any comparison among alternative applications of R&D resources must be made based upon a consistent set of data. The most important parts of the data base are judged to be the cost of operation of the existing systems, the cost of deployment of new systems or extensions to existing systems, and the cost of improvements to these existing systems. This judgment is driven by the general public's concern about the cost of operating existing systems and the cost growth associated with the deployment of new systems such as Bay Area Rapid Transit (BART) and Washington Metropolitan Transit Authority (WMATA).

Another important part of the data base is the state of technology. Technology can be categorized as (1) in-use in transit systems, (2) available and in-use in non-transit applications, or (3) potentially available through research and development. Due to the manner in which rail transit has developed in the United States, there is a wide variety of technology in use throughout the U.S. Also, due to the complex infrastructure which has evolved in this industry, much technology which has been developed for other applications and foreign transit has not been applied to U.S. rail transit. The major near-term task in R&D is to apply this available technology to rail transit. In these cases, the project activities may consist mainly of coordination among the affected parties and encouragement on the part of the government. There exists, however, much technology which, on the surface, appears to be readily adaptable but in reality, requires much effort to apply to the demanding environment of rail transit. The development of a qualitative understanding of these categories is important to a comprehensive data base on technology status. The activities of this project, due to both budget and time limitations, must concentrate on a broad, general approach, leaving the detailed project implementation plans to others.

2.2 Developing Candidate Projects

A literature search was conducted to identify the apparent needs of rail transit as reported in the literature. Next, presentations were attended where the staffs of operating properties spoke of the needs of R&D from their perspective. In addition, several discussions were held with engineers and other professionals working in public transportation. Through these efforts, several common areas became prevalent. Common activities were then merged under consistent headings and structured into project areas. Finally, estimates of the cost of each project were assigned, based upon the anticipated magnitude of the project, and the benefit of the project was estimated.

2.3 Developing a Methodology

Ultimately, the selection of specific projects will be made based upon a number of factors which go beyond the capability of the analysis presented here. However, a structured method will aid decision makers to properly understand the impact of their decisions. The aim is to make as much relevant information available to decision makers in a readily understandable format and in such a manner that sensitivities to decisions can be evaluated. That is not to say, however, that this type of systematic evaluation can replace the judgment of those who are working with the day-to-day problems. A systematic approach will help to avoid undertaking a course of action which has little chance of success or expected benefits. In addition, it will help to address the full set of problems which must be overcome in order to deploy technology.

From the outset, it has been recognized that within the framework of federal policy, the needs of the transit community and the complexity of the transit infrastructure, there are many objectives which cannot be collapsed into a single, scalar payoff function. However, the most common problem faced by this industry today is cost - cost of operation from year to year and the cost of new systems. Thus, a multi-stepped methodology has been developed which begins with cost-benefit comparisons. This first step can be used as a first-pass filter after which a multi-attribute payoff function can be defined for comparing alternative projects.

The cost-benefit relationship has been defined in terms of the present value of the cost of a particular project and the present value of the benefit (cost reduction to the property) of that project. The present value of benefit requires an assessment of how the technology will be used. Due to the severe financial pressures of operating properties today, it is assumed that new technology will be placed into service through replacement of existing equipment as it is retired or rehabilitated. In the case of a change in procedures, it is assumed that UMTA will bear the cost of proving the effectiveness of the procedural change. In the case of a change in design practice or construction practice, it is assumed that UMTA will assure the adequate demonstration of the practice prior to the allocation of capital or operating grants.

To determine the benefit, it is necessary to estimate the replacement rate of items which would be affected by R&D. For example, the benefit of R&D for vehicle components would be realized as those components are replaced in the vehicle fleets, thereby necessitating estimates of component replacement rates. In the case of revitalization of fixed facilities, an estimate is required for the rate of revitalization for the affected facilities. In the case of a modification in design practice, an estimate of the rate of implementation of new designs is required. There may be instances where the actual rates could be higher after the actual benefit of the new technology is proven in practice. However, such an optimistic assumption should not be made in light of the cautious attitude of the industry to new technology.

3. DATA BASE ON COST, SYSTEM CHARACTERISTICS AND TECHNOLOGY

3.1 Sources of Information

A cost data base was developed for this task. Presented here are the cost and characteristics of rail rapid transit systems. These costs are expressed in 1979 dollars. The capital cost data was basically extracted from the Dyer [1] study and the operating cost data was derived for the year 1975 from the APTA Transit Operating Report. [2] Other reports include the DeLeuw Cather [3] study on the state-of-the-art review of light rail transit and the OTA report on Automatic Train Control in Rail Rapid Transit [4]. Additional published reports and transit agency studies are noted as presented.

3.2 Recent Trends in Costs

Cost escalations over time for various subsystems in rail transit systems require the use of appropriate inflation rates. Operations and maintenance costs are mostly attributable to labor costs. Capital costs, especially in construction and materials, have in recent years gone up faster than the consumer price index.

Table 3-1 shows the escalation factors and relative inflation rates used in estimating capital and O&M costs in October 1979 for various elements of the cost breakdown structure.

The consumer price index increase for the years 1972-1978 averaged 7.72%.

3.3 Baseline System Characteristics

Basic system characteristics of the rail rapid transit systems in the United States are summarized in Table 3-2, which describes the various systems in terms of route miles and number of vehicles. Systems planned and under construction are also included. Track mileage is separated on the basis of its location, whether at grade, elevated or subsurface.

Table 3-1. Escalation Factors for Rail Transit System Costs

	Cost Item	Relative Inflation Rate %	Annual Installation Rate %
1.	Routeway (ROW, Preparation & Restoration)	ENR Construction Cost Index, +2.5	10.22
2.	Guideway Construction	ENR, CCI, +2.5	10.22
3.	Station Construction	ENR, CCI, +2.5	10.22
4.	Maintenance Facilities	ENR, CCI, +2.5	10.22
5.	Administrative Facilities	ENR, CCI, +2.5	10.22
6.	Communications and Control	WMATA, Train Control, +.92	8.64
7.	Power Subsystem	WMATA-Traction Power Escalation Factors, +2.38	10.10
8.	Vehicle Subsystem	WPI, Railroad Equipment + 3.18	10.9
9.	General, Other	Wholesale Price Index + 0.98	8.7
10.	Operations, Labor	BLS, Union Wages + 2.5	10.22
11.	Energy, Propulsion	WPI-Electrical Power + 3.94	11.66
12.	Maintenance, Labor	BLS, Union Wages + 2.5	10.22
13.	Administration, etc.	BLS, Union Wages +2.5	10.22

Source: General Research Corp., "Life Cycle Cost Model for Comparing AGT and Conventional Transit Alternatives", 1976. [5]

UMTA, "Life Cycle Cost Model for AGT."

ENR = Engineering News Record
BLS = Bureau of Labor Statistics, U.S. Department of Labor
WPI = Wholesale Price Index

Table 3-2. Basic System Characteristics [4] [6]

		Track (Mileage)				
	Stns	At Grade	Elevated	Tunnels	Total	Vehicles*
BART	34	25	23	23	71	390
WMATA	86	42	9	47	98	560
NYCTA	463	23	72	137	232	6660
CTA	142	41	39	10	90	1090
MBTA	42	16	4	10	30	340
PATCO	12	9	1	4	14	75
SEPTA	54	24	-	-	24	460
CTS	29	18.7	-	0.5	19.2	110
PATH	13	6.5	-	7.5	14	300
MARTA***	41	27	16	10	53	335
MTA/MD**	3	-	-	-	6	30
MIAMI**	13	-	-	-	20	150

* 1975 estimate

** Not in operation, under construction

*** First phase now in operation

Most track gauges used in U.S. systems are the standard 56.5 inches, except for BART which uses 66 inches, portions of SEPTA which are narrow gauge, and WMATA where there is a ¼" difference from the standard. There is a considerable difference in car widths among various systems. A summary of car widths used in various U.S. systems is shown below.

System	Width of Car [3]
BART	10 ft 6 in.
MBTA	8 ft 3 in., 9 ft., 9 ft 10 in., 10 ft.
CTA	8 ft 10 in., 9 ft 4 in.
CTS	10 ft., 10 ft 5 in.
NYCTA	9 ft., 10 ft.
PATH	9 ft 3 in., 9 ft 4 in.
SEPTA	9 ft 1 in., 10 ft.
WMATA	10 ft 2 in.
MARTA	10 ft 6 in.
SOAC*	9 ft 11 in.

The fare collection systems used by various transit agencies is shown in Table 3-3. While these differences have evolved over time, considerable O&M cost differences occur based on the system chosen.

Table 3-3. Fare Collection Systems in Use on North American Rapid Transit Systems [3]

Property	Medium	Manner of Collection	Fare Structure
MBTA	Coin-token	Turnstile Fare box on vehicle	Flat fare - zone Pay to enter
CTA	Coin or token	Turnstile Station attendant Conductor on Train	Flat fare Pay to enter or en route
CTS	Coin	Station agent Turnstile Fare box on train	Flat fare Pay to enter
MUCTC	Ticket Manual dispensing	Turnstile	Flat fare Pay to enter
NYCTA	Token or coin	Station Agent Turnstile Conductor on train Coin box	Flat fare Pay to enter or en route
PATH	Coins	Turnstile	Flat fare Pay to enter
PATCO	Magnetic ticket Vending machines Manual Sales	Electronic gate	Flat fare - zone Pay to enter Checkout to exit
BART & WMATA	Magnetic ticket Automatic dispensing	Entry gate Exit gate	Variable fare Buy ticket to enter; subtract fare to exit (automatic)
TTC	Token-ticket	Station agent Turnstile (token)	Flat fare Pay to enter
MARTA	Monthly Pass Coins	Turnstile	Flat fare (?)

The third rail voltage used in most systems is 600V DC. However, newer systems have adopted slightly higher voltages. BART operates at 1000V DC, and WMATA is using 750V DC. MARTA, MIAMI and Baltimore systems are planned for 750 V and the vehicles for MIAMI and Baltimore are expected to be similar to WMATA.

Service characteristics of some of the systems in the U.S. are summarized in Table 3-4. They include level of automation, speeds, headway and maximum train lengths. The O&M costs differ considerably based on level of automation used. Systems being planned, such as MARTA, are expected to eventually have fully automated train protection, train operation and train supervision.

Table 3-4

Service Characteristics in Typical Transit Systems [4]

	Automation *			Speed (mph)		Headway (min.)		Max. Train Length (cars)
Transit System	ATP	ATO	ATS	Max.	Av.	Peak	Base	
NYCTA	X			50	20	2	10-12	11
CYTA (Dan Ryan)	X			55	30	3	5	8
MBTA (Red Line)	X	X		50	30	2½	4½	4
PATCO	X	X		75	40	2	10	6
BART	X	X	X	80	40	6	6	10

* A check (X) indicates the function is automated. All systems have an on-board operator to run the train or monitor automatic system performance. ATP: Automatic Train Protection, ATO: Automatic Train Operation, ATS: Automatic Train Supervision

Smaller headways require full automation. Train lengths have a major impact on station construction costs.

3.4 Baseline System Costs

A. Capital Costs

The capital costs shown in this section are extrapolated to 1979 costs from the Dyer Study. The costs described in this section include costs of acquiring right-of-way, route construction, guideway construction, utility relocation, signal and communication equipment, constructing and equipping stations, yards and maintenance shops and vehicles. Not included in capital costs are the costs of administrative buildings, maintenance and diagnostic equipment and start-up costs. It should be noted that the costs shown in this section are based on actual costs in the U.S. in recent years. Recent UMTA efforts in utilizing innovative tunnel construction technology resulting in lower capital costs is not reflected in these costs.

1. Route Construction

Construction costs depend on whether the route is elevated, at grade or subsurface and the geology. The cost is expressed in October 1979 million dollars per mile of double track.

	Suburban Areas		City & Core	
	Low	High	Low	High
At Grade	1.863	6.1236	-	-
Elevated	4.568	13.510	23.50	27.78
Depressed (Open Cut)	6.804	19.80	-	-
Subsurface				
Depressed (Cut & Cover)	-	-	29.16	54.64
Tunnel, Rock	-	-	16.2	32.4
Tunnel, Earth	-	-	24.3	48.6
Sunken Tube	-	-	-	80.0

Costs Include:

Grading, drainage, utilities, structures, traffic handling, demolition and fences.

2. Guideway Construction, per mile (million $)

	Suburban	City	Core
Track Structure			
At Grade & Subsurface	1.09	1.43	1.57
Elevated	1.20	1.32	1.45
Special Trackwork			
At Grade & Subsurface	.20	.189	.21
Elevated	.132	.147	.16
Totals:			
At Grade & Subsurface	1.290	1.619	1.78
Elevated	1.332	1.467	1.61

3. Signal and Communications, per unit (million $)

Item	Unit	Low	High
Wayside ATC	Mile	.729 - 1 1.296 - 2	1.053 - 1 1.782 - 2
Supervisory Control	Mile	.268 - 1 1.61 - 2	.335 - 1 2.01 - 2
Communications	Mile	.0469	.0603
Total - 1		1.04	1.4483
Total - 2		2.95	3.85
Vehicle, Communications and Control Equipment		.032/per vehicle	

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1 Without speed regulation
2 With speed regulation

Storage yards, up to 150 vehicles, cost/yard (million $)

1.	Push Button Control	1.94
2.	Controlled Trailable Switches	4.53
3.	Fully Interlocked Control	5.83
4.	Full ATC	17.00

4. Electrification Construction Costs, per mile, (million $)

Double Track	Low	High
600 V DC, Including Substations	1.13	1.377

5. Land Acquisition Cost, per mile double track, (million $)

	Low	High
Suburban	.210	.641
City	2.13	6.40
Core	4.27	12.80

6. Station Construction, million $ per station

	Suburban		City		Core	
	Low	High	Low	High	Low	High
Elevated	1.13	8.36	1.539	4.617	2.25	7.50
At Grade	.570	6.723	-		-	
Depressed, open cut	1.40	8.91	-		-	
Depressed, cut & cover	-		2.19	6.80	8.10	19.44

Cost includes parking, access, platform, station facility, and awning.

7. Storage yards, (million $)/yard

Low	High
5.52 (30 vehicles)	21.01 (300 vehicles)

Yard cost includes grading, drainage, utilities, track, power, fence and buildings.

8. Maintenance Shops (million $)

Low	High
12.5	45.0

Cost includes buildings, drainage, utilities, power, yard track, fence and grading.

9. Vehicles (million $)

Vehicle cost depends on fleet size for a minimum order of 100-200 vehicle fleet.

Low	High
.567	.891

At WMATA, a recent car buy cost $563,000 per vehicle in 1976 which is equivalent to about $750,000 in October 1979 cost.

B. Rapid Rail Rehabilitation Costs

These costs are based largely on commuter rail system costs developed by Dyer (1977). Items of rail transit not addressed by the Dyer study consist of the refurbishing of the tunnels and station costs to accommodate the elderly and handicapped. While the requirement to equip stations to accommodate elderly and handicapped people is being evaluated by the industry at this time, there is definitely a need to develop accurate cost estimates for repairing the tunnels. These repair costs are expected to vary widely because of the differences in age and structural state of the tunnels.

1. Route Upgrading Costs (dollars per route of double track mile)

	Low	High
At Grade	538,000	5,000,000
Depressed	4,050,000	12,000,000

2. Guideway Upgrading Costs (dollars per route of double track mile)

	Suburban	City	Core
Track Structures	955,800	1,053,000	1,156,680
Special Trackwork	121,500	133,650	147,420
	$1,077,300	1,186,650	1,264,100

3.5 Unitized Costs and Variations

Total O&M expenditures for systems shown in Table 3-5 amount to $1.47 billion per year in 1979 dollars. The data available was broken down by the categories of maintenance of way, equipment, power, and transportation and administrative expenses.

An analysis of these expenditures show that maintenance of way expenditures per vehicle-mile vary from $0.269 at CTA to $1.575 at MBTA. The maintenance of equipment per vehicle mile cost varies from $0.368 at PATCO to $0.796 at MBTA. The higher cost at MBTA probably reflects extensive revitalization occurring there.

Table 3-5. 1979 System O&M Cost Projections

	PATH	CTA	CTS	NYCTA	MBTA	BART	SEPTA	PATCO	WMATA
M/W, $/Mile	650,448	129,614	59,108	676,940	420,891	--	225,240	107,483	--
M/E, $/Vehicle	19,780	21,780	12,539	19,786	24,005	--	7,210	20,685	--
Power, $/VM	0.413	0.195	.293	.499	.657	--	.595	.511	--
Transportation, $/VM	1.52	1.00	.905	1.440	2.488	.595	1.852	.691	--
Administrative $/VM	1.631	0.676	.164	.441	1.861	.53	1.275	.514	--
M/W, $/VM	1.287	0.269	.343	.527	1.575	2.30**	.926	.370	--
M/E, $/VM	0.555	0.482	.383	.432	.796	--	.750	.368	--
Total O&M, $/VM	5.406	2.622	2.088	3.339	7.377	4.42	4.648	2.454	
Annual VMT	10.6E6	50.E6	3.6E6	306.E6	10.5E6	22E6	14.6E6	4.2E6	
Annual O&M ($*$10^6$)	57.3	131.1	7.516	1021.7	77.45	97.24	67.86	10.30	35.3+

Total U.S. Annual O&M Expenditure* in 1979 = $1.47 billion

M/W = Maintenance of Ways and Structure
M/E = Maintenance of Equipment
VM = Vehicle Mile
VMT = Vehicle Miles Traveled
O&M = Operation and Maintenance

* Excluding WMATA

**Includes Maintenance of Equipment

\+ 1978 Cost

However, maintenance of way based on expenditure per mile varies from $107,483 at PATCO to $676,940 at NYCTA. These costs essentially reflect the age of the track and extent of subways in the track at NYCTA. Maintenance of equipment based on a per vehicle basis shows that this cost is lowest at SEPTA ($7,210) and highest at MBTA ($24,005). While the maintenance costs are generally labor dependent, the labor cost variations on an hourly basis do not account for the substantial differences in the actual costs at various systems.

Most systems include bus systems operations and the administrative cost comparison becomes complicated. However these costs vary from $0.441 at NYCTA to $1.861 at MBTA.

Power costs generally are higher on the east coast compared to the midwest and west coast. An analysis of kWh/vehicle mile showed little variation among the systems when corrected for vehicle weight. Transportation costs vary between $0.90 at CTS to $1.852 at SEPTA except for MBTA which showed $2.488 per vehicle mile. The rapid rise in the price of oil beginning in 1973 has encouraged transit agencies to conduct vigorous efforts to lower their power costs. These efforts include: less frequent service, shorter trains during off hours, increased coasting, and a stronger negotiating stance with the power utility. This has caused power costs to grow at a slower rate than indicated in Table 3-5. In estimating 1979 power costs, more recent and specific data, as in Table A-1 should be used.

Comparison of costs at various properties is not meaningful because of varying type of service, age of the rolling stock and track, and labor costs.

3.6 New York City Transit Authority (NYCTA) Data Base

Detailed cost data from the New York City Transit Authority was published as a "Financial and Statistical Report for Fiscal Year ending June 30, 1976." It allows some observations of the relative costs for some major vehicle subsystems, as well as detailed costs for all areas of rapid transit operation. For example, "Maintenance of Way" information is given in terms of 46 sub-areas. A complete listing of the data is given in Table A-1.

The major vehicle component repairs are listed as bodies, painting and varnishing, wheels and axles, other repairs, car brakes, control apparatus and wiring, motors, storage batteries, air compressors and governors, light, heat and fan circuits, radio equipment and accessories, and air conditioning equipment accessories. The relative percentages of these costs to each other is given in Table 3-6.

Table 3-6. Relative Weights of Selected Costs Affecting the Transit Vehicle at NYCTA

Cost Category	Percentage of Vehicle Costs
Car Bodies	10.3
Painting and Varnishing	3.0
Wheels and Axles	6.3
Other Repairs (car trucks)	14.0
Car Brakes	15.0
Car Control Apparatus and Wiring	24.0
Motors	19.0
Storage Batteries	0.4
Air Compressors and Governors	3.3
Light, Heat and Fan Circuits	1.0
Radio Equipment and Accessories	1.3
Air Conditioning Equipment Accessories	2.4

3.7 Bay Area Rapid Transit District (BART) Data Base

Thorough and detailed cost data has been supplied by the Bay Area Rapid Transit District. The cost, in dollars, and the man-hours spent working on various subsystems, were both given for the six month period ending June 30, 1979.

BART vehicle repair records are broken into four categories: unscheduled, vandalism, preventive maintenance, and heavy repairs or overhaul. Table 3-8 presents a breakdown of the heavy in-house repairs at BART. Two special circumstances must be noted when interpeting this table. Wheel truing which is normally a large cost component is listed under preventive maintenance. Traction motors, although a heavy repair, are not listed in this table since they are serviced under a vendor contract, with an approximate value of $1,000,000 annually.

In-house heavy repair costs were supplied for a total of twelve major programs, broken into thirty-six subprograms and hundreds of their components. Among the information supplied was a comprehensive detailed breakdown of cost associated with transit vehicle components and electronics (Table A-2). About 25% of the cost and about 28% of the man-hours were spent on vehicle electronics and communications maintenance as opposed to vehicle component repair. A detailed breakdown of the relative percentage of maintenance costs and hours is given in Table 3-7.

Table 3-7. Percentage of Vehicle Maintenance in Specific Areas

Description	Percentage of Total Cost	Percentage of Labor Time
Traction Motor	2.9	2.0
Line Switch Box Assembly	1.8	1.9
Brake Grid Assembly-24 Tube R/H	1.9	2.1
Brake Grid Assembly-36 Tube L/H	0.7	0.3
Motor Reactor	negligible	negligible
Line Filter Reactor	negligible	negligible
Current Collector Assembly	0.7	0.4
Motor Control Box	4.7	4.6
Brake Control Unit	2.8	3.5
Parking Brake Control Unit	7.0	3.1
Hydraulic Power Unit	3.4	3.6
Caliper Assembly	3.9	3.4
Condenser Assembly	0.3	0.5
A/C Compressor	14.2	12.1
Evaporator Assembly	0.7	0.9
Air Compressor	0.6	0.7
Air Suspension Control Panel X-End	0.3	0.3
Leveling Valve Assembly	0.9	1.1
Motor Alternator	0.1	0.2
Auxiliary Box Assembly	0.2	0.1
Blower & Air Filter Assembly	negligible	negligible
Light Assembly	negligible	negligible
Retractable Coupler	1.4	1.7
Door Operators	1.5	1.6
Door Control Relay Panel	0.2	0.2
Vehicle Doors	0.2	0.2
Battery Assembly	negligible	negligible
Windshield Wiper Assembly	0.1	0.2
Sun Visor	0.1	0.1
Defroster Assembly	negligible	negligible
Run Number Sign Assembly	negligible	negligible
Attendants Foot Rest	negligible	negligible
Documentation & Miscellaneous	0.2	0.3
ATO Equipment	1.8	1.9
Semi-Conductor Box	10.1	6.5
Truck Assembly	0.3	0.4
Built Component Test Equipment	1.0	1.2
Harness Repair	0.8	0.8
Special Assignments -- (Vehicle Component Repair)	4.6	6.3
Upholstery Repair	4.0	2.9
Carpet Repair	negligible	negligible
Parts Testing/New & Warranty	negligible	negligible
Parts Cleaning	2.4	4.2
Motor Assemblies	0.6	0.4

Table 3-7 (cont.)

Percentage of Vehicle Maintenance in Specific Areas

Description	Percentage of Total Cost	Percentage of Labor Time
Vehicle Cab & Equipment	0.4	0.7
Maintenance Emergency Equipment	negligible	negligible
Electrical/Mechanical Shop Set-Up	negligible	negligible
Track Signal Antenna-Fabrication	0.1	negligible
Plating PC Boards	0.2	0.3
Revenue Vehicle E&C Maintenance	negligible	negligible
Special Assignments -- (Vehicle Electronics & Communications Maintenance)	4.1	6.3
Revenue Vehicle E&C Repair	17.9	20.6
PC Board Artwork Repair	0.2	0.3
ATO Manufacturing	negligible	0.1
Propulsion Manufacturing	0.6	0.6
AFC Manufacturing	negligible	negligible

3.8 Southern California Rapid Transit District (SCRTD) Data Base

Operating cost estimates for several rail alternatives being considered for Los Angeles were prepared and developed by the SCRTD in categories which generally conform to the transit industry's accounting practices.[8] The categories include maintenance of ways and structures, maintenance of vehicles, operating supplies and power, transportation and general administration.

Conventional rail costs were based on comparative analyses using both analytical and empirical cost information. The figures are in 1977 dollars. Detailed 1977 operating cost information was obtained from PATCO and Toronto by the SCRTD. The unit operating costs for several alternatives were thereby derived using analytical procedures (Table 3-8).

It should be noted, however, in considering the costs of administration in the transportation area, that this figure is significantly lower than would be expected in a property which had only rail rapid transit. This is due to the fact that overhead-sharing between rail and non-rail areas of the RTD was taken into account in determining the estimated costs.

3.9 Annual Replacement Rates

Information concerning annual replacement rates and costs at the New York City Transit Authority was supplied in early 1979 by the Transit Authority in response to a transit operator questionnaire sent to them.

The costs included material and labor (by in-house forces) in most cases. The following information represents a very thorough and up-to-date description of the physical features of the New York rail rapid transit system and their associated replacement costs (Table 3-9) and are comparable in most instances to the rest of rail transit industry in general.

Table 3-8. Derivation of Unit Operating Cost

Item	Unit of Measure	Base O&M Cost (1977 Dollars)
Maintenance of Way		
Administration	Lump Sum	245,000
Track	VMT	0.155
Yards & Shops	Vehicle	5,000
Electrification (1)	VMT	0.074
Stations	Each	28,750
Parking	Space	40
Control & Communication	Track Mile	6,325
Maintenance of Vehicles	VMT	0.50
Power		
Vehicles (2)	VMT	0.27
Stations (3)	Each	105,120
Yards & Shops (4)	Lump Sum	262,800
Transportation		
Vehicle Operations (5)	Each	30,000
Administration	Lump Sum	210,000
Stations	Each	125,000
Passenger Service	Lump Sum	600,000
Line Supervision (6)	Lump Sum	250,000
Planning	Lump Sum	175,000
Security (7)	Lump Sum	1,200,000
Control Center (8)	Lump Sum	500,000

(1) Based on PATCO type vehicle.
(2) At 3¢/kWh; 9kWh per mile.
(3) At 400 kVa, 24 hours, 3¢/kWh.
(4) At 1000 kVa, 24 hours, 3¢/kWh.
(5) SCRTD accounting department
(6) At 344 man hours per week; $13.08 per hour.
(7) At 45 men; $26,667 per year.
(8) At 688 man hours per week; $13.08 per hour.

Table 3-9. New York City Transit Authority - Physical Features, Structures and Maintenance of Way

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This table describes equipment types, numbers, service life, and replacement cost. Unless otherwise noted, replacement cost is by in-house forces and includes all labor and material.

a.1. Track - (replacement cost based on a 39 linear feet rail section)

Type I - Wood ties and stone ballast in a structural invert
- Replacement cost approximately $3700
- Normal Service Life - 25+ years
- Time interval between routine maintenance - 10 years
- Between major overhaul - 15 years

Type II - Wood tie blocks in concrete ballast in a structural invert
- Normal Service Life - 30+ years
- Time interval between routine maintenance - 10+ years
- Between major overhaul - 15 years

Type II (Modified) - Same as Type II except that the contact rail ties are 6 in. x 8 in. x 9 ft. 0 in. long with resilient fasteners used in lieu of steel plates

Type III - Wood ties on steel open deck bridges and trestle type structures (elevated track)
- Replacement cost approximately $3600
- Normal Service Life - 20 years
- Time interval between routine maintenance - 10 years

Type VI - Wood ties and stone ballast for use in cut and embankment areas without a concrete invert (surface track)
- Replacement cost approximately $3300

Type VII - Wood ties and stone ballast for use in yard tracks and non-revenue sidings
- Replacement cost is approximately $3300

Type VIII - A concreted track for direct fixation for use in subway structures aerial decks, cut and embankment areas with a concrete invert (for new routes)

---

a.2. Length (track miles)

Elevated Structures	--	182.64 track miles
Surface Structures	--	73.38 track miles
Subway Structures	--	448.45 track miles

Table 3-9. (cont.)

New York City Transit Authority - Physical Features
Structures and Maintenance of Way

a.3. Track Miles by Type

Type Track	Track Miles
I	175
II	185
II (Modified)	95
III	185
VI	57
VII	122 (yards only)
VIII	10

a.4 Miles of Track According to Curvature
Tangent track - approximately 573 miles (approximately 81% of total)

R   7500 ft, approximately 2.5 miles

7500 ft   R   1500 ft, approximately 62 miles

Replacement cost approximately $4000
Normal Service Life - 20+ years
Time interval between routine maintenance - 8+ years
Between major overhaul - 12+ years

1500 ft   R   900 ft, approximately 22.5 miles

Replacement cost approximately $5200
Normal Service Life - 20+ years
Time interval between routine maintenance - 6+ years
Between major overhaul - 12+ years

900 ft   R   500 ft, approximately 24 miles

Replacement cost approximately $5200
Normal Service Life - 15 years
Time interval between routine maintenance - 4 years
Between major overhaul - 10+ years

500 ft   R   200 ft, approximately 23.5 miles

Replacement cost approximately $5200
Normal Service Life - 15 years
Time interval between routine maintenance - 3+ years
Between major overhaul - 8 years

R   200 ft, approximately 2 miles

All other factors same as 500 ft   R   200 ft
All curves under 1500 ft are guarded - year tracks are excluded

Table 3-9 (cont.)

New York City Transit Authority - Physical Features, Structures and Maintenance of Way

b. Rail Lubricators

High pressure grease type systems with treadle operated applicators
224 systems in operation
28 systems are planned
Replacement cost - $40,000
Normal service life - 15 years
Major overhaul - 15 years
Number of units requiring emergency repair - 15

c. Switches (Mainline)

Total in service - 2,459
Elevated - 394
Surface - 982
Subway - 1,083

Service Life

Average replacement cost - $51,000
Normal service life - 20 years
Routine maintenance - 3 years
Major overhaul - 10 years

d. Switch Heaters

1,376 switches are exposed to icing conditions and are equipped with tubular electric heaters applied to the stock rails of each switch. Power is supplied by the contact rail.

Service Life

Replacement cost per heater is $200
Normal service life - 1-10 years
Major overhaul - 1-10 years

Table 3-9. (cont.)

New York City Transit Authority - Physical Features, Structures and Maintenance of Way

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e. Contact Rails

In the past, the hand scraper was used to clean the third rail followed by the application of a mixture of alcohol and diesel fuel. Presently, the method favored to prevent accumulation of ice and snow has been the use of contact rail heaters. The heaters are applied at intervals along the contact rail.

Service Life

Replacement cost for the third rail heater is $100
Normal service life - 5 years
Routine maintenance, annually
Major overhaul - 5 years

---

f. Wood Decking

1. At Stations	100,000 sq ft There is an ongoing program to replace wooden platforms with concrete platforms. The program has a 2 years completion estimate.
2. Walkways	3,900,000 sq ft or approximately 90 acres of catwalk.

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g. Escalators

1. Types	112 heavy duty 24 light duty
2. Treadle Controls	29 escalators have treadle controls. They start when a passenger steps on mat switch.
3. Service Life	The cost is $5,000** per foot of rise for 32" escalators. $6,000** per foot of rise for 48 in. escalators Normal service life is 15-20 years. Routine maintenance is weekly. Major overhaul is 25 years. ** (by contract)

Table 3-9. (cont.)

New York City Transit Authority - Physical Features, Structures and Maintenance of Way

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h. Fare Collection Equipment

Turnstiles - Numbers

flat fare/token	low mechanical 2,447 low electrical 111 high entrance 205
special fare (two token)	low mechanical 14

Service Life

Normal service life is 20 years.
Routine maintenance every 45 days per unit.
Major overhaul every 8-10 years.
Unscheduled repairs on approximately 2,550 units monthly.
Replacement cost is approximately $2,000.
Approximate purchase price of a high entrance turnstile is $5,000.

---

h.1. RR Clerk Booths/Numbers

24 hour service 521
Part time 225
Total of 746

Type

508 are of the bullet resistant type with electronic communications and air-conditioning.

Service Life

Replacement cost is approximately $40,000** for a bullet resistant booth.
Approximately 20 to 25 booths per month require emergency repairs.
** Average Contract Cost

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h.2. Gates/Numbers

Exit gates 2108
Approximately 800 per year are repaired or repainted.

Table 3-9. (cont.)

New York City Transit Authority - Physical Features,
Structures and Maintenance of Way

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i. Level Changes Devices

Breakdown of retrofitting stations for ambulatory handicapped

243 subway stations
162 elevated stations
34 on grade

Total of 439 stations
Plus 17 interdivisional stations counted as one,
37 if counted individually

Elevators

An average of three elevators required per station
2 from platforms to mezzanine
1 from mezzanine to street

Level Changes (Subway Stations)

Average height from platform to mezzanine varies from 10 ft to 18 ft
From mezzanine to street, 15 ft to 30 ft

Level Changes (Elevated Stations)

Average height from street to mezzanine varies from 13 ft to 25 ft
From mezzanine to platform, 14 ft to 25 ft

Level Changes (Interdivisional Stations)

Average height from street to platform varies from 10 ft to 30 ft
From mezzanine to street, 15 ft to 40 ft

Table 3-10. (cont.)
Distribution of Car Maintenance Costs by Vehicle, (Scheduled and Unscheduled)

Subsystem	Maintenance Cost (1972 $)				
	Routine	Major	Overhaul	Total	%
Car Body	63	0	0	63	.5
Doors	75	183	0	258	2.0
Couplers	200 (300 ATO)	164	196	560	5.0
Draw Bars	11.5	2	19	32	.3
Motor-Generator	27	140	60	227	2.0
Converter	2.5	0	58	61	.5
Battery	12.5	14.5	74	101	1.0
Air Compressor	16.5	7	75	98	1.0
Motors	912	1248	0	2160	21.0
Resistors	0	0	432	432	4.0
Motor Blower	9	26	23.5	59	.5
Gears	228	160	546	934	8.5
Propulsion Control	205	114	267	585	5.2
Brake Control	205	114	183	502	4.5
Master Control	8.1	73	25	106	1.0
Brakes	109	145 Tr. (102 disc)	08	462	4.1
Heaters	685	77.5	28.5	175	1.6
Lights	66.5	30.5	11.5	108	1.0
Fans	21.5	12	16	50	.5
Misc. Electric	56.5	33	175	264	.2
Trucks	160	193	853	1206	11.0
Air Cond. Comp.	56.5	13	64	134	1.5
Air Cond. Condenser	56.5	14	24	94	1.0
AC Evaporator	144	13	29	186	1.7
AC Filters	83	0	0	83	.7
Bearings	12	0	36	48	.5
Wheels	100	1236	868	2204	21.0
	2909	4012	4272	11193	100%

3.11 Power Costs

As indicated in Table 3-5, the costs of electrical power consumption are within the same range as car maintenance costs. Distributing power costs among its several components will facilitate their inclusion in subsequent life cycle cost analyses of alternative research and development projects.

The largest demand for power consumption is electric traction. A 1960[11] study of several transit systems estimated the power consumption for most U.S. systems to be between 4.5 and 5.4 kWh per car mile. These values were calculated by dividing the system wide power costs by the annual car miles traveled and by the charge per kW, which varied between 1.07 and 2.22 cents.

The traction power consumption depends on the car weight, station spacing, maximum speed, acceleration rate, braking rate, track alignment, the design of the control equipment and operating policies.

Transit cars used in the 1960s were usually smaller and slower than those purchased in the 1970s. A simulation of these larger, higher speed type cars used on a system with station frequency of approximately one per mile yielded a power consumption rate of 7 kWh per car mile. The energy consumption could be reduced by 33%, on level track, with only a 5% increase in travel time by proper application of coasting.[12]

The power costs related to non-traction car operations can be approximated by the following set of regression equations. These were developed after an extensive survey of existing transit experiences.[10] The equations were developed by testing different variables in the regression analysis. The original selection of variables was based on known physical relationships and variables added or discarded according to their ability to explain the variations.

These types of equations are valid for the range and condition in which they were developed and are useful for estimating potential benefits of research and development.

kWh (ventilation) = -.0027 (Avg. vel.) + .0289 (.0019) (L) (W) + .0649

L: car length

W: car width

kWh (air conditioning) = -.027 (Avg. vel.) + .016 (2.3 tons) + .636

Tons: coding capacity of air conditioning system in tons

Note: These captions are derived for cars that have either an air conditioning system or a ventilation system.

kWh (lighting) = -.005 (Avg. vel.) + .033 .034(L) +.02 (ft. cand.) + .9 +.116

Ft cand: Level of illumination in foot candles, typically 35fc.

kWh (heating) = -.023 (Avg. vel.) + .017 (17.1 (D) + .86 (L)
-.36 (winter temp.) -.03(Hp) -.04 (car cap) -8.86)
+ .521

D: station spacing in miles

Water temp: Average winter temperature ^{o}F

e.g.	Chicago	26^{o}F
	New York	33^{o}F
	San Francisco	51^{o}F

kWh (Air compressor) = -.0066 (Avg. vel.) + .01 (5.6) + .225
- -.0066 (Avg. vel.) + .281

kWh (Motor generator) = -.017 (Avg. vel.) + .035 (.15 (Amp Hrs) - 5.5)
+ .343

Amp Hours = 2.8 (L) - 93.1, the ampere hour in rating of batteries shared by two cars.

The subsytems powered by the motor generator usually include trainline circuits, public address system, doors, and recharging of batteries.

The preceding equations were developed for the auxiliary powered subsystems being in operation for the fraction of the service time shown below. If a different operating time is used, the equation should be multiplied by the ratio of the new operating time to the assumed time.

Car Item	% Service Time Operating
Motor generator/alternator/converter	90
Lights	70
Fans	60
Heat	35
Air Compressor	50
Air Conditioning	
Compressor	20
Evaporator	20
Condenser	20
Blower	80

The above equations can be used to develop estimates of power consumption. A substitution of the following representative values into the equations yields the following power consumption rates:

Average Velocity	25 mph
Car Length	70 feet
Car Width	10 feet
Tons Cooling	10
Foot Candles	35
Station Spacing	0.6 mile
Winter Temperature	33 °F
Car Capacity	300 passengers
HP	560 horsepower per car

kWh (ventilation)	.036 kilowatt hours/car mile
kWh (air conditioning)	.697
kWh (lighting)	.080
kWh (heating)	.300
kWh (air compressor)	.166
kWh (motor generator)	.266

The previous air conditioning expression was developed for an air conditioner turned on for 1/3 of the year and in service for 60% of that time it is turned on. A more contemporary approach would assume that the air conditioning was turned on for at least 1/2 the year. The previous air conditioning estimate will be increased by 33% from .697 to 1.06 kWh per car mile.

The total power consumption per car mile is estimated below.

Table 3-11

Transit Car Power Consumption

Function	Power Consumption	Percent
Traction	5.0 kWh per car mile	72
Air Conditioning	1.06	15
Heating	.30	4
Lighting	.08	1
Air Compressor	.16	2
Motor Generator	.27	
	6.87	100%

Measurements of the instantaneous air conditioning power requirements on test subway car revealed that they could represent between 30 and 50% of total car requirements.[13] This corresponds well with the value in the above table, where the air conditioning system was assumed to be in service 50% of the year.

4. CANDIDATE PROJECT LIST

4.1 Development of Candidate Projects

Several sources were used for the development of the candidates project list. The prime source was the suggestions developed in a series of meetings with the staff of several operating transit agencies. Recent research on the development and implementation of product innovations has indicated that the users of a product are usually the best source of suggestions for operational improvements. Heavy reliance on the proposals from the transit operators will help ensure that the candidate project list addresses real and important problems and that the final product of this research, development and deployment program will be accepted and implemented. Additional project suggestions were selected from various publications of APTA, existing, planned, and proposed UMTA programs, the general literature, and JPL staff analysis.

Project development sessions were held at seven different transit agencies: New York City Transit Authority, Port Authority Trans Hudson, Toronto Transit Commission, Massachusetts Bay Transportation Authority, Chicago Transit Authority, South Eastern Pennsylvania Transportation Authority, and the Bay Area Rapid Transit System. These sessions were arranged by APTA in support to the UMTA STARS project. In attendance were APTA, the staff from the UMTA Office of Technology, Development, and Deployment and the various regional offices, JPL staff, and a representative from the Transportation Systems Center. Personnel from the operating agencies were from various departments such as car maintenance, engineering, stations, etc., and research when such a department existed.

Prior to the meetings, agencies were requested to complete a one-page summary for each project with a description of the problem, an estimate of the benefits desired from the project, and an estimate of the cost to develop the solution. The project needs were described very well, but understandably very few agencies had sufficient data to estimate benefits or costs. In addition to the formal suggestions presented on paper, others were developed in the course of the conversations.

APTA's 5-year research and development plan and the proceedings from the UMTA/APTA sponsored research and development priorities conference were also reviewed for suggestions.[14]

The projects developed by this process were combined with the considerable work done by UMTA in their existing, presently planned, or proposed future projects.

A project represents a specific UMTA R&D activity having a tangible end product which can readily be converted to products and services provided by the transit industry and purchased or used by operators. This definition requires some additional effort to yield a format that UMTA can use for budget preparation purposes. For example, several projects may each require high expenditures for extended testing. It is likely that UMTA may decide to aggregate these testing expenses into a lump sum for the Transportation Test Center. Similarly, the projects also plan expenditures for value engineering and product introduction, and assume the continued involvement of UMTA and APTA staff.

Similar R&D suggestions were grouped together to form a series of more comprehensive projects for the candidate list. Several suggestions although valuable, were not included as they were local capital improvements and not research and development projects. The resultant candidate project list offers a selection of R&D projects most of which could have a significant impact on the rail transit system of the nation, within reasonable time and money constraints.

4.2 Purposes of R&D

R&D projects should be justified from the operators' point of view for one of the six following purposes.

1. Capital Cost Reduction

Many of the operators are now at the stage of having to revitalize their system by procuring or refurbishing rolling stock and wayside equipment. In addition, at least one property is faced with the requirement of restoring the roadbed. Further, there are extensions being made to several of the operating properties. From the operator's point of view, these represent major investments at a time when it is difficult to meet operating costs alone. Thus, they have appealed to UMTA for assistance. R&D projects which can significantly reduce capital costs will, therefore, have a major impact on UMTA expenditures for capital improvements.

2. Operating Cost Reduction

Operating costs are important to transit properties, taking priority over improvements in reliability, improvements in safety and security, etc. It is the major concern of transit properties. R&D initiatives which could reduce operating costs in the near-term are viewed as high priority projects. However, projects aimed at reducing operating costs will not have as significant a benefit as projects which reduce capital costs to UMTA to reduce federal expenditures in support of the transit properties.

3. Reliability Enhancement

Reliability is a primary concern to the operators since failures usually occur during rush hour when they can be least afforded. The basic design of a transit system requires efficient use of trackage and a failure on one segment of track essentially blocks the use of that track until the failure is corrected, which may not occur until the rush hour is over. Thus, there are a few key elements where failures cannot be tolerated but where they do occur with current technology.

4. Increased Public Acceptance

In the established transit properties, there has been a gradual decline in ridership. R&D which could make the rail transit system more attractive to the general public would have the long-term benefit of increasing patronage and, increasing the willingness of the general public to support their transit system.

5. Safety and Security

Although rail transit has historically been a relatively safe mode of transportation, it, like other mass transportation systems, cannot afford failures which jeopardize lives. Thus, safety will continue to rank highly among the purposes of R&D. As security is in the eyes of the beholders, it is important that the public perceive that they are secure in the use of the transit system. In light of the increase in crime in major cities, especially crimes of violence in public places, the properties are looking to R&D as one means of improving the perceived and actual security in the use of the system.

6. Satisfying Federal Objectives

The above purposes would suffice for the operators as a list of reasons for conducting research and development. However, they are viewing R&D in the narrow sense of satisfying the requirements of their individual agencies. But, requirements levied upon them by federal objectives must likewise be satisfied. The clearest current example of these federal objectives is that of service to the handicapped and other transportation disadvantaged individuals. They also see that reduction in noise pollution is on the horizon as another major federal objective toward which they will have to contribute. Near-term projects undertaken by the UMTA Office of Rail and Construction Technology must be designed to support goals of the existing systems as well as the goals of DOT. In certain cases, the DOT priorities may conflict with existing priorities of the operators. However, project success requires a cooperative effort between UMTA and the transit industry (operators and suppliers). Thus, care must be exercised early in the project definition and scope to assure a cooperative effort. Specifically, that set of projects which satisfies mutual goals will have the best chance of success. Recently, JPL conducted an analysis of DOT Near-Term Transportation Research, Development and Demonstration Activities, JPL Report 78-49.[15] In review, the six DOT technology goals were found to be:

(a) Modernize Regulation/Legislation. Update the economic regulation of interstate transportation, eliminate unnecessary restrictions on intermodal competition, improve processes for resolving transportation issues, and investigate inequitable means for recovery of costs from beneficiaries for federal expenditures on transportation.

(b) Increase Efficiency and Service. Primarily, improve existing transportation systems.

(c) Improve Safety and Security. Protect the Nation's transportation system, the operating personnel, passengers, and freight from harm or destruction from natural or accidental causes.

(d) Lessen Unfavorable Environmental Effects. Reduce deleterious effects of transportation on the natural environment.

(e) Minimize Adverse Impacts of Energy Constraints. Reduce the energy requirements of transportation systems.

(f) Increase Knowledge Base. Advance the overall level of knowledge about the nation's transportation system, its capabilities, and its problems.

As can be seen, the stated goals are quite broad. However, as applied to the current needs of the operators, the following goals are notable:

(a) Increase efficiency and service equipment, construction, operating and maintenance costs must be reduced while maintaining the level of service. Paramount are revitalization of wayside and rolling stock and improvement in wheel life.

(b) Improve safety and security in the older systems, the general public (and even the staff of the transit operators) perceives that its transit system is not secure from acts of violence. In addition, there is the continual concern over fires and collision.

(c) Lessen unfavorable environmental impacts noise in the cities is of growing social concern. Low cost technology options must be developed to reduce noise from rail systems to acceptable levels.

(d) Minimize adverse impacts of energy constraints more efficient propulsion and energy management systems are needed.

(e) Minimize cost of making systems accessible to the elderly and handicapped.

4.3 Stages of R&D

It is evident after discussions with the engineering, operations and maintenance departments of the transit properties that a major area in which UMTA could assist the industry is in the transfer of existing technology to the operators. At the other extreme of possible UMTA projects is applied research. Thus, recognizing that there is a spectrum of possible R&D projects, we have categorized them into the following.

A. Applied Research

Applied research is necessary when there is sparse technical data. The purpose of applied research projects is to develop models and obtain the required technical data on the physics and nature of the problem. One good example of an applied research project is that of investigating rail corrugation. In this case, it appears that there is an inadequate data base to determine why rail corrugation occurs and what the physical effects of corrugations are; i.e., the exact physical distortion of the rail is not adequately understood. Thus, applied research encompasses those projects where even the basic data is missing.

B. Advanced Development

In this category, it is assumed that the basic technical and physical information is available but that the technology has not been completed to the point where it can be applied to rail transit. An example of this type of project might be an advanced control strategy which would employ redundant microprocessor elements. Here the control requirements are fairly well understood and the capabilities and limitations of digital hardware elements are well understood. But the two have never been brought together in a complete control system, even though BART is using mini-computers at wayside as backup to the primary control system. Another control example would be the redundant control system used in the Morgantown PRT demonstration. This control strategy deviates significantly from the historically accepted use of vital relays. However, it has been referred to by some as "fail safe" even recognizing that nothing can be purely classified as such.

C. Near-Term Development

In this category, it is assumed that the technology exists but that it has not been engineered for the specific application in mind. For example, one could include as a near-term development item specially designed elevators for use by the physically handicapped in transit stations. Near-term developments are restricted to those items which would have universal application to transit operations and not something to meet the unique requirement at one property. In other words, products are sought which can be successfully marketed by the supplying industry to the users as a whole.

D. Technology Deployment

In this category of project, it is assumed that the engineering is complete; that is, the prototype hardware or software has been developed and tested in a controlled environment and has been demonstrated in some revenue service operation. The final step still needs to take place. That is, the supplier industry relationship with the users (operators) must be developed. This last step is vitally important in order to achieve success for near-term developments.

The above definitions are not very sharp at their interfaces. Recognizing that one is dealing with a continuum from basic research to technology deployment, it would be impossible to define very sharp boundaries between project types. However, it is necessary to categorize projects into one of the four areas above in order to scope the necessary activities from project start to finish.

One conclusion which was reached from reviewing the results presented by the operators is that, with four exceptions, all of the proposed projects fall into the category of near-term development or technology deployment. The four exceptions are wheel/rail interaction, stray current corrosion, tunnel integrity, and management systems. In these four cases, the amount of information available on the physical and sociological characteristics of the system is so limited as to warrant applied research. Those will be discussed in detail subsequently.

4.4 Project Selection Criteria

Based upon our discussions with the operators, it appears that there are at least four criteria which must be satisfied prior to UMTA undertaking a development project. These are:

1. Initial Consensus on Need

Prior to undertaking a project, the project objective must be well understood and the means of completion to the success condition must be clearly visible to operators and to UMTA.

2. Adequate Pre-Revenue Service Test Program

Testing of developmental items must be thorough enough to assure that operators can place the equipment in revenue service, expecting that there will be no major failures which could have a significant impact on their day-to-day operations.

3. Agreement by Operators and Manufacturers on the Definition of Success

Success will only occur when the products developed are manufactured by the established industry and procured and used by the operators on a day-to-day basis.

4. Agreement by Operators to Employ Development Items in Demonstration

This is crucial and represents an early commitment by the operators to the concept of the particular item being developed.

5. Gradual Risk Assumption by Manufacturers

It is extremely important that as the R&D program proceeds, UMTA involvement can be gradually reduced with the responsibility being assumed by the operators and manufacturing infrastructure which will supply the resulting items to the operators. Some caution is needed here as it might be possible to develop an item within one manufacturing infrastructure with that infrastructure not having the capacity or the capability to deliver that item over the long-term to the rail transit operators.

The above criteria are of course only preliminary but should serve as a basis for subsequent development of a complete set.

4.5 Project Areas

Research and development projects have been broken down into the following categories:

1. Structures

This category of projects is aimed at improving the technology which is used to construct transit systems. This includes tunneling and construction at grade or in elevated areas. It also includes the construction of maintenance facilities and stations and the development of technology to protect those structures from the elements.

2. Vehicles

This category includes all hardware elements on the vehicle except the truck and primary propulsion unit.

3. Wheel and Rail

This category includes all hardware aimed at providing and supporting a guideway for the vehicle and the onboard equipment (that is, the trucks) which are used to propel the vehicle along the guideway. A portion of the traditional vehicle hardware has been joined to the rail hardware since it is the wheel/rail interface which is the predominant concern in the maintenance of rail systems.

4. Signaling, Communication and Control

These projects deal with hardware in the above categories of an electrical or electronic nature except that which is on board the vehicle. In addition, wayside equipment which would normally be supplied by the signaling contractor is included.

5. Operations

This category includes all hardware and software used for system management and monitoring.

6. Maintenance of Way

This category includes all hardware and software used to keep the tracks, roadbed, and stations in a satisfactory operational condition.

7. Power Distribution and Primary Propulsion

This category includes all hardware required to deliver propulsion power from the utility to the traction motor. This includes substations, third rail, power system control, traction motors and tractive effort control systems. In essence, all high voltage elements are included here.

8. Systems

In this category are efforts to integrate the transit property into a more efficient system, integrate transit properties and their supplier into a more efficient infrastructure, and provide interfaces to other transportation modes and urban systems.

4.6 Candidate Project List

The candidate projects are listed in two groups. The first group consists of projects requiring initiation and is called tentative new projects. The latter group are projects that are presently funded or planned to be funded by UMTA. Within each group the projects are classified into eight project areas.

A. Tentative New Projects

1. Structures Project Area

Project 1. Materials (Category B, C; Purpose 2,5)

Improved materials can significantly decrease initial costs and/or maintenance costs of both primary and architectural items. Furthermore, it is also possible to improve the safety aspects by use of such materials. In this manner, the effects of vandalism can be markedly decreased and fire safety can be enhanced. The life expectancy of recently purchased ties and lumber decking is considerably less than it had been, resulting in increased replacement costs and service interruptions. In subways, water damage is another area that would greatly benefit from improved materials. Many surfaces on walls and ceilings have a poor appearance and are not vandal resistant.

The project will develop and demonstrate economically feasible solutions to these problems.

Project 2. Durable Station Equipment (Category B,C; Purpose 2,5)

There are three important types of benefits that can be realized by improving the durability of station equipment: (1) the flow of users will not be unnecessarily impeded (such as by break-down in the escalators); (2) the cost of maintenance and replacement can be decreased to more than off-set the possible increase in initial costs; and (3) the equipment that is normally put into place before the station is built around it must have extended lifetimes. Intense use of escalators causes frequent maintenance problems. Mat or treadle controls for patron-operated escalators do not operate as reliably as they could, and are not having the desired effect on reducing escalator maintenance. Light fixtures in subway stations should be more resistant to vibration and vandalism. The project will develop and demonstrate economically feasible solutions to these problems.

2. Vehicles Project Area

Project 1. Vehicle HVAC Maintenance
(Category B,D; Purpose 2, 3, 4, 6.2)

Heating, ventilation and air conditioning (HVAC) equipment failures and service requirements impose shortened vehicle service intervals and interrupt service. The objective of this project would be to remove HVAC as a critical maintenance item and substantially reduce HVAC failures. This project would first survey each operator and supplier to assess equipment used, determine equipment configurations, identify failure modes and frequency and identify impact on operation and maintenance. Subsequently, alternative concepts would be developed, prototyped and validated in selected operational environments. Improvements to car heat insulating capabilities through semi-reflecting windows will be considered. Requirements and design standards would be developed around available technology. Effort would be concentrated on modular design, fast repair, servicing soft-failures and energy efficiency.

Project 2. Multiplexed Trainlines
(Category B,D; Purpose 1, 2, 3, 5, 6.2, 6.3)

Cars as currently built include a large number of subsystems requiring logical interconnection. Extensive use of wire harnessing is used with each wire having a single signal associated with it. Many of the signals must be transmitted between cars, requiring a large number of contact points on the coupler which gives opportunity for intermittent false signals. Onboard diagnostic instruments require additional presently unavailable signal transmission capacity to function.

This project would develop a system architecture for signal transmission between subsystems and between cars. Multiplexing would be used for non-vital signals. Categories of signals would be defined (e.g., vital, high-priority, etc.) and design rules developed. MUX interface units would be designed, prototyped, and tested in operation. Use of LSI would be emphasized to reduce parts count, improve reliability and reduce cost. This project could have a significant impact on car cost in both procurement and maintenance.

Project 3. Low Maintenance Subsystems
(Category B,D; Purpose 2, 4, 6.2)

Vehicle maintenance is a major cost of system operation. At BART it is 15% of the annual budget, excluding attendant facility costs. At NYCTA, there are nearly twice as many maintenance personnel as motormen. Maintenance costs appear to be dictated by a few subsystems, with different subsystems at different properties. Maintenance costs could be significantly reduced if service intervals of selected subsystems could be lengthened. The subsystems and specific problems that have already been identified include: auxiliary batteries, methods to control state of charge of batteries, rapid deterioration of car controller contacters due to electrical arcing, door failures due to lack of redundancy on indication switches, lack of commercially available electrical fuses that can withstand high surge currents, glass that will not break or scratch readily and produce a good thermal insulation, and methods for field checking compressor oil stored at inspection stations.

This project would conduct an in-depth survey of each property and manufacturer to identify critical subsystems, develop and demonstrate prototype subsystems and document findings.

Project 4. Vehicle Standards and Procurement Practices
(Category A,D; Purpose 1, 2, 3, 4, 6.2)

The industry is plagued by proliferation of vehicle types. This is caused by the lack of sufficient quantity for mass production, development of new specifications by each operator each time a new car buy is made and the exceptionally long life of vehicles. Each buy requires suppliers to essentially start over. Vehicle specifications reflect the experience of only the particular buyer dictating design requirements - where form, fit and function would be preferred - and lacking in the experience of other operators. In addition, procurement practices require mockups, approvals of the buyer, etc.; thus prohibiting meaningful R&D by the suppliers, lack of product lines and high initial and life cycle costs to the operators.

This project would develop form, fit and functional standards and omit mockups and buyer approval for subsystems, critical components and systems integration procedures. Standards and procedures would be coordinated with operators and suppliers to reach concurrence. Standards and procedures would be coordinated with UMTA Capital Grants and would be used on a future vehicle buy by a selected operator.

Project 5. Cab Signal Maintenance
(Category C,D; Purpose 2, 4, 5, 6.2, 6.3)

Malfunctions of cab signaling in revenue service are often not replicable in the shop, increasing the difficulty of correcting the problem. An on board device to record control signals coud lead to reduced maintenance costs and improved reliability.

Many cars are equipped for both cab and wayside signals. The cab signals must be maintained at great cost, even though they are not used since the guideway is only equipped for wayside signals. In addition, as new systems are deployed, initial operation may not be in a fully automated mode, but the capability for such automation may be needed to increase system capacity through reduced headway as ridership increases. A method for modularly uncoupling cab signals would be developed.

Feasible solutions to these problems would be developed and demonstrated.

3. Wheel-Rail Project Area

Project 1. Wheel-Rail Interaction Research
(Category A, B, C; Purpose 4, 2)

The wheel rail interaction is a source of noise, vibration, and wear for both the car and track structure. An improved understanding of this interaction would be developed by a combination of empirical testing on existing transit lines and special test facilities and basic research.

The testing would be directed toward developing design curves for optimum wheel rail performance. The effect of the following on wheel rail maintenance and noise would be determined: wheel hardness, torque impulses during propulsion notching, welded rail, reduced adhesion from oil, water, and dirt, lubricators, damping rings, and methods to increase adhesion.

Project 2. Truck Design Improvement
(Category B, C; Purpose 2, 4)

Truck design has probably undergone the least development of any major piece of railroad-type hardware used in rail transit systems. It has already been shown that significant improvements in the operation of the trucks (less noise, shimmy, derailment, wear) can be obtained by some fundamental changes in the design.

Once a good understanding has been developed of the basic wheel-rail interface, effort should be started on requirements for a truck, and then the design proceeded with. The truck design includes things such as the wheel-axle bearing combination, motor drive, brakes, and any materials that would improve the overall operation of the truck including adhesion.

Project 3. Material Development
(Category B, C; Purpose 2, 4)

The reaction of the wheel to the rail, such as noise, can be altered by a change in the wheel material or by the incorporation of multiple materials. Also, the same may be true for both wear and adhesion. Further, the friction braking effectiveness and durability might be extended by the use of alternate materials. Thermal capacity and resistance to normal stress might be increased by use of alternate materials. Effort on this project should be integrated with the wheel-rail interaction characteristic project.

Project 4. Track Design (Category C, B; Purpose 2, 1)

Once ride and safety requirements have been determined, it is necessary to understand the corresponding conditions placed upon the track design. Then it will be possible to determine just what the requirements should actually be. As a consequence, the conditions that the track must meet while in use will be established. Methods for predicting wheel induced forces and vibrations on track and supporting structures will be developed. The areas of concern to be covered include safety, ride quality, durability, noise, and overall cost.

4. Signaling Communications and Control Project Area

Project 1. Train Control Systems Design and Standardization
(Category A, B, D; Purpose 2, 3, 5, 6.2, 6.3)

Existing transit control systems are primarily an outgrowth of evolutionary designs for railroad applications. These systems in conjunction with operation rules and procedures assure safe train operations for transit properties. Train control failures account for only a tiny fraction of passenger deaths in transit facilities. Failures, however, even though they may be safe, are a major factor in delays. In addition, systems are difficult and expensive to maintain due to non-standard parts and aging technology.

This project would develop a design concept using available and proven technology and a coordinated and compatible set of rules. It would define control systems in a modular sense so that as new technology is made available, it could be implemented. Differences in equipment between different systems would be primarily in software. Minimum criteria for train detection on tracks would be determined. Standards would be developed to permit interchangeability at the component level. This would be a coordinated project involving each operator and the supply industry. It would culminate in modules being demonstrated at selected properties.

Project 2. LRV Vehicle Control and Protection
(Category C, D; Purpose 2, 4, 5, 6.2, 6.3)

LRV operations are principally under manual control. At-grade operations are uncoordinated with automotive traffic. Retrofit control elements can be easily developed to provide coordinated traffic control with traffic signal lights and can provide more efficient movement of LRVs.

This project would examine means of retrofitting existing vehicle protection backup to manual means now employed and to provide control system integration with wayside systems. This project would be coordinated with FHWA, Office of Research. This project would also examine a means of detection of highway vehicles stalled or blocked in grade crossings to avoid collisions with LRVs. As this is of concern also to railroad operations, this project would be coordinated with FRA.

Project 3. Communications (Category C, D; Purpose 2, 4, 5, 6.2, 6.3)

Coordinated voice, video and digital communications are vital to efficient operations of transit systems. Minor disturbances in vehicle movements and other occurences require communications with individuals located throughout the system-on board, central, power substations, maintenance, stations, public safety (fire and police), etc. Currently, each property has some equipment but it is generally aging and does not always meet current needs. There exists an immediate need to update train-to-wayside communications, and improve methods of informing the public of service interruptions.

This project would develop a set of system requirements through coordination with each property. It would develop system concepts using currently available technology to satisfy these requirements. Finally, system prototype modules would be developed in coordination with supplies and concepts demonstrated on selected properties. This project would be coordinated with the Law Enforcement Assistance Administration to assure that system designs are compatible and complementary to above-ground public safety systems.

Project 4. Automated Wayside Car Inspection
(Category B, C, D; Purpose 2, 3)

On board car diagnostics offer the potential of increasing reliability and reducing operating costs. Automated wayside car inspection can measure only a few of the many variables that the on board system can; however, it can be implemented without major retrofits of existing car fleets or waiting for the introduction of new cars. Significant car variables that can be measured from wayside will be identified and automated techniques for performing and analyzing the measurement will be developed. Several of the data items and associated benefits that would be considered for such a system are: the car number could be used to maintain car mileage records; the wheel diameter could be measured and used to detect unequal wheel diameters on the same axle, preventing wheel cracking and derailments due to increased bending stress; the wheel temperature could help detect and prevent wheel spalling due to thermal stress.

Prototype inspection systems would be developed and demonstrated on several operating rapid transit lines.

5. Operations Project Area

Project 1. Passenger Interface Improvements Including Elderly and Handicapped (Category D; Purpose 4, 6)

The goal of this project is to improve the passenger interface with the system occuring mainly at the station areas. There is essentially no standardization of signs, graphics and lighting for the industry. The project objective is to design a system of information display for the passenger so that he can proceed without any assistance. The standardization of such devices would help in reducing procurement problems and would also lower the costs of such devices.

Handling of elderly and handicapped riders also falls in this category. The constraints of station designs and limited type and size of available elevators poses some problems for the operators. A particular need for a narrow elevator that could be readily adapted to existing stations and for low (3.5 feet) level change devices has been identified. Older properties could utilize equipment based on specifications developed by this project.

Project 2. Operations Management (Category B, D; Purpose 2, 3, 4)

The projects in this area attempt to help management of transit systems efficiently use the resources available to them. The projects include studies involving scheduling of train crews, development of a measure of transit system productivity and development of efficient management information systems.

Train crew dispatching will allow for efficient allocation of manpower. A measure of rail transit productivity measure is lacking in the industry and needs to be developed. Finally, the management information system will produce information so that management will have better visibility of maintenance cost and identification of components that need to be redesigned for lower life cycle costs.

Project 3. Fare Collection Devices (Category B, D; Purpose 2, 4, 6)

Reliability of fare collection equipment is a major problem in most of the transit systems. A recent study by the Toronto Transit Commission led them to conclude that the cost of available automated fare collection equipment was as high as that of manual systems. While fully operational equipment can avoid queue formation at entrance, the manfunctioning equipment can affect the perception of reliability of the whole system. It appears that the cause of the failure is the breakdown of the fare card transport mechanism and the money handling equipment such as coin acceptors and bill validators.

This project would develop and design a system using existing technology. The need for transport mechanisms needs to be addressed. Cubic Co. is supplying the equipment to BART and WMATA. Vapor Corp. has recently developed a new system that avoids a transport mechanism. This project would require the demonstration of the reliability of equipment in a closely monitored and controlled environment. Methods of modifying existing single price token systems to accommodate special fares and improved money handling equipment will be developed.

Project 4. Improved Operating Procedures
(Category D; Purpose 3, 4, 6)

In developing a better image of their transit systems, operators are concerned about the ridership perception of the service reliability, such as on-time performance of trains. Through additional improvements using new technology, an effort can be made to come as close as possible to on-time performance. The operating properties indicated a need for such trade-off studies so they can operate at a cost-effective level of performance.

This project will try to evaluate the consequences of on-time performance, reduced boarding times and effective means of handling passengers during system failures such as stalled trains.

Project 5. Operations Efficiency Improvements
(Category d: Purpose 2, 5, 6)

There are many instances in operations where technology can be substituted for manpower, such as using one operator in the train or the use of television surveillance instead of an attendant at the stations. The transit properties are undecided whether the switch to technology can result in lower costs in these instances. This project will analyze situations in rail rapid transit operations to determine the benefits and costs of alternatives to the use of manpower.

Project 6. Fire and Safety (Category C, D; Purpose 5)

It is imperative to minimize damages from fires and accidents. Several problems or needs that have been identified are: safety training manuals, study of passenger behavior in stalled trains, smokeless replacement for PVC insulation, fire resistant car interior linings, smoke and fire control measures, techniques to reduce passenger falls on staircases, and quicker methods for passengers to summon emergency aid. Solutions to these problems would be developed and demonstrated.

6. Maintenance of Way Project Area

Project 1. Track Maintenance (Category B, D; Purpose 2, 6)

The projects in this category relate to improved maintenance procedures in keeping the track operational. Many of the operating properties are concerned about the integrity of tunnel walls and are interested in non-destructive testing of the tunnel walls to determine the level of maintenace to be performed.

Maintaining the track in operational condition requires that standards and instrumentation be developed for analyzing the condition of track geometry, track alignment, rail flaw, rail wear, and joints.

Some properties indicated that tamper blades and rail lubricators were major maintenance items. The need for a ballast undercutter that would function in a confined rapid transit environment was identified.

Project 2. Cold Weather Equipment & Techniques
(Category B; Purpose 2, 3, 4)

Ice and snow are major problems for most U.S. transit systems. Cold weather affects equipment performance and passenger comfort.

The objective of this project is to develop equipment or techniques that help in keeping the track, switches, third rail, and platforms clear of snow and ice. Most properties use shovels to clear the snow on platforms but seem to be interested in better equipment. PATH uses an antifreeze agent to keep the third rail de-iced. The effectiveness of such agents is now known but they are known to cause corrosion, as is evidenced at PATH. Improved methods for providing a comfortable environment to waiting passengers are also required. Solutions to these problems will be developed and demonstrated.

Project 3. Station Cleaning (Category C, D; Purpose 1, 4)

Improved station cleaning equipment could lead to cleaner stations and lower costs. Equipment needs that have been identified include pressure washers, lightweight mechanical sweepers, and water-pressure rotating wall brushes. Older transit systems, without elevators, may require equipment that can easily be carried up stairways. Prototype equipment would be acquired, or developed and demonstrated.

7. Propulsion Unit and Power Distribution Project Area

Project 1. Power Efficiency and Reliability
(Category B, C; Purpose 2, 6.5)

Electrical energy costs can run as high as 15% of the total operating cost of a rail mass transit system. Power is usually purchased during peak hours and is subject to utility company peak demand charges. Localized failures in the utility company power network can lead to complete and sudden shutdowns of entire transit lines. Surges in third rail voltages necessitate the use of more expensive, specially designed car equipment. Heat generated by dynamic braking energy-dissipating resistors lowers car component reliability and increases station temperatures.

A national survey of utility rate structures for public benefit corporations would be made. This could aid operating agencies in negotiating for lower rates. Alternative regeneration and storage methods such as wayside flywheels, wayside cyrogenic power storage, batteries, and AC inverters would be examined. The capability of these systems to conserve energy, provide power in the event of utility company failures, regulate voltage surges, and to permit power purchase at non-peak times would be examined. Special voltage surge suppression networks would also be considered.

A feasibility study would select the most desirable system and a prototype would be built and demonstrated on an existing system.

Project 2. Propulsion Reliability Enhancement
(Category B, C; Purpose 2, 3)

The primary maintenance effort for the rail transit vehicle is in the propulsion system, primarily the motor itself. The reason for the relatively high incidence of breakdown in the motor must be analyzed. Then it might be possible to incorporate alternate designs that will minimize, if not eliminate, these motor problems. However, similar effort should be put into the rest of the on board propulsion system. Success in this area will significantly decrease the overall maintenance costs of the vehicle and lead to fewer inoperable vehicles. As a result, the fleet size would not need to be as large. Concurrently, procedures must be developed to give adequate notice of an impending problem. This will not only further decrease maintenance costs, but will minimize the number of in-service propulsion system failures. Specific problems identified include use of power contactors, winding dielectric breakdowns, the need for a test to predict remaining coil life, and the need for a portable tester for trip settings of traction-supply circuit-breakers. Prototype solutions to these problems will be developed and demonstrated.

Project 3. Vehicle-Wayside Interface Design
(Category B; Purpose 2, 1)

Wear and power transfer of both the on board power pick-up device (shoe or trolley/pantograph) and the wayside power "line" can be substantially improved. Furthermore, the reliability of a firm contact also needs improvement. Finally, more versatility may be able to be incorporated in the design of the wayside power distribution if the on board power pick-up can be "repackaged."

Project 4. Grounding (Category B, Purpose 2, 5)

Existing grounding procedures result in three major problems: electrolytic corrosion, shock and power dispatch. Effective but practical grounding standards must be established, but first it is necessary to determine the courses of the stray currents. It may be more effective to fight electrolytic corrosion by eliminating the stray currents then by designing equipment to resist electrolytic corrosion. But it must be determined which approach is better with the evaluation including other problems of stray currents, those already discussed and potential signaling and communication interference.

8. Systems Project Area

Project 1. Procurement Practices and Procedures
(Category A, Purpose 1, 2, 6.2, 6.5)

There are fewer than a dozen metropolitan areas using urban rail systems in the United States. With the 30+ years of life demanded from structures and equipment in these systems, the market is very small. Suppliers provide products to this market from spinoffs of other markets, railroads, utilities, etc. Each property procures equipment to unique specifications, procurement practices and procedures. The market is highly unpredictable and risky due to lengthy programmatic and contractual delays, and insufficient capacity to assure a reasonable profit and product price. Many products are of vintage technology. Acquisition, operating and maintenance costs are high and the infrastructure is in a general state of decay.

This project would examine the industry, operator infrastructure and procurement practices and procedures, comparing it to other transportation industries; aviation, automotive, and marine. Practices and procedures which are roadblocks to technology development and deployment, which hinder cost-effective use of technology and which contribute to the weakening of the industry would be identified. Corrective measures and policy changes would be identified. This project would be coordinated with operators, their suppliers, and other government offices involved in procurements of transit equipment and services.

Project 2. Systems Standards & Test Procedures
(Category A; Purpose 1, 2, 3, 4, 5, 6.1, 6.2, 6.3, 6.5, 6.6)

There is much interest within UMTA, and the operators and the suppliers in developing standards for facilities, equipment operating procedures and industry-wide test procedures. If possible, such a transition to industry-wide use has the potential of reducing risk for all parties (operators, suppliers, UMTA, local government) and would encourage price reduction, competition and investment in R&D. In addition, it would encourage use of the best available and proven technology.

This project would examine the benefits of standards and test procedures, including cost savings, and would identify means for implementation. The products from this effort would be a set of standards and procedures which could be used in operations, records management, and procurement.

Project 3. Urban Infrastructure and Policy
(Category A; Purpose 1, 2, 4, 6.1, 6.6)

Transit systems operating in large metropolitan areas interface with a large set of other agencies and government bodies. Principal among these are: (1) electric utilities, (2) local bus companies, (3) funding authorities, (4) taxing authorities, and (5) regulatory and governing authorities. It is important to understand how this infrastructure behaves and its impact on the costs of transit and the impediments to deployment of new technology.

This project would conduct a nationwide survey on urban infrastructure and define these impacts. Particular attention would be given to costs for energy and services and policy impacts on costs and revenues for transit.

Project 4. Model Interface Designs

Point to point (home to office, office to home, etc.) use of transit requires easy and convenient access between modes. At a transit station, there must be facilities for transfer between rail transit and bus, taxi, vanpool, airport, pedestrian, and personal (car, moped, bicycle) modes. However, most existing systems were developed with little regard for these design considerations. In addition, modal transfers must accommodate the elderly and handicapped. There is a need to examine the functional and performance requirements for modal interface designs and translate these into design guidelines.

This project would examine the functional and performance requirements for modal interfaces and would develop design guidelines for interfacing to each mode through modification of existing facilities as well as construction of new facilities. Requirements woud be examined for accommodation of E&H. Attention would be given to inter-modal scheduling and related passenger information systems for improving rail/bus transfer.

Project 5. Systems Requirements
(Category A, D; Purpose 1, 2, 3, 4, 5, 6)

New requirements on transit systems for environmental considerations (noise, visual, etc.), for accommodation of E&H and for improvements in safety, security, energy efficiency, etc., need to be translated and converted into meaningful engineering terms and design practices. In addition, system requirements for safety, reliability, repairability, etc., derived from the experience of current properties need to be collected for future use.

This project would take existing documentation (Environmental Design Handbook) and recent legislation and provide an overview set of systems requirements. It would review existing properties and highlight methods of design to satisfy these requirements. It would collect systems requirements and design practices from current properties in the areas of reliability, maintainability, etc.

Project 6. Passenger Information (Category C, D; Purpose 4)

Transit ridership is limited by lack of route and schedule information. Many systems operate telephone information centers. Due to the expense of manually answered information requests, users of these centers often encounter long delays in obtaining service.

Methods of improving service by developing automated procedures to answer certain information requests would be developed. A prototype using existing technology would be demonstrated.

Project 7. Rehabilitation Scheduling (Category C, D; Purpose 1)

During the life of a transit system, many of its major component systems such as track, ties, signals, and lighting will be individually rehabilitated with a resultant interference in service. The cost of piecemeal rehabilitation could be greater than the cost of an equivalent new line. The existing planning and rehabilitation process would be examined, and alternative methods of staging and coordinating the rehabilitation process evaluated. If proven feasible, a test section on an existing line would be demonstrated.

B. Current or Planned UMTA Rail Research and Development Projects

Currently, there exists a set of projects which are underway in UMTA. In addition, several new projects are in the planning stage. There may be considerable overlap between these projects and those listed in Section A. These projects are listed below.

1. Structures Project Area

Project 1. Construction Technology (Category C, D; Purpose 1)

Methods will be developed and demonstrated to reduce construction and rehabilitation costs for rail transit systems. Efforts will be concentrated in the following areas: design and construction standards/criteria, ground control and stabilization, maintenance and rehabilitation, contracting and management practices, environmental factors, test section demonstrations, and technical workshops.

Project 2. Tunneling Technology (Category C, D; Purpose 1)

Methods to reduce the costs of tunneling construction will be developed and demonstrated. Specific areas of investigation will include: construction procurement, tunnel standardization, economic factors, technical workshops, funding of a precast concrete test section, development of liner design criteria, exchange programs, extruded liners, emergency ventilation, WMATA construction monitoring, demonstration of a slurry wall installation, development of a tunnel brochure, and analysis of BART tunnel data.

2. Vehicles Project Area

Project 1. Advanced Concept Train (Category C, D; Purpose 2, 3, 4)

Two test vehicles have been built which are evaluating improved components that could be used in future car purchases. The areas under evaluation include: flywheel regeneration, increased automation, design for improved reliability, improved slip-side control and composite wheels.

Project 2. Advanced Subsystems Development Program
(Category C, D; Purpose 1, 2, 3, 4)

Several components which have shown potential to increase the safety, reliability, and economics of rail transit vehicles are being evaluated. These include: self-synchronous AC traction motors, monomotor trucks with active suspension, and the synchronous spin-slide control braking system.

Project 3. Test Gas Turbine Electric Commuter Rail Cars
(Category B, C, D; Purpose 4)

These cars offer the potential of providing service from unelectrified areas to underground major city transit terminals without change of trains, and eliminating the need for many electrification programs.

Project 4. Light Rail Passenger Interface
(Category C, D; Purpose 4, 6.2)

Passenger lift devices and wheelchair lift devices for light rail vehicles will be developed.

3. Wheel and Rail Project Area

Project 1. Track & Wayside (Category B, C, D; Purpose 1, 2, 3)

Methods of reducing track and wayside wear will be developed and demonstrated. This will include a concrete tie test installation, study of vehicle induced forces, track testing, and the development of track design standards.

4. Operations Project Area

Project 1. National Reliability Data Bank
(Category B; Purpose 2, 3)

A data source indicating the reliability of various transit operations and components will be developed.

5. Systems Project Area

Project 1. Subsystem Technology Applications to Rail Systems (STARS)
(Category C, D; Purpose 1, 2, 3, 4, 5, 6)

The objectives of the STARS program are to identify rail rapid transit operators' pressing technical and operational problems, apply existing technology to their solution and demonstrate and deploy these solutions in the near term. Specific projects that will be demonstrated are within the following five categories: car equipment, signals power & communications, maintenance, operations & stations, and technology studies (technology coordination, human factors, etc.).

Project 2. Rail Car Standardization
(Category C, D; Purpose 1, 2, 3)

The goal of the project is to achieve lower per unit cost (first cost and life cycle), reduced maintenance problems and costs, increased car availability, reduced requirements for car customization and provision for evolutionary improvement in technology. The project includes development of a "National Design Practices Manual," transit car specification analysis, and an economic study.

Project 3. Noise Abatement Technology
(Category A, B, C, D; Purpose 4, 6.4)

The objective is to reduce noise and vibration on urban rail transit systems. A "Noise Abatement Technology Handbook" will be developed. Studies and tests of resilient wheels and rail grinding and a steerable truck will be conducted.

Project 4. Systems Analysis
(Category A, B; Purpose, 1, 2, 3, 4, 5, 6)

The use of systems analysis will develop a feedback mechanism between actual rail transit needs and experience and current research and development efforts. It will help ensure that research and grant dollars are effectively spent and achieve the desired objectives. The project includes planning support, comparison of central control algorithms, minimization of life cycle costs, and a review of management techniques.

5. PROJECT EVALUATION AND SELECTION METHODOLOGY

5.1 Cost Savings Methodology

The selection of the best set of research, development and demonstration projects ranks among the most complex problems for three reasons. First, the net benefits and uncertainty of such projects are difficult to quantify. Second, research and development projects have multiple purposes, including benefits that may accrue to a small subset of individuals in society such as increasing accessibility for the elderly and handicapped, and benefits that accrue to a large subset of individuals in society such as enhancement of safety, or reduction in emissions and noise. Third, while many of these research and development projects are purported to have a positive net present value, the R&D budget is generally much smaller than the demand for resources for research and development. Thus, a project selection methodology is a useful adjunct to the selection process.

A. The Need and Benefit of a Methodology

The problems of the urban transit industry are somewhat unique. This uniqueness arises from several causes. First, because of large capital investment in rail systems, there is strong reluctance to adopt marginally improved new systems requiring large capital expenditures. Second, reluctance to change also arises from the fact that there is a great deal of responsibility associated with transporting people. Proposed changes must be thoroughly tested before being placed in service. In addition, older transit systems have been plagued by declining ridership limiting the benefits of economics of scale. With these considerations, there is a clear need for a methodology to evaluate a set of applicable candidate projects.

A useful methodology for project evaluation and selection should provide a framework in which project candidates can be critically reviewed for their costs and benefits, explicitly stating the data and assumptions behind the R&D decision process so that they can be scrutinized, and be able to handle both quantitative and qualitative values associated with particular projects. Using a standard methodology to compare projects forces issues into the open, where they can be discussed by both proponents and opponents of a particular project and where the real merits and risks of a project can be assessed by the R&D decision makers.

B. The Need of a Generalized Method

It seems eminently clear that efficient resource usage is paramount among the objectives of any research and development activity associated with urban rail transit. The rising costs of labor and new facilities and equipment are the main problems which plague the transit industry today.

Other important R&D objectives are improvement of facilities to provide service to the elderly and handicapped, reduction in noise caused by urban rail transit systems, improvement in service reliability, enhancement of safety, etc. A complete model must consider all of these objectives and allow choice based upon some selection criteria. This is a multi-attribute approach to decision analysis. A long-term goal is to develop a multi-attribute methodology appropriate for urban rail transit problems. However, the current effort is restricted to evaluating projects based upon the first priority, reduction of cost, although a multi-attribute methodology is also outlined.

C. Characteristics of Transit Projects

The factors of production of a transit system are identified as: (1) labor, (2) energy, (3) materials, and (4) capital. Though a new improvement can be introduced through any one of the four inputs, historically, a predominant amount has been through the fourth element - capital. Thus, the end result is to displace components of labor, energy and materials.

Unfortunately, the labor requirement of this industry is highly resistant to change due to contract commitments with transit unions. There appears to be a bias against labor-saving types of innovations. Energy costs are dictated once a system choice is made. Thus, labor-saving innovation will mainly take place at newly formed transit authorities, and energy-saving innovation will mainly take place at propulsion system replacement points. Material replacement is likewise difficult unless wholesale replacement is possible.

Thus, historically technological improvement has been predominantly in the area of capital expense items - new or replacement equipment, and new or replacement facilities. New technologies should be developed to divert the historical trend. Such technologies should be flexible, permitting improvements even in the operation phase. Also, these technologies should emphasize low capital investment so that entry and exit is easy, hence revealing their economic competitiveness to other forms of transportation.

D. The Role of Federal Government

The demand side of a transit system can be identified by those who benefit from the system. There are four dominant groups who will benefit from technology development and deployment: (1) the manufacturers who design and construct transit systems and supply equipment, (2) the operators who manage the system, (3) consumers - the public or a segment of the public - who benefit from the innovation, (4) union workers who share the benefits of innovation through increased productivity. The supply industry will benefit by improved profit margin. The consumers will benefit by increased satisfaction. The union workers will benefit by having higher wages.

The Federal Government, with its concern about externalities and its ability to assume risk can be a prime mover of new technologies. However, once analysis has shown the existence of a market and R&D has shown technical and economic feasibility, private industry should enter in developing the technology and assuming at least a portion of the costs of market development, and product demonstration and diffusion. The degree to which the private industry is willing to assume these costs is a strong indication of project success. If, after prototype completion, private industry does not carry out further development and is unwilling to share in the cost of demonstration and deployment, the project should be considered a failure.

The Federal Government role in any project should be to reduce risk to innovators, who are thereby encouraged to invest, and to reduce barriers to the development of improved technology. Those projects which show large positive present net value benefit should receive more attention. If the industry (manufacturers and operators) shows interest and is willing to share in the cost of a project, the government should give that project special consideration. However, government RD&D costs and social benefits must also be considered.

Barriers to R&D can be reduced through government encouragement of interface standardization so that R&D costs can be distributed over a larger number of purchases. Also, sponsoring extensive field tests will increase the confidence of operating agencies in the performance of new purchases. Finally, the technical and economic data gathered from testing and demonstrations should be disseminated systematically to those who may benefit in having the data, and who may then foster technological adoption and diffusion.

The Federal Government role is to bear the risk to the point where it can be overcome by the industry and user, and to disseminate the technical and economic data to potential users of the technology. Risk has two components - technological risk and economic risk. The government should ameliorate the influences of both elements in developing new technologies. However, the final test of new technologies is their economic viability. The degree of willingness of industry and users to share in the cost of a project can be used as one measure of the expectation of success of a project. In addition, having industry participation will facilitate information dissemination.

Every R&D project can be viewed as a sequence of positive decision points from concept to completion. A negative decision at an intermediate decision point means either that the project has not matured as expected to that point in the process or that information gained during the project shows that the project objective cannot be reached. In the former case, the project would be rescheduled and reevaluated. In the latter case, it would be terminated. Therefore, procedures or mechanisms to terminate an R&D project must be developed. Stopping a failing R&D project was proven to be difficult.

E. Review of Cost Savings Upper/Lower Methodology

There are four problems associated with using a cost savings methodology. The first pertains to the meaning of cost savings. Consider an existing component which costs $30K. Suppose an R&D project costing $8K can reduce the total component costs to $20K. Can it therefore be said that the cost savings due to the R&D project is $10K and that therefore the net benefit of the R&D project is $2K? The answer is ambiguous. New components that have been developed and are ready for adoption must be considered. Suppose there are on-the-shelf new components which cost $23K. The immediate cost savings to an innovator is $7K. Additional cost savings due to the R&D project will only be $3K. Thus, the net benefit of the R&D project is -$5K. This example indicates that cost data from transit operators and from R&D project managers alone are not sufficient for rational R&D budget allocation. Component manufacturers must be consulted and cost data collected on the latest available components as well.

Furthermore, when speaking of cost savings the best alternative should be used as a reference point. Consider a system operating at a total loss of $10K as compared to the best available alternative. Suppose a new system can be developed by an R&D project so that there will be a $4K net reduction in the system cost. Now, if the revenue remains constant, the new system will be operated at a total loss of $6K. The $4K cost reduction due to the R&D project cannot be considered as the net benefit of the R&D project. There is no positive net benefit since the system still operates at a loss of $6K, as compared to the best available alternative.

Second, there is the problem of joint cost in the use of cost savings. Consider two independent R&D projects. Suppose the first project, considered alone, yields a reduction in component costs and at the same time lowers reliability so that net cost savings is $2K. Also suppose the second project, considered by itself, increases system reliability so that net cost savings is $5K. However, if both projects are successful, their complementary effects may yield a net cost savings in excess of the sum of the net cost savings from each of the projects considered independently. For example, assume the total net cost savings is $8K. How should the extra $1K net cost savings be allocated? Unfortunately, there is no unambiguous answer to that question.

Third, one needs to identify to whom cost savings apply. An economically viable new technology will benefit distinct groups differently. Project managers, for example, are probably most interested in minimizing project cost. Consumers are, of course, interested in cheaper transportation. Finally, union workers may be most concerned with high productivity, hence, providing a basis for bargaining for higher wages. Thus, the vector of cost savings to groups within society may be a possible attribute of the multi-attribute decision analysis. Cost savings, therefore, should include change of ridership, lower resource costs to society from having the transportation options, and other social reductions such as air and noise pollution, etc.

Fourth, and perhaps the most troublesome problem of cost savings, is the collection of data to estimate cost savings. Cost information which is ideal for calculating cost savings is rarely available, as appears to be the case for the urban mass transportation industry. (However, data collection may be improved by the UMTA FARE project.) Judgmental decisions are usually required to aggregate and/or disaggregate the available cost data, to understand the definition of cost accounts and accounting practices, and to disentangle the existing financial assistance from the public sector. If financial inducements change at the same time a new technology is introduced, care must be taken not to include this pseudo "cost savings".

These four key problems of cost savings should be considered when one wants to use the concept of cost savings. When the concept is used correctly, it should be helpful in organizing and interpreting correctly the data and information relevant to a decision maker.

5.2 Allocation of R&D Funds Based Upon Maximizing Net Benefit

The optimal allocation of an R&D budget needs to be determined. As a starting point a model for maximizing the net benefit of R&D has been developed. Benefit is defined to be the present value of the results of an R&D project which are implemented in transit systems throughout the useful life of the R&D. Cost is defined to be the present value of the cost of the complete R&D project. Net benefit is the difference of benefit and cost.

The objective is to maximize the net benefit of R&D subject to R&D budgetary constraints. Specifically, that subset of all possible R&D projects which will maximize the expected net benefit and stay within budgetary constraints is sought. (How to determine the proper budget constraint itself is an important R&D resource allocation problem. This needs to be considered in the future.)

The total cost and benefits of R&D can be viewed from a cash flow perspective. R&D requires an "investment" for some number of years in the future, with a varying annual cash flow from the time of conceptual design to demonstrated transit system. Likewise, the benefits will begin to accrue at the completion of the R&D and continue to accrue until the technology becomes economically obsolete. Expressions for the benefits and the costs of each candidate project will be developed.

Although the immediate problem of an R&D manager is to select the "best" subset of projects within the current fiscal year's budgetary constraints, the decision-maker must look also at downstream efforts. Assume that the R&D planning horizon is N years into the future. Suppose an annual R&D budget estimate is available. The objective is to maximize the present value of net benefits subject only to the budgetary constraint and that the net benefit of each project is non-negative. Projects which were funded in previous years will normally be ranked higher in the current year because the present value of the cost to completion is lower due to previous expenditures, while the present value of benefits is higher due to the reduced time before benefits begin to accrue. However, the probability of success may change over time due to information gathered during previous years' R&D effort. Thus, R&D decisions should be updated over time.

One problem which may be encountered is that of concurrent peaking of resource demands by several projects. That is, if each project has a "bell-shaped" cost-time history and there are several "new starts" in any one year, their funding growth may exceed resources in future years. Any R&D budget allocation model must also consider this problem.

A. Present Benefit of Research and Development

Consider a transit system that is operating at a profit. Assume that an R&D project begins (or is continued) at the present and is to be completed in the future at a year, y_f. At y_f, the R&D is complete and the equipment or service resulting from the R&D will be provided by the suppliers and purchased by the operators.

For R&D to have an impact on urban rail transit cost, it must be implemented. The implementation will be through one or more of three mechanisms, or applications areas. These are:

(1) Ways, Facilities and Structures--The R&D result is incorporated into the process of constructing or revitalizing ways, facilities, and structures,

(2) Vehicles and Equipment--The R&D result is incorporated into the new or replacement equipment purchased by the operators, and

(3) Operations and Maintenance--The R&D result is incorporated into the methods of O&M.

Note that the impact on life cycle cost of a particular project may be across all of the above areas. For convenience, assume that the effect of R&D is introduced into revenue service through <u>units</u> of equipment, service, etc. Examples of units are vehicles, miles of track, number of stations, etc. For each unit incorporating the result of a project, the reduction in transit system life cycle cost can be expressed by:

$$PV\ (\delta LCC_j) = PV\ (CI_j) + PV\ (CS_j)$$

where PV = present value operator

CI_j = associated change in system capital investment in year y_j, and

CS_j = associated change in system service costs in year y_j.

The impact of R&D begins the first available year its effect is implemented and lasts until the units incorporating it are replaced by a new technology.

The aggregate present benefits (in current year dollars evaluated at the current year) of an R&D project, is the sum of the yearly benefits over the unit production life. That is,

$$B = \sum_{j=f}^{f+L} N_j \left[PV\ (\delta LCC_j) \right]$$

where $f = y_f - y_p$ (the number of years to complete the R&D),

L = the technology life of the results of the project, and

PV is the operator that transforms costs at y_j to the value at y_p, the planning year.

Assuming that the units are introduced into the market uniformly from year to year,

$N_j = \bar{N}$, the number of units incorporating the results of the R&D project introduced annually,

Then, the present value of the benefits are

$$B = \bar{N} \sum_{j=f}^{f+1} PV\ (\delta LCC_j)$$

Since, δLCC_j is the change in life cycle cost (valued at y_j) per unit introduction into revenue service of the results of an R&D project in year y_j, it follows that

$$PV\ (\delta LCC_j) = (\delta LCC_j) \left(\frac{1+g}{1+k}\right)^j$$

where $j = y_j - y_p$,

g = an appropriate escalation rate, and

k = the appropriate discount rate.

By substitution,

$$B = \bar{N} \left(\frac{1+g}{1+k}\right)^f \left[\sum_{j=f}^{f+1} (\delta LCC_j) \left(\frac{1+g}{1+k}\right)^{j-f} \right]$$

Occasionally, system-wide benefits may not accrue to an operator until all old units are replaced with new units. However, it is not unreasonable for the purposes of this model to assume that the benefit of the R&D per unit is more or less constant. In other words,

$$\delta LCC_j = \delta LCC \text{ for all } j.$$

Then,

$$B = \bar{N} \left(\frac{1+g}{1+k}\right)^{f} \left[\sum_{j+f}^{f+L} (\delta LCC) \left(\frac{1+g}{1+k}\right)^{j-f} \right]$$

$$= \bar{N} \left(\frac{1+g}{1+k}\right)^{f} (\delta LCC) \left[\sum_{j=f}^{f+L} \left(\frac{1+g}{1+k}\right)^{j-f} \right]$$

$$= \bar{N} \left(\frac{1+g}{1+k}\right)^{f} (\delta LCC) \left[\sum_{j=o}^{L} \left(\frac{1+g}{1+k}\right)^{j} \right]$$

Let $\alpha = \frac{1+g}{1+k}$

Then,

$$B = \bar{N} \; (\delta LCC) \; (\alpha)^{f} \left[\sum_{j=o}^{L} \alpha^{j} \right]$$

$$= \bar{N} \; (\delta LCC) \; (\alpha)^{f} \left[\frac{1-\alpha^{L+1}}{1-\alpha} \right]$$

This equation is useful for a computer solution of project benefit calculations. For a limited number of cases, as in Section 5.8, traditional engineering economy methods can be used. These employ tables of values of present worth factors, and factors to convert a gradient series of annual payments to a uniform series. Relative escalation rates can be treated by replacing the initial interest rate by a modified interest rate $(\frac{i-z}{i+z})$ where z is the relative escalation rate, and by using the standard engineering economy tables.

B. Present Value Cost of Research & Development

Funding needs for a particular R&D project will vary as a function of time. In the early stages, the project consists of formulation of a plan, gathering of data, development of design or procedural concepts, etc. As designs evolve into "prototypes," activity picks up. Next, "pre-production" models are developed and placed into a test and validation environment, which may involve a "demonstration." Finally, as full production begins, the R&D activity winds down to a final assessment stage.

The year to year variation in project activity is difficult to predict. For simplicity, assume that a four-step funding curve is adequate. Let

TR = R&D "Life" of project P,
CR = the cost of the project in current year dollars,
a_o = the year when the R&D project starts,
a_i = the year when the i'th step of the project ends, $i = 1, 2, 3, 4$, and
$t_i = a_i - a_{i-1}$, the number of years in the i'th step of the project.

The funding timeline would look like that of Figure 5-1. During each period, some fractions F_j of the total project cost will be required, subject to

$$\sum_{J=1}^{4} F_j = 1.$$

Assume that the cost during the jth step is estimated in current year dollars. The present value of the cost during that step must take into account the discount rate as well as the general rate of inflation. Assume that a single factor, b, represents both of these effects.

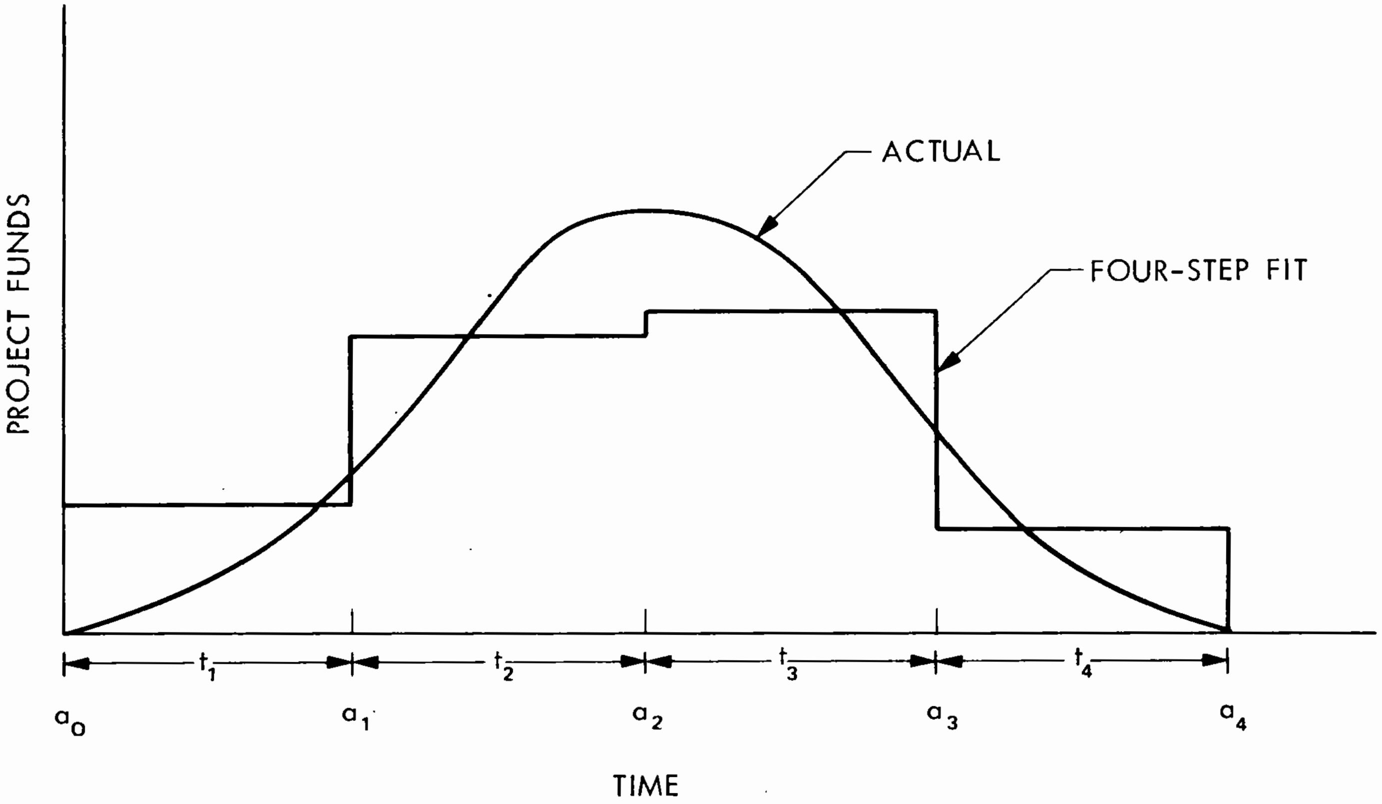

Figure 5-1. Project Cost - Time History

The present value of the cost of R&D during the Sth year (a_s) of the R&D is simply

$$PV(CR_s) = CR_s \; (1+b)^{-s}$$

where; b = the factor mentioned above for R&D projects, including the effects of general inflation* and the discount rate.

Summing over all R&D years the total present value of the cost of an R&D project is found to be

$$C = \sum_{h=o}^{TR-1} CR_h \quad (1+b)^{-h}$$

Now, CR_h depends on the step during which year a_h falls. Therefore,

$$CR_h = \frac{(CR)\ (Fj)}{t_j}$$

when $a_{j-1} \leq a_h < a_j$.

Substituting and simplifying leads to the result,

$$C = CR \left\{ \sum_{h=o}^{t_1-1} \left(\frac{F_1}{t_1}\right) (1 + b)^{-h} + \sum_{h = t_1}^{t_1+ t_2-1} \left(\frac{F_2}{t_2}\right) (1 + b)^{-h} \right.$$

$$\left. + \sum_{h = t_1+ t_2}^{t_1+ t_2+ t_3-1} \left(\frac{F_3}{t_3}\right) (1 + b)^{-h} + \sum_{h = t_1+ t_2+ t_3}^{t_1+ t_2+ t_3+ t_4-1} \left(\frac{F_4}{t_4}\right) (1 + b)^{-h} \right\}$$

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* See OMB Circular A-94 for the suggested rate.

C. Life Cycle Cost Model

In the previous sections, it is shown that the benefit of an R&D project is a function of the reduction in system life cycle cost resulting from introduction of units incorporating results of the R&D. The system life cycle cost will be affected through the following:

1. Capital Investment. At the time a unit is placed into revenue service, the cost of the unit with the R&D results incorporated will be different than a similar unit without the R&D. The cost may be lower or higher. In addition, other capital investments may be required to permit operation of the new unit. For example, new maintenance equipment may be required. All of these effects are aggregated into a cost of capital investment.

2. Annual Service Cost. Once a new unit is in revenue service, the transit property must provide services to that unit to permit it to perform its intended function. Services include operating personnel, maintenance, a supply of energy, etc. The types and quantities of services provided may be modified as a result of the R&D incorporated in the unit. These effects must be summed up over the lifetime of the unit.

In order to find δLCC (the reduction in transit system life cycle cost), the actual life cycle cost of the R&D project's results, consisting of capital cost and service cost, must first be developed.

Capital Investment

Let a purchase, which incorporates the results of R&D, be made at year y_r, with the cost of that purchase being C_r. The cost of purchase in planning year dollars would be

$C_p = C_r (1 + g_c)^{+r}$ where
$r = y_r - y_p$,
y_p = the planning year, and
g_c = the escalation rate for capital items affected by purchase.

For simplicity, assume that the year of first revenue service coincides with the year of purchase, so that $y_r = y_o$, the year of first revenue service. In certain types of procurements (e.g., major construction) this method requires that contracts include escalation rates and that purchase price include cost of capital during the course of construction. Certain types of R&D projects are aimed at reducing the time of construction and controlling the real cost escalation. These effects must be accounted for separately.

The present value of the capital improvement, when taking into account the discount rate, is

$$PV\ (C_r) = Cr \left(\frac{1 + g_c}{1 + k} \right)^r$$

where k is the discount rate, which includes the effects of general inflation. Note that a common accounting practice is to discount to the end of the year. This would add a "1" to the power above. Assume throughout that the transit system is publicly owned. Thus, all capital comes from public debt. Therefore, there are no tax terms. Assume that the operators are self insured.

Annual Service Costs

Once a capital improvement is purchased and placed into revenue service in year y_o, it requires annual services to maintain its intended function during its life. These services are; (1) operations, (2) maintenance, and (3) energy.

Let

Cx_{ij} = cost of service x_i during year j, expressed in current year dollars where x_i is a variable representing the type of services provided; i.e., operations, maintenance, energy supply, etc.

Then

$(1+g_i)^{j-y_o}\ (Cx_{ij})$ = cost of service x_i during year j expressed in current year dollars

where g_i = escalation rate of service x_i.

Taking into account the discount rate, k, the present value of the cost of service x_i in year j is

$$PV\ (Cx_{ij}) = Cx_{ij} \left(\frac{1 + g_i}{1 + k} \right)^{j-y_o}$$

Service costs are referenced to the end of the service year.

Total Anticipated Life Cycle Cost

The total life cycle cost, LCC, is the sum of the present value of the capital improvement (purchase) cost plus the costs of all types of service over the system life.

So,

$$LCC = PV\ (C_r) + PV \left(\sum_{i=1}^{S} \sum_{j=0}^{L-1} Cx_{ij} \right)$$

$$= C_r \left(\frac{1 + g_c}{1 + k} \right)^r + \sum_{i=1}^{S} \sum_{j=0}^{L-1} Cx_{ij} \left(\frac{1 + g_i}{1 + k} \right)^{j-y}$$

where C_r = the cost of purchase in y_r $(=y_o)$ of the capital improvement,

g_c = the escalation rate for capital items affected by purchase,

k = the discount rate, which includes the effects of general inflation,

Cx_{ij} = the annual service cost of service x_i during the year j,

j = the (+ 1)st year of revenue service of the R&D project results,

L = the technology lifetime (years),

x_i = service type i, and

g_i = the escalation rate of service x_i

5.3 "Erosion" of R&D Effectiveness by Time

The value and cost of R&D is always subject to debate because any gain as a result of R&D is in the future. This problem is especially acute for rail transit for several reasons. There is current reluctance for private R&D investment due to uncertain federal policy and due to a complex and small market for new products. But the larger problem is due to the protracted times for R&D and the limited time over which the R&D can take credit for improved system performance or reduced system cost. The effect of these on the perceived value of R&D is illustrated here.

The period for R&D as compared to other industries is perceived to be relatively long. The R&D period is the time from development of a new technology concept until that concept has evolved into a set of products produced by the transit industry suppliers and purchased by the operators as a normal course of business. This time interval is large for two dominating reasons. First, in such a complex environment as that in which equipment must be used, requirements are difficult to define. In this industry, functional and performance requirements are usually understood by designs which have evolved over years of incremental improvement. Second, any product must have acceptance over a small, but diverse, set of users. Gaining product acceptance in that marketplace is a formidable task.

Once a product has been accepted, it may be applied over a long period of time - 20 to 30 years. But decision-makers are reluctant to allow credit for R&D over such a long period of time. Emphasis is now on near-term payoff. Thus, the planning horizon is usually 10 years or less.

These effects can be expressed in mathematical form.

Let t_o = time when R&D is initiated, the present,
t_f = time of first commercial application,
t = "credited" time of last commercial application,
k = discount rate,
g = escalation rate, and
LCC = life cycle cost if purchased at t_o.

If LCC_i is the unit life cycle cost of equipment purchased at time i, $PV(LCC_i)$ is the present value of life cycle cost (in this year's dollars), and m_i is the total number of units purchased in the ith year.

Then,
$$PV(LCC_i) = LCC \left(\frac{1+g}{1+k}\right)^i$$

Over the "credit" life of the R&D (i.e., from year of first to last year of credited application), the total life cycle cost of all affected purchases is

$$LCC^{*} = \sum_{i=f}^{\ell} m_i \quad LCC_i \left(\frac{1+g}{1+k}\right)^{i}$$

Let us assume that $m_i = m_j = m$, where m is the average purchase rate, which is a reasonable assumption for a market dominated by replacement items. Also, let

C_A = unit acquisition cost, and
γ = ratio of life cycle cost to acquisition cost

Then $$LCC^{*} = m \gamma C_A \left\{ \sum_{i=f}^{\ell} \left(\frac{1+k}{1+g}\right)^{i} \right\} = m \gamma C_A \; z$$

But the term, $z = \sum_{i=f}^{\ell} \left(\frac{1+k}{1+g}\right)^{i}$, can be

viewed as the "deflated purchase years."

That is, if $g=k=o$, then $z = \ell - f$, the number of puchase years. Thus, if $k>g$, it has the effect that the time required to complete R&D and the limited planning horizon reduces or "deflates" the number of purchase years.

The effect of time on "deflated purchase years" is shown in Figure 5-2. For example, assume that from now until commercialization, five years is required for research, development, demonstration and product development. Further, assume a ten year horizon. That is, $f=5$, $\ell=10$. This gives five years of commercial application. But the affect of time erodes this to only 4.4 years, a decrease of 0.6 years. Consider instead when $f=10$ and $\ell=15$. That is, the R&D takes longer but the horizon is extended. Then, $z = 3.6$ years, a further "loss" of 0.8 years due to the prolonged R&D period.

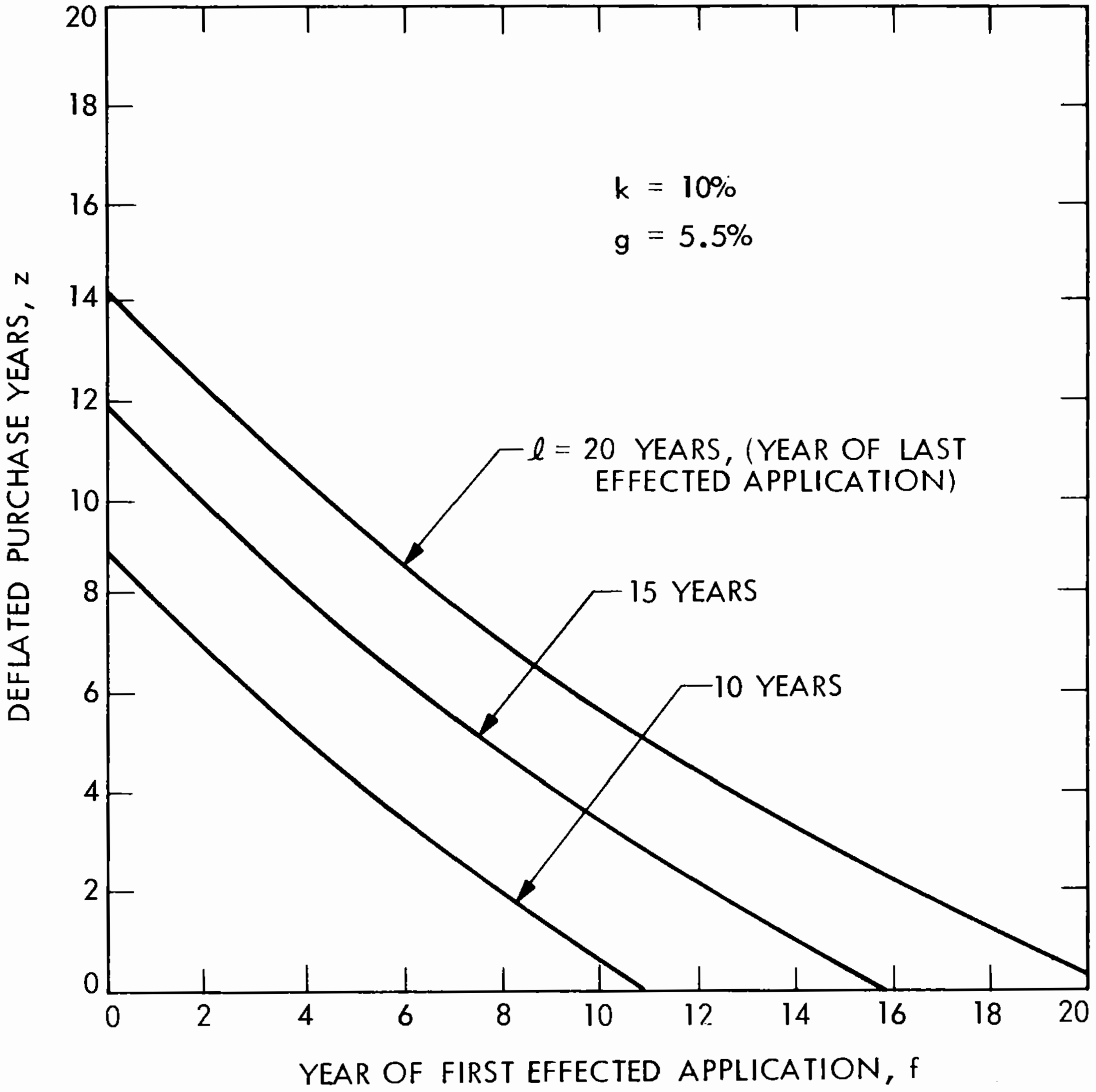

Figure 5-2. Effect of Time on Deflated Purchase Years

5.4 Framework for a Probabilistic Cost Analysis

The point estimation of benefits and costs has a long tradition. However, any such estimate represents, at best, only expected benefits and costs. Frequently, the overestimation of expected benefits or underestimation of expected costs may occur, resulting in unjustified RD&D projects. Furthermore, expected cost itself provides a limited amount of information; for a new technology the expected cost may well be higher than that of the existing technology. However, the variance of the cost estimate may be large enough to indicate a significant probability that the new technology may be competitive. Hence, the risk preference of decision-makers should be incorporated in the choice of RD&D projects. Providing expected benefits and expected costs alone to decision-makers precludes any consideration of risk.

It is wrong to assume that calculating a point estimate requires only minimal information, because calculating the expected value implicitly uses all the relevant information. It is also wrong to assume that sensitivity analysis could reveal the reliability of point estimates. The usefulness of sensitivity analysis hinges upon the knowledge of the likelihood of parametric changes. Thus, if the determination of expected benefits and expected costs is highly sensitive to the variation of a parameter, but the likelihood of any variation of the parameter is zero, then the concern with this parameter is minimal.

An important distinction between R&D projects and other investment projects is the degree of uncertainty involved. The cost of RD&D is difficult to estimate without a wide margin of uncertainty. In addition, the time required to complete an RD&D project to a predefined level of acceptance is uncertain. If time preference counts, time uncertainty is a key issue. Related to this is the uncertainty of how long new technology will remain in use before it becomes economically obsolete. These will, in turn, introduce considerable uncertainty into benefit measurements of the RD&D projects.

Hence, a probabilistic benefit/cost model is needed to capture the key aspects of uncertainty. There are two advantages in using this approach. First, assessment of uncertainty factors will be made explicit so that proponents and opponents of an RD&D project can examine both the benefit/cost and risk of the RD&D projects. Second, risk preferences of decision-makers can be introduced.

In order to develop a probabilistic benefit/cost model, an assessment of the likelihood of occurrence of each relevant event, conditioned by the relevant prior events is needed. It is proposed that conditional probability statements and a decision tree approach be used to delineate the stages of RD&D progress. Once this is done, a branch of the decision tree can be selected and the benefit/cost of all relevant events can be appropriately aggregated. The probability of their joint occurrences can then be calculated. Finally, a probability distribution of the estimated net benefit can be plotted. A decision model can then be used to rank in order these distributions.

In the development of a probabilistic benefit/cost model, care must be taken to identify interdependent stages of an RD&D project. Care must also be taken to incorporate the effect of a random variable in benefit/cost calculation. Behavioral aspects are also crucial. If union wage rates are closely aligned to productivity changes, care must be taken to distinguish exogenous variables (e.g., material cost) and endogenous variables (e.g., union wage rate).

Providing decision-makers with pertinent information not only facilitates decision making but also helps in making better decisions that also appear to be less arbitrary. The probabilistic benefit/cost model would be designed to do that.

5.5 A Brief Summary of the Transelect Project Selection Algorithm

A. Introduction

UMTA Research and development program managers are frequently asked to make choices regarding the funding of potential projects. Typically there will be a large number of candidate projects, only a few of which can be funded. When the budget requirements of the potential projects, and the availability of funds vary by year, project selection can become very complex. The selection of an attractive high benefit project with an unusually high budget requirement in any one year may preclude the funding of a number of other projects, which collectively may provide a better benefit.

No algorithm can substitute for the insight and expertise of a program manager and the UMTA staff. A computer algorithm, however, can aid a decision-maker to more quickly and efficiently answer some questions.

The "TRANSELECT" methodology developed by JPL was designed to assist decision makers in the selection and scheduling of transportation related research and development projects. The algorithm helps answer such questions as:

(1) Which projects should be funded and when should they start?

(2) What are the period resource requirements?

(3) What is the effect of a particular project on the ability to fund other projects?

(4) What is the collective expected benefit of a particular combination of projects?

(5) When is partial funding appropriate?

(6) To what extent should funds be "carried over" and what is the best use of these funds?

All these questions can be answered quickly, inexpensively, and under a number of different scenarios with the TRANSELECT algorithm.

B. A Sample Problem

For example, a program manager has ten and a half million dollars to spend on research and development. The money should be spent in the next five years, but unspent funds may be carried over. There are currently twenty projects from which to choose, ranging from two to five years in length. There are different costs, benefits, inflation rates, and probabilities of success for each project.

You may delay, and/or partially fund projects in order to fit them in. However, there are certain policy constraints on the solution. Suppose one project ("FIRE PROC") already has been started, and there is a commitment to complete it regardless of its benefit. Moreover, for discretionary reasons you decide to eliminate the "anti-gravity" project as unrealistic.

For illustrations sake, suppose further that it is desirable to spend a large portion of funds in year one, and a declining amount thereafter.

These inputs are illustrated on page 5-24. The twenty projects are shown, along with their funding requirements, cost escalation rates, benefits, benefit discount rates and probabilities of success. The initial spending limits by year, and alternate funding levels (for partially funded projects) are also shown.

The problem now, is to select that set of projects which approximately optimizes the total expected net benefit. The total budget of the selected projects should be as close as possible to the originally submitted spending limits.

The sample output is on page 5-25. The suggested project selection is given, along with funding levels, year to start, and the required funding by year for each project. Total project requirements are shown, and the revised budget (i.e. after carry-over of funds) is given in the row labeled "adjusted budget".

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UMTA RAIL R&D PROJECT SELECTION DEMONSTRATION-FICTITOUS DATA                                  DATE 011879        PAGE      7


                                           INPUT DATA

 PROJECT   OPTION    PROJECT REQUIREMENTS BY YEAR:                                                         ESCALATION   BENEFIT    DISCOUNT     PROB.
                         1       2       3       4       5       6       7       8       9      10        RATE                   RATE
TUNNEL TECH   0        .550    .605   1.996   2.196   1.611    .000    .000    .000    .000    .000        .10        300.       .15       .900000
CONST TECH    0        .440    .484    .532    .586    .644    .000    .000    .000    .000    .000        .10        250.       .15       .800000
HVAC          0        .109    .119    .259    .282    .154    .000    .000    .000    .000    .000        .09          9.       .15      1.000000
LOW MAIN SUB  0        .218    .119    .389    .423    .154    .000    .000    .000    .000    .000        .09         18.       .15       .650000
WY CAR INS    0        .109    .119    .389    .565    .154    .000    .000    .000    .000    .000        .09         30.       .15       .710000
WHEEL RAIL    0        .545   1.198   1.295   2.823    .769    .000    .000    .000    .000    .000        .09        150.       .15       .350000
TRAIN CONTRO  0        .218    .238    .648    .706    .923    .000    .000    .000    .000    .000        .09         18.       .15       .950000
CAB SIG       0        .218    .238    .130    .000    .000    .000    .000    .000    .000    .000        .09          5.       .15       .480000
LRV           0        .324   1.400    .504    .136    .000    .000    .000    .000    .000    .000        .08          1.       .15       .650000
PASS INT      0        .428    .687   3.675   1.311    .000    .000    .000    .000    .000    .000        .07        200.       .15       .400000
FARE COLL     0        .321    .458   1.225    .393    .000    .000    .000    .000    .000    .000        .07         22.       .15       .830000
OPER PROC     0        .214    .343    .368    .131    .000    .000    .000    .000    .000    .000        .07          0.       .15       .900000
FIRE PROC     1        .107    .229    .245    .000    .000    .000    .000    .000    .000    .000        .07          0.       .15       .930000
COLD WEATHER  0        .214    .229    .368    .000    .000    .000    .000    .000    .000    .000        .07         11.       .15       .980000
STATION CLEA  0        .107    .572    .245    .262    .000    .000    .000    .000    .000    .000        .07         10.       .15      1.000000
POWER REGEN   0        .336    .502   2.810    .315    .176    .000    .000    .000    .000    .000        .12        270.       .15       .650000
NUCLEAR TRAI  0        .000   1.832   2.450   3.932   5.750    .000    .000    .000    .000    .000        .07         15.       .50       .620000
MODEL INT.    0        .428    .458   1.225    .131    .140    .000    .000    .000    .000    .000        .07         15.       .15       .650000
MONORAIL      0       1.100    .050    .000    .000    .000    .000    .000    .000    .000    .000        .07          9.       .10       .990000
ANTI-GRAVITY  2        .428    .458   1.225    .131    .140    .000    .000    .000    .000    .000        .07        200.       .15       .850010
                     ---------------------------------------------------------------------------------
TOTAL ALL PROJECTS    6.414  10.327  19.976  14.324  10.616    .000    .000    .000    .000    .000


   INITIAL BUDGET:
              YEAR       1       2       3       4       5       6       7       8       9      10
                       4.000   3.050   2.000   1.000    .500    .000    .000    .000    .000    .000

   FRACTIONAL FUNDING
    LEVEL 1       2
        .75     .50


  NOTE: OPTION=0, OPTIONAL
              =1, MANDITORY
              =2, EXCLUDE
```

Table 5-1. Program Funding Illustration
Budget Level I, Data Input

```
UMTA RAIL R+D PROJECT SELECTION DEMONSTRATION-FICTITIOUS DATA                                    DATE 011879        PAGE     8

                                              PROJECT SELECTION

   PROJECT       FUNDING    YEAR TO    REQUIRED FUNDING BY YEAR:                                                      BENEFIT/   EXPECTED   RANK
                 LEVEL %    START        1       2       3       4       5       6       7       8       9      10     COST     BENEFIT

  CONST TECH     100.%        1        .440    .484    .532    .586    .644    .000    .000    .000    .000    .000    61.1        99.        5
  HVAC           100.%        1        .109    .119    .259    .282    .154    .000    .000    .000    .000    .000     5.4         4.        7
  LOW MAIN SUB    50.%        5        .000    .000    .000    .000    .308    .070    .076    .183    .271    .296     1.3         1.        9
  WY CAR INS     100.%        1        .109    .119    .389    .565    .154    .000    .000    .000    .000    .000    13.9        11.        4
  CAB SIG        100.%        1        .218    .238    .130    .000    .000    .000    .000    .000    .000    .000     5.6         2.        5
  FIPE PROC      100.%        1        .107    .229    .245    .000    .000    .000    .000    .000    .000    .000    -1.0         0.      RAN
  COLD WEATHER   100.%        1        .214    .229    .360    .000    .000    .000    .000    .000    .000    .000     9.3         7.        1
  STATION CLEA   100.%        1        .107    .572    .245    .262    .000    .000    .000    .000    .000    .000     4.7         6.        7
  MONORAIL       100.%        1       1.100    .050    .000    .000    .000    .000    .000    .000    .000    .000     5.9         7.        2
                                   ----------------------------------------------------------------------------------
                PROJECT REQUIREMENTS $ 2.404   2.040   2.167   1.695   1.260    .070    .076    .183    .271    .296
                ADJUSTED BUDGET      $ 2.493   2.040   2.167   1.695   1.260    .070    .076    .183    .271    .296
                                   ----------------------------------------------------------------------------------
                 FUNDS REMAINING     $  .089   -.000    .000    .000    .000    .000    .000    .000    .000    .000
                                                                                                      TOTAL BENEFIT  138.

@FIN
```

Table 5-2. Program Funding Illustration:
Budget Level I, Data Output

The "benefit/cost" figure for each project is

$$\frac{\text{PV (BENEFIT}_j) - \text{PV (COST}_j)}{\text{PV (COST}_j)}$$

where PV stands for present value.

The "expected benefit" is

$$\left\{\text{PV (BENEFIT}_j)\right\} \text{PROB}_j$$

where PROB_j is probability of success of project j.

In the column labeled "Rank", the order in which projects were selected is indicated. A "Man" in the rank column indicates the project has no rank, but was mandatorily included in the solution. Note that those projects with the highest benefit/cost or expected benefit were not necessarily chosen first.

The use of selection algorithms is almost invariably an iterative process in which variables are altered and refined, and different scenarios are tested. Suppose for example, it is desirable to test the effect of a different initial budget on project selection. Will project selection remain stable? Will total benefits decline?

Another initial budget is tested (see page 5-27) in which more funds are available in years three and four, and less in year one. No funds are allocated in year five, thus the only funds spent in that year are "carried over" funds. The solution is on page 5-28.

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UMTA RAIL R+D PROJECT SELECTION DEMONSTRATION-FICTITOUS DATA                                              DATE 011879         PAGE     3


                                            INPUT DATA

 PROJECT  OPTION   PROJECT REQUIREMENTS BY YEAR:                                                            ESCALATION  BENEFIT  DISCOUNT    PROB.
                       1      2      3      4      5      6      7      8      9     10                       RATE                RATE
TUNNEL TECH    0     .550   .605  1.996  2.196  1.611   .000   .000   .000   .000   .000                      .10       300.      .15      .900000
CONST TECH     0     .440   .484   .532   .586   .644   .000   .000   .000   .000   .000                      .10       250.      .15      .800000
HVAC           0     .109   .119   .259   .282   .154   .000   .000   .000   .000   .000                      .09         9.      .15     1.000000
LOW MAIN SUB   0     .218   .119   .389   .423   .154   .000   .000   .000   .000   .000                      .09        18.      .15      .650000
HY CAR INS     0     .109   .119   .389   .565   .154   .000   .000   .000   .000   .000                      .09        30.      .15      .710000
WHEEL RAIL     0     .545  1.188  1.295  2.823   .769   .000   .000   .000   .000   .000                      .09       150.      .15      .350000
TRAIN CONTRC   0     .218   .238   .648   .706   .923   .000   .000   .000   .000   .000                      .09        18.      .15      .950000
CAB SIG        0     .218   .238   .130   .000   .000   .000   .000   .000   .000   .000                      .09         5.      .15      .490000
LRV            0     .324  1.400   .504   .136   .000   .000   .000   .000   .000   .000                      .08         1.      .15      .650000
PASS INT       0     .428   .687  3.675  1.311   .000   .000   .000   .000   .000   .000                      .07       200.      .15      .420000
FARE COLL      0     .321   .458  1.225   .393   .000   .000   .000   .000   .000   .000                      .07        22.      .15      .890000
OPER PROC      0     .214   .343   .368   .131   .000   .000   .000   .000   .000   .000                      .07         0.      .15      .700000
FIRE PROC      1     .107   .229   .245   .000   .000   .000   .000   .000   .000   .000                      .07         0.      .15      .990000
COLD WEATHER   0     .214   .229   .368   .000   .000   .000   .000   .000   .000   .000                      .07        11.      .15      .780000
STATION CLEA   0     .107   .572   .245   .262   .000   .000   .000   .000   .000   .000                      .07        10.      .15     1.000000
POWER REGEN    0     .336   .502  2.810   .315   .176   .000   .000   .000   .000   .000                      .12       270.      .15      .650000
NUCLEAR TRAI   0     .000  1.832  2.450  3.932  5.750   .000   .000   .000   .000   .000                      .07        15.      .50      .520000
MODEL INT.     0     .428   .458  1.225   .131   .140   .000   .000   .000   .000   .000                      .07        15.      .15      .650000
MONORAIL       0    1.100   .050   .000   .000   .000   .000   .000   .000   .000   .000                      .07         9.      .10      .990000
ANTI-GRAVITY   2     .428   .458  1.225   .131   .140   .000   .000   .000   .000   .000                      .07       200.      .15      .850010
                    ------------------------------------------------------------------------
TOTAL ALL PROJECTS  5.414 10.327 19.976 14.324 10.616   .000   .000   .000   .000   .000


   INITIAL BUDGET:
          YEAR         1      2      3      4      5      6      7      8      9     10
                     2.500  3.050  2.500  3.000   .000   .000   .000   .000   .000   .000

   FRACTIONAL FUNDING
    LEVEL 1      2
       .75      .50


  NOTE: OPTION=0, OPTIONAL
              =1, MANDITORY
              =2, EXCLUDE
```

Table 5-3. Program Funding Illustration
Budget Level 2, Data Input

```
UMTA RAIL R+D PROJECT SELECTION DEMONSTRATION-FICTITIOUS DATA                                   DATE 011879        PAGE      4

                                              PROJECT SELECTION

   PROJECT      FUNDING    YEAR TO    REQUIRED FUNDING BY YEAR:                                                   BENEFIT/  EXPECTED  RANK
                LEVEL %    START         1       2       3       4       5       6       7       8       9      10    COST     BENEFIT

  COAST TECH     100.%       2         .000    .484    .532    .586    .644    .709    .000    .000    .000    .000   53.0         86.     6
  WY CAR INS     100.%       1         .109    .119    .389    .565    .154    .000    .000    .000    .000    .000   13.9         11.     7
  CAB SIG        100.%       1         .218    .230    .130    .000    .000    .000    .000    .000    .000    .000    5.6          2.     5
  FARE COLL      100.%       1         .321    .458   1.225    .393    .000    .000    .000    .000    .000    .000    5.3         11.     3
  FIRE PROC      100.%       1         .107    .229    .245    .000    .000    .000    .000    .000    .000    .000   -1.0          0.   MAN
  COLD WEATHER   100.%       1         .214    .229    .368    .000    .000    .000    .000    .000    .000    .000    9.3          7.     1
  STATION CLEA   100.%       1         .107    .572    .245    .262    .000    .000    .000    .000    .000    .000    4.7          6.     2
  MONORAIL       100.%       1        1.100    .050    .000    .000    .000    .000    .000    .000    .000    .000    5.9          7.     4
                                     ---------------------------------------------------------------------------------
               PROJECT REQUIREMENTS  $ 2.176   2.379   3.133   1.806    .798    .709    .000    .000    .000    .000
               ADJUSTED BUDGET       $ 2.225   2.379   3.133   1.806    .798    .709    .000    .000    .000    .000
                                     ---------------------------------------------------------------------------------
                FUNDS REMAINING      $  .050   -.000    .000   -.000    .000    .000    .000    .000    .000    .000
                                                                                                      TOTAL BENEFIT  130.

@FIN
```

Table 5-4. Program Funding Illustration:
Budget Level 2, Data Output

C. Methodology

The "TRANSELECT" methodology is designed to select and schedule an approximately optimal (i.e. maximal expected net benefit) set of transportation related projects given multiple budget requirements and constraints, as well as considering certain other information about each project.

The methodology is not designed to make decisions or second guess the program manager. Rather, it deals only with a set of quantifiable and relatively objective measures and comes to an approximately optimal solution based on only these measures.

Inputs to the methodology include

(1) Budget requirements of each project (up to ten years worth).

(2) A benefit measure of each project.

(3) A benefit discount rate for each project.

(4) An inflation or cost escalation rate for each project.

(5) Probability of success for each project.

(6) Overall spending limits.

(7) Two fractional funding levels which will be used to generate alternate patterns of funding for projects we wish to fit in.

(8) Discretionary "flags" which the manager may use to arbitrarily include or exclude particular projects from the solution.

The methodology is divided into two distinct parts. The first treats spending limits as fixed, and attempts to optimize within this criteria. This tends to make the final overall budget requirements of the solution set as close to the originally submitted budget constraints as possible.

The second part of the methodology treats both remaining unspent funds and project budget requirements as semi-variables which can be manipulated in order to maximize the marginal benefit. Funds remaining unspent in any one year may be carried over to the next or subsequent years to help fit in desirable projects. In addition, some projects may be delayed and/or partially funded (i.e. stretched out over a number of years) in order to fit them into the solution.

Part one of the methodology works as follows. First, the projects which are flagged as mandatory or excluded are included in or excluded from the solution set, respectively. The program then assigns a value measure to the remaining projects based upon the following index.

$$\text{VALUE}_j = \frac{\left\{ \text{PV } (\text{BENEFIT}_j) - \text{PV } (\text{COST}_j) \right\} \text{PROB}_j}{\max\limits_{1 \leq y \leq t} \left\{ \text{BUDREQ}_{jy} / \text{BUDREM}_y \right\}}$$

where

PV = present value,

BUDREQ_{jy} = budget requirement of project j in year y,

BUDREM_y = remaining or unallocated funds in year y, and

PROB_j = probability of success of project j.

The remaining variable names are self-explanatory. In words, this unusual looking value measure takes the expected net benefit of a project and divides it by an index of resource-consumptiveness for that project's most resource-consumptive year. Thus, the value measure is a modified benefit-cost index.

A value measure is found for each project not yet in the solution set. That project with the highest value measure which also is capable of being funded given the remaining levels of unallocated funds, is included in the solution. This process continues until no more projects can be funded given the remaining fixed budget constraints. Then part two of the methodology comes into play.

In the second part of the methodology four funding configurations are developed for each project:

(1) Fully funded
(2) Fully funded, delayed 1 year
(3) Partially funded at level 1
(4) Partially funded at level 2

All of these project-versions receive ranks based upon the following value function:

$$\text{VALUE}_{ij} = \frac{\text{PV } (\text{BENEFIT}_{ij}) - (\text{PV COST}_{ij}) \quad \text{PROB}_{j}}{\text{PV } (\text{COST}_{ij})}$$

where

VALUE_{ij} = value of project j version i,
PV = present value,
BENEFIT_{ij} = benefit of project j version i,
COST_{ij} = cost of project j version i, and
PROB_{j} = probability of success, project j.

The yearly costs of each version of each project are adjusted for inflation (the rate of which is a function of the project). The first year of partially funded projects is always fully funded, but the remaining years are funded at reduced levels. The algorithm strives to retain the original "shape" of the proposed budget configuration for partially funded projects while concurrently stretching the budget over a longer period of time.

The highest ranked project-version is selected first. This project-version is tested to determine if it fits within the remaining budget constraints. If it does, it is included in the solution. If it does not, then the project is tested to see if it can be included if funds are carried over from previous years. Thus, the algorithm tries to fit in the most desirable projects. This process continues for all project-versions, in the order of their ranks, until every project-version has been tested, or no more funds remain.

Once a project-version is selected, all other versions of the same project are no longer considered. If funds remain at this point, the four versions for each remaining project are delayed 1 more year and rankings are re-assigned. Attempts are then repeated to fit appropriate versions within the remaining budget constraints. This process continues until practical funding constraints prevent any further funding.

D. Conclusion

The use of the TRANSELECT algorithm places a high degree of analytical power at the fingertips of a program manager. Complex project selection and scheduling problems can be efficiently analyzed without any loss of discretionary power over the outcome. Numerous budget configurations and data scenarios which might ordinarily be ignored due to time/cost considerations can be inexpensively explored. Moreover, the process by which a final project selection is made is documented, reproducible and defensible.

5.6 Policy Considerations Relating to R&D in Rail Transit

The enabling legislation of the Urban Mass Transit Authority (UMTA) is the Urban Mass Transportation Act of 1964 (as amended). One purpose of the Act (p.2(b)(1)) is to "assist in the development of improved mass transportation facilities, equipment, techniques and methods with the cooperation of mass transportation companies, both public and private." Further, Section 6 of the Act states, in part, "the Secretary of Transportation is authorized to undertake research, development and demonstration projects in all phases of urban mass transportation (including the development, testing and demonstration of new facilities, equipment, techniques, and methods) which he determines will assist in the reduction of urban transportation needs, the improvement of mass transportation service, or the contribution of such service toward meeting urban transportation needs at a minimum cost." Clearly the enabling legislation authorizes UMTA to fund research, development and demonstration R&D in urban mass transportation.

The history of UMTA R&D may be briefly outlined as follows: During the period 1964 to 1970 UMTA R&D funding was at a very low level and was primarily responding to local initiatives. The unrest of the late 1960's and the growing desire of people to find solutions to problems of our own cities led to the 1970 amendments to the Urban Mass Transportation Act. These amendments significantly increased UMTA RD&D funding and the period 1970 to 1973 was characterized by continuously increased funding and an ambitious RD&D program. Factors contributing to the short duration of this period appear to be the overestimation of the urban mass transit market and unexpected problems in applying the new technologies. The early years of the period after 1974 represent a period of retrenchment away from high technology. Overall, this period is perhaps best characterized by an increasing reluctance to undertake highly capital intensive initiations. The desire was to gradually improve existing facilities with a stong emphasis on cost effectiveness through better managerial and marketing techniques, service and operational improvements, and the introduction of new, non-capital intensive concepts in transit systems.

Despite a long period of often intense discussions, the role of the federal government and UMTA in transportation RD&D is not clearly specified. RD&D in the nongovernment sector can, in part, be measured by its degree of acceptance in the market place. Other federally sponsored, civil oriented RD&D programs would apparently like to use this same measure. According to George Pastor (the current Associate Administrator, Technology Development and Deployment, Urban Mass Transportation Administration) in testimony before the House Subcommittee on Transportation, Aviation and Weather: "In the final analysis, the only measure of a Federal civil R&D program is the number of ideas, products, and processes which become successfully adopted for operational use by the civilian sector." However success of federally funded RD&D is measured, a more fundamental issue is the role of federal RD&D in the nongovernment sectors.

With respect to the federal role in urban transportation RD&D, two divergent viewpoints are discernable. These are (1) the laissez faire Federal role, in which the RD&D decisions would be entirely the responsibility of the local grant recipients, and (2) the aggressive federal role, which represents a completely federally managed ("NASA type") approach to RD&D management. The proper federal role does not appear to be resolved yet. In addition to uncertainty over the federal role in RD&D, a second controversy underlines UMTA RD&D policy during the last decade. Two extreme viewpoints may serve to illustrate this controversy. High technology advocates argue that the existing urban transit system is the product of the late 19th and early 20th centuries and has failed to maintain patronage growth because cities have changed. Thus it is argued that only radically new, high technology systems with innovative service concepts and levels can solve the urban transportation problem. On the other hand, technology advocates view the urban transportation problem not only as an issue of social priorities and resource allocation, but most importantly as an economic problem which is not amenable to technological solutions. UMTA RD&D policy appears to be taking the middle ground between these extremes.

The direction given to the Department of Transportation (DOT) Ground Transportation R&D programs and the RD&D programs of UMTA's Office of Technology Development and Deployment (TD&D) can be briefly summarized as follows. In November, 1976, the House Subcommittee on Aviation and

Transportation R&D issued a report on DOT ground transportation R&D programs. In its report this subcommittee found that "investments in R&D are far more beneficial, in the long-term, in promoting a healthy transportation system than are operating subsidies." The committee therefore recommended that "the ground transportation administrators should move to balance their R&D programs by substantially increasing the content of basic research and technology that is needed for improvements in system productivity and services as well as future technical innovations."

Further, the Subcommittee report stated that "the purpose of UMTA's R&D effort is to provide knowledge about alternative technologies that can be used to improve mass transit service." The report also stated that "UMTA's R&D effort in hardware development is aimed primarily at those high risk high payoff opportunities where Federal involvement is essential if potential benefits are to be realized."

In addition, the Subcommittee report concluded that equipment manufacturers are not keeping pace with necessary product improvements due to the following factors: (1) the 'lowest price' procurement practice usually associated with UMTA assistance is not conducive to the incorporation of extensive product improvements, (2) the manufacturing industry for transit vehicles is not a healthy one at present, and (3) the market for transit vehicles is relatively small. Thus, the Subcommittee report found that there is an urgent need and national interest in producing near-term measures that can reduce life-cycle costs, attract additional patronage or improve the efficient utilization of vehicle fleets and facilities. Finally, the report concluded that UMTA's R&D activity, therefore, must strike a balance between present day product improvement and longer range, high risk, high payoff technology innovations.

In March, 1977 the House Subcommittee on Transportation, Aviation and Weather held hearings on DOT R&D programs (presumably at least partially to further consider issues raised in the previously mentioned report.) During these hearings William D. Owens, Acting Assistant Secretary for Systems Development and Technology, Department of Transportation, stated that "the present condition of our transportation system demands we concentrate on major problems of immediate concern." Among those major problems he specified were the energy crisis, protection of the environment, congestion in cities, and improved safety.

George Pastor, testifying on behalf of the TD&D Office of UMTA stated that the "Office of Technology Development and Deployment is responsible for hardware and software technologies in support of research, development and deployment of transit systems, products and processes. Furthermore, responsibilities for safety and product qualification and standardization of equipment as well as implementation of new, untried systems in urban deployment have recently been assigned to my office."

Further, Mr. Pastor testified that the objectives of RD&D, as he interpreted them, are 1. In conventional bus and rail transit design, equipment manufacture or construction to obtain either (a) substantial reduction in life-cycle costs without sacrificing performance or service capability, or (b) substantial improvements in safety or performance capability in a cost-effective manner (in other words, introduce benefits which outweigh the costs). 2. To support selected high risk high technology R&D initiatives which promise significant potential increases in productivity through the introduction of automation into transit operations. 3. To support national priorities such as central city revitalization, accessibility for the elderly and handicapped, energy conservation and environmental protection.

Finally, Mr. Pastor testified that the "fiscal year 1978 budget request for technology development and deployment reflects the following changes in R&D policy toward the objectives listed earlier: An increasing emphasis on sponsoring subsystem and component research and development for demonstrating technical and economic feasibility thereby supporting improved specificatons and incorporation of proven improvements by manufacturers.

In summary, it would appear that the highest priority objective of UMTA's R&D policy is cost reduction. As the 1976 Subcommittee report pointed out, any contribution in the form of reduced cost or increased revenues resulting from technological improvement is every bit as valuable as direct UMTA financial assistance to transit operators. Other objectives are frequently mentioned, but none as consistently as cost reduction. The following list of objectives includes all those which have been espoused by UMTA and DOT officials in public testimony in recent years. The list is not necessarily in order of priority.

UMTA R&D Policy Objectives

1. Reduce life cycle costs
    a. Reduce capital costs
    b. Reduce operation and maintenance costs
2. Increase performance
    a. Enhance reliability
    b. Increase schedule performance
3. Increase service levels
    a. Increase safety
    b. Increase patronage
    c. Increase accessibility for elderly and handicapped
4. Minimize environmental impacts
    a. Reduce noise levels
    b. Increase efficiency of energy usage
5. Increase public visibility of improvements

Rail transit has, in the last decade, faced numerous criticisms from the using public and their elected representatives. Thus, the last objective on the list is included because it seems important that, in view of this criticism, product improvements should, when possible, be clearly brought to public attention.

5.7 A Multi-attribute Model for R&D Project Selection

Allocating R&D funds to competing R&D projects given a limited budget is a very complex problem. A procedure for maximizing expected cost savings subject to budget constraints, such as the TRANSELECT algorithm, can provide a valuable input to the decision process; it can provide a rational basis for one aspect of the problem. Thus, the use of such a procedure represents a significant improvement over an ad hoc decision process. However, the implementation of such a procedure does not represent a panacea for the problem. Most decison makers feel it is necessary to consider various other objectives besides cost savings in allocating limited R&D funds. This appears to be especially true for the R&D funding decisions within UMTA (see part 4 above). Thus, because multiattribute decision methodologies are able to incorporate several objectives into a procedure for evaluating competing R&D projects, it seems well suited to the problem. However, this approach represents only an incremental improvement over the single attribute (cost savings) approach and is also not a panacea for the problem.

A multiattribute decision methodology can assist the decision maker in several ways.

(1) It provides a rational basis for decisions involving several objectives that can be documented and justified.

(2) It aids in a good definition of the problem and assists in generating and explicitly defining alternatives.

(3) It identifies what information is relevant to the problem and therefore what information should be collected prior to making the decision.

(4) It identifies issues of concern and hence promotes more efficient interaction between affected parties.

Several multiattribute decision models were reviewed, and of these two were selected as the most applicable for UMTA's R&D budget allocation problem. One, the multiattribute budget allocation model, is a mathematical model, while the other, multiattribute decision analysis, is a paradigm. Although the multiattribute budget allocation model has the advantage of an algorithmic solution procedure, it is not the proposed approach. The primary reason that multiattribute decision analysis is the proposed approach is that even with a relatively small number of R&D projects, the multiattribute budget allocation model is of such magnitude and the algorithmic solution procedure (a 0-1 integer program) so inefficient that obtaining a solution is either impractical or virtually impossible. Secondarily, but by no means inconsequentially, reasons for this recommendation are JPL's recognized expertise in multiattribute decision analysis including successful applications of the methodology and the ability of the TRANSELECT algorithm to be easily modified to use the results of the multiattribute decision analysis as input.

The primary advantage of multiattribute decision analysis over other multiattribute decision methodologies is that it incorporates an explicit treatment of uncertainty and preferences over both quantitative and qualitative data. Further, the mathematical basis for multiattribute decision analysis is theoretically sound and its usefulness in R&D budget allocation has been demonstrated (see, for example, D. L. Keefer, "Allocation Planning for R&D with Uncertainty and Multiple Objectives," IEEE Transactions on Engineering Management, February, 1978.)[17]

Multiattribute decision analysis is a systematic decison procedure which incorporates the preferences and judgments of a single decision maker. The procedure can be viewed as consisting of the following five elements:

(1) Structuring the problem.
(2) Determining the consequences of each alternative.
(3) Establishing probabilities associated with each consequence.
(4) Determining the preference structure of the decision maker.
(5) Synthesizing the information.

Each element will be discussed briefly below. For a more detailed discussion of the procedure see Abe Feinberg, A Brief Introduction to Multiattribute Decision Analysis, JPL Report 5030-222, June, 1978,[18] or Ralph L. Keeney and Howard Raiffa, Decisions with Multiple Objectives: Preferences and Values Tradeoffs, Wiley, 1976.

The first step in a multiattribute decision analysis is to define the objectives (goals or criterion) of the problem. For the R&D budget allocation problem of UMTA, this has been tentatively accomplished by a review of the open literature. Part 4 of this report listed ten objectives of UMTA R&D policy. It is suggested that these ten objectives be used (at least initially) in the multiattribute decision model. Once the objectives are determined, the degree to which the objective is achieved by a particular alternative must be measured. Attributes are these measures. Notationally, let $X_1, \ldots, X_{10}$ represent the attributes associated with the ten objectives of UMTA's R&D policy listed above. Then $x_1 x_2, \ldots, x_{10}$ are the particular values of these attributes. Each possible alternative (R&D)

project) associated with the problem may thus be represented as a vector of attribute values, i.e., $\underline{x} = (x_1, x2, \ldots, x10)$. Table 5-5 gives a list of objectives and possible attributes.

Table 5-5. Objectives and Possible Attributes for a Multi-Attribute Decision Analysis of UMTA's R&D Budget Allocation

Objective	Possible Attribute
Reduce life cycle capital costs	Cost savings (in $)
Reduce life cycle O&M costs	Cost savings (in $)
Enhance reliability	Average miles between breakdown
Enhance schedule performance	Percent on-time arrivals
Increase safety	Injuries & death per vehicle mile
Increase patronage	Passenger trips & miles per vehicle & capacity mile
Increase accessibility for elderly & handicapped	Percent of elderly and handicapped for which system is accessible
Reduce noise level	Average decible level per vehicle mile
Increase efficiency of energy usage	Energy consumed per passenger mile
Increase public visibility of improvements	Qualitatively assessed levels.

In order that the cardinal utilities ultimately assigned to each alternative by the multiattribute decision analysis accurately represent the decision makers preferences, a minimal condition, called preferential independence, on the attributes must be satisfied. Checking that this condition is satisfied generally involves interviewing the decision maker. If the condition is not satisfied, a new set of attributes (with at least one attribute distinct from the previous set) must be chosen until the condition is satisfied.

The second element of the multiattribute decision analysis is the determination of the value of each attribute for every alternative. For UMTA's R&D budget allocation problem, this involves determining the value of each of ten attributes for every R&D project under consideration. A start on this element of the multiattribute decision analysis has been made by JPL in determining the cost savings associated with several rail-related R&D projects.

For each alternative, it is likely that there are many possible values of the attributes. Thus, it would be desirable to assign probabilities to the possible attribute values of each alternative. This is the third element of the multiattribute decision analysis. Such probabilities should be able to be determined from existing data and engineering models or the subjective judgment of knowledgeable professionals. However, if it is not believed to be feasible to determine these probabilities for all alternatives, it is possible to begin with parametric analysis that considers various bounds on alternatives to see if some can be eliminated. One then need only specify probabilities of values of the attributes for remaining alternatives. Finally if it is believed not feasible to specify probabilities of values of the attributes for even this reduced set of alternatives, the multiattribute decision analysis can still be done.

The fourth element in the multiattribute decision analysis is the determination of the decision maker's cardinal utility for all possible attribute vectors, $u(\underline{x})$. An implicit assumption in this procedure is that the decision maker's criterion is the maximization of expected utility.

The first step in eliciting the decision maker's cardinal utility function over attribute values, $u(\underline{x})$, involves his assigning probabilities to lotteries. Consider the $i^{\underline{th}}$ attribute and let x_i and x_i be the decision maker's most preferred and least preferred values, respectively, of this attribute. Then through an interview process, the decision maker is asked to specify the probability, p, that he is indifferent between the value x_i of the $i^{\underline{th}}$ attribute and the lottery in which the $i^{\underline{th}}$ attribute takes the value x_i with probability p and x_i with probability 1-p. The probability p can be shown to be the decision maker's utility for the value x_i of the $i^{\underline{th}}$ attribute, i.e., $u_i(x_i) = p$. The decision maker is required to specify, in a consistent way, such probabilities for several relevant values of each attribute.

It can be shown mathematically that, if the attributes chosen are preferentially independent, then the decision maker's cardinal utility function over the attribute vectors is

$$u(\underline{x}) = \frac{1}{k} \left\{ \prod_{i=1}^{10} \left((1 + k\, k_i\, u_i\, (x_i) \right) - 1 \right\}$$

where k_i is the weight assigned to the $i^{\underline{th}}$ attribute and k is a scaling constant.

The weights, k_i, are also elicited from the decision maker through an interview process (conducted at the same time as the interview eliciting utilities for attribute values). Again the decision maker must assign probabilities to lotteries. Let $\underline{x}^*$ and $\underline{x}^o$ be artificial alternatives in which each attribute is at its most preferred and least preferred value, respectively. Also let $\underline{x}^i$ be an artificial alternative in which the $i^{\underline{th}}$ attribute is at its most preferred value and all other attributes are at their least preferred values. The decision maker must then specify a probability, p, such that he is indifferent between the alternative $\underline{x}^i$ with certainty and the lottery in which alternative $\underline{x}^*$ is the outcome with probability p and alternative $\underline{x}^o$ is the outcome with probability 1-p. The probability specified by the decision maker is the weight of the $i^{\underline{th}}$ attribute in his utility function, i.e., $k_i = p$.

The fifth, and last, element of a multiattribute decision analysis may involve two steps. First, if probabilities over various attribute values for each alternative were determined, then the expected utility of each alternative should be calculated. Second, the expected utility of each alternative is entered into the TRANSELECT algorithm to determine the R&D budget allocation which is best in terms of the decision maker's cardinal utility.

It should be noted that the multiattribute decision analysis described above is for a single decision maker. If there is more than one decision maker, the fourth element of the analysis may be repeated for each one. However, the utilities assigned to an alternative by different decision makers cannot be compared except on an ordinal basis. That is, it may be relevant to note that one decision maker ranked a specific alternative higher than did a second decision maker, but a comparison of the utilities assigned by the two decision makers is not meaningful. Therefore, it does not make sense to aggregate the utilities of more than one decision maker into a group utility function.

The selection of R&D projects by the decision makers of UMTA will require value judgments. Since voters have given the consent of these value judgments to legislators and they, in turn, have delegated limited authority to UMTA, the value judgments relating to R&D made by the decison makers of UMTA are an implied consent by the voters. Thus, it follows that an UMTA decision maker using multiattribute decision analysis to assist him in allocating R&D funding should not specify his own preferences during the analysis but what he can ascertain to be the preferences of the voters. But how does he know those preferences? Probably through subjective impressions formed through numerous contacts with manufacturers, operators and users.

Impressions formed in this manner, however, may not be as accurate as desired. Thus, it is urged that user preferences be determined and supplied as background information to the decision maker using the multiattribute decision analysis in allocating R&D funds. Specifically, it is proposed that one need look at the market of urban mass transportation. There are three pertinent issues in the study of any market; supply, demand, and the market institutions that allow information exchange and transactions between suppliers and buyers.

On the supply side, it is necessary to determine the attribute packages offered by different transportaton modes. What is the factor substitutability between labor, fuel, system efficiency, and capital for different transportation modes? For a given factor mix, what is the possible range of output attributes in terms of cost, safety, speed, etc? What sort of internal and external economies of scale are available for each transportation mode? Are there economies of scope in producing attribute packages? How averse to risk are manufacturers in terms of new technology development and initiation? How averse to risk are operators in terms of new technology adoption? How strong are labor unions in bargaining wages, and how are union wages set? How much improvement can be made on each of the different modes of transportation? What are the risk and uncertainty involved? What regulatory standards are imposed on the supply side? Are there ways to improve supply side performance?

On the demand side, it is necessary to determine the preference of individuals towards the attributes of different modes of transportation. What price elasticity is associated with each attribute? What cross price elasticity is associated with subsets of attributes? How do we measure consumer preferences with respect to a change in the set of attributes?

Finally, on the market institution side, it is necessary to delineate the institutional relationships and how they function. Who are the regulators in the different transportation modes, e.g., taxicabs, automobiles, buses, rapid transit, etc.? How are prices set in each transportation mode? What is the market performance in terms of risk-bearing for introducing a new tranksportation technology? What are the permitting and licensing procedures for starting a new operation or initiating a new route? How efficient are the current contracting procedures of UMTA? How are urban mass transportation projects financed? What are the legal interpretations of the terms "discrimination" and "fairness of competition"?

5.8 An Example of Life Cycle Costs of Transit Equipment

Life cycle cost is made up of two components; acquisition cost and service cost, where service is in the vector of labor, facilities, materials and energy necessary to operate and maintain the equipment in its normal use to provide its intended function. For example, services for a transit vehicle would include:

(1) Operators
(2) Maintenance
(3) Propulsion energy
(4) Insurance
(5) Storage

Life cycle cost can be expressed as,

$$LCC = C_A + C_S = C_A + \sum_{i=1}^{n} \left\{ \left(C_{s_i} \right) \left(\frac{1+g}{1+k} \right)^{i} \right\}$$

where
LCC = the life cycle cost values at the time of purchase,
C_A = the acquisition cost,
C_S = the service cost over the life of the vehicle,
C_{s_i} = the service cost for the ith year,
k = the discount rate per year,
g = the escalation rate per year, and
n = the number of years of useful life.

For transit vehicles, designs and maintenance practices are such that the annual service effort varies little from year to year. Thus,

$C_{s_i} = C_{s_j}$ for all i and j.

Therefore

$$LCC = C_A + C_s \left\{ \sum_{i=1}^{n} \left(\frac{1+g}{1+k} \right)^{i} \right\}$$

where

C_s = annual maintenance cost

Assume that k, g and n are given. Although these are judgmental values, they can be selected within reason. For example, the useful life of transit vehicle is quite long. Using NYCTA as an example, IRT cars date to 1948 (31 years old). Although some BMT-IND cars date to the mid-1930's, these are now being replaced by the R-46 cars, leaving the oldest cars the P-10's built in 1948-49. Thus, 30 years is a reasonable life for vehicles.

$$LCC = C_A + 9.4\ C_s$$

Another way of looking at the effect of discount rate and escalation rate is a net reduction of service life. That is, define

$$n_e = \sum_{i=1}^{n} \left(\frac{1+g}{1+k} \right)^1$$

Then

$$LCC = C_A + n_e \left(C_s \right).$$

Due to an assumed high discount rate, a real service life of 30 years is reduced to an equivalent service life of less than 10 years. The effect of discount rate and escalation rate on equivalent service life is shown in Figure 5-3.

It is seen that for reasonable variations of escalation and discount, the equivalent service life varies between 10 and 20 years.

The effect of maintenance cost can be seen in the following.
The ratio of life cycle cost to acquisition cost is:

$$LCC/C_A = 1 + n_e \left(C_s/C_A \right)$$

The ratio of C_s/C_A is the annual service cost compared to acquisition cost. For automobiles, this can be as low as 3 percent for maintenance, fuel, tires, insurance, etc. This can represent a lower extreme for transportation vehicles - even better than frequently used bicycles. Such complex vehicles as commercial aircraft and transit vehicles can exceed 12%. For example, the BART maintenance cost is about 10% of the purchase price. Thus, it is shown in Figure 5-4 that the life cycle cost can be on the order of 1.5 to 3 times the acquisition cost.

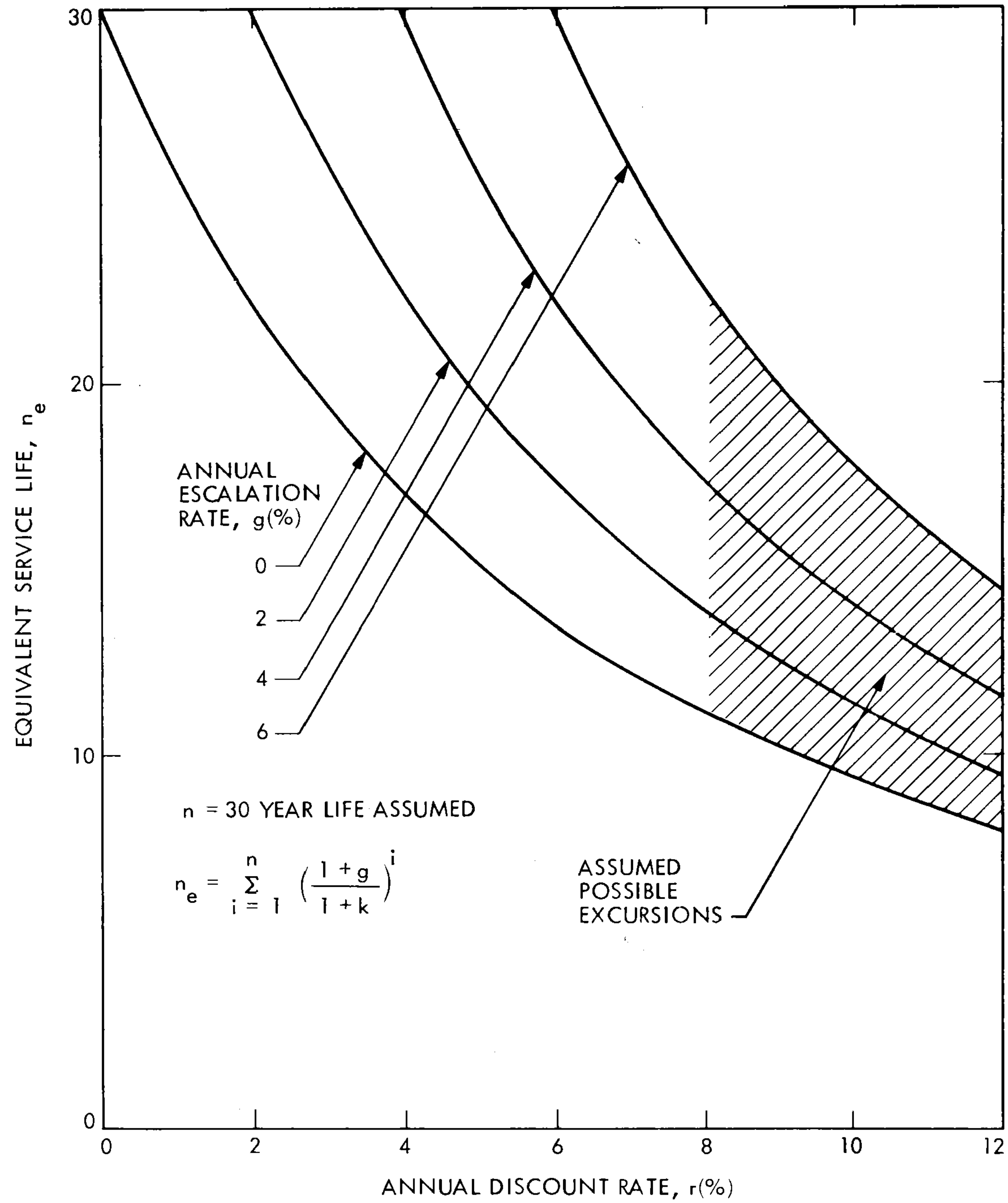

Figure 5-3. Effects of Discount Rate and Escalation Rate on Equivalent Service Life

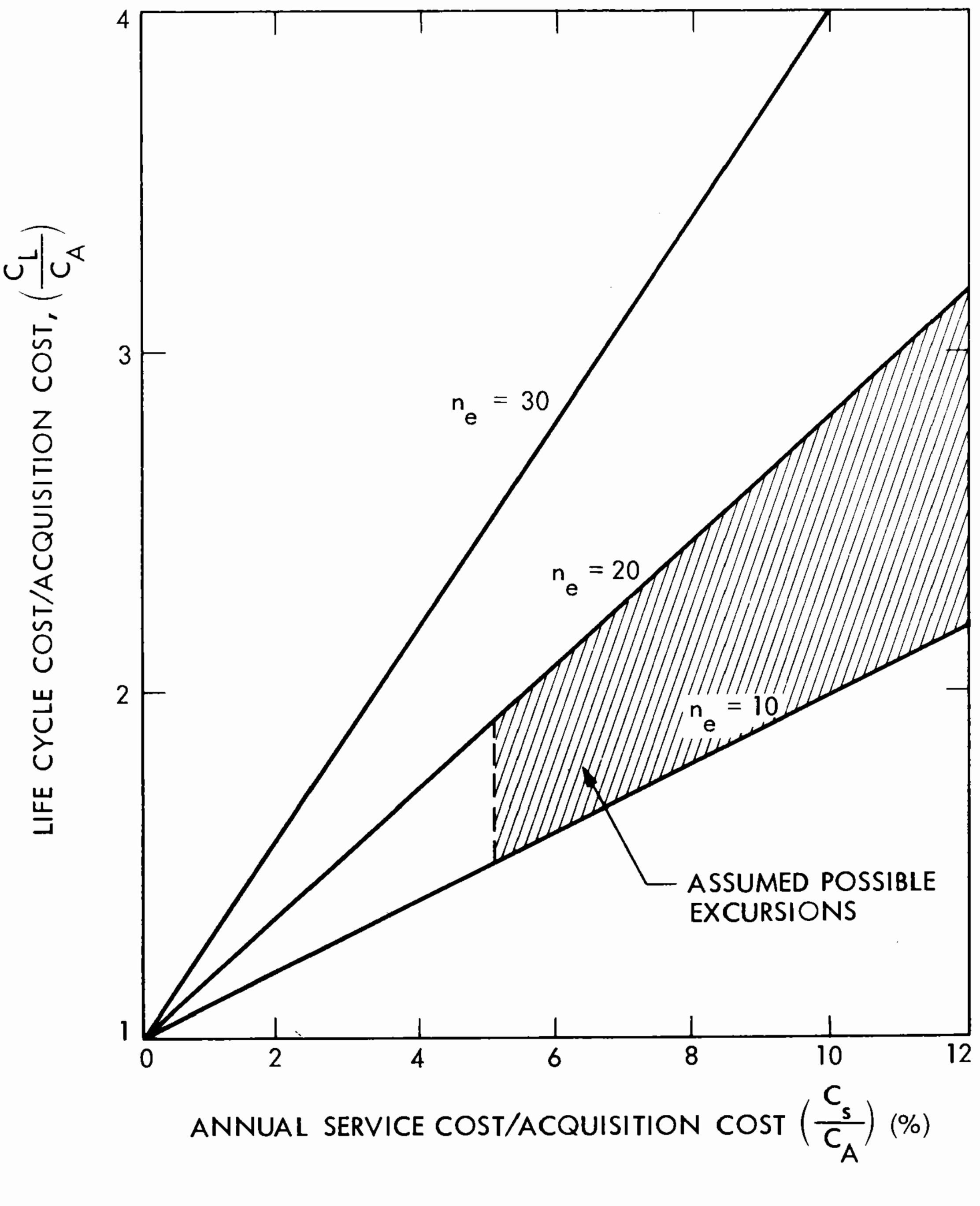

Figure 5-4. Effect of Service Cost on Life Cycle Cost

5.9 Illustrative Application of Economic Benefit Analysis of R&D Projects

The economic benefit analysis methodology will be illustrated by applying it to five projects, for which planning data are available or can be reasonably estimated. These are also the projects in which the transit industry has shown a strong interest and that are being considered by UMTA for project initiation. This exercise will test the model, identify limitations, and provide useful information for the management of the projects.

The projects selected and a brief description are:

1. Improved air comfort system - Changes in the design of rail transit car air comfort systems will be evaluated. These will be directed toward improving the reliability of these systems and reducing their operating, maintenance, and installation costs.

2. Static inverters for auxiliary power - Use of this type of inverter would make feasible the use of AC powered instead of DC powered air conditioning on rail transit cars. This would contribute substantially to the deployment of the "Improved Air Comfort System Project." Present American made AC air conditioners, when used, are powered by motor alternators, which have their own maintenance problems. Development of a static inverter would alleviate the need for the motor alternator.

3. Door system design - Several transit systems report that a large portion of their service delays are related to door operation. This project would stress reliability improvement and reductions in maintenance costs of door systems.

4. Escalators - The use of escalators in transit systems is increasing. There are several design issues that impact the capital and operating costs of escalators. This project would explore these issues and provide the system designer with the necessary information to specify the most appropriate escalators.

5. Fare collection systems - Various methods of collecting fares are in use. They range from simple operated turnstiles implementing a flat fare system to gates actuated by magnetically encoded cards implementing a graduated fare structure. Each system design has its own revenue generation, service flexibility, reliability and operating cost characteristics. A fare collection system research and development program would consist of several projects directed toward reducing the life cycle costs of fare collection systems while maintaining or enhancing their revenue generation and service capabilities.

For each of the five projects or programs, the research and development project costs and the changes in life cycle cost that result as the research and development is deployed will be estimated. The cost reductions and the project costs will be referenced to the same planning year (1979).

For each project, an optimistic, nominal, and worst case estimate will be made for each of the following items, which determine the change in life cycle costs.

N = average number of units deployed each year
ΔC = reduction in unit purchase price
ΔA = reduction in annual operating and maintenance cost/per unit
F = years to first delivery
L = technology life
ℓ = economic equipment life
k = discount rate
g = escalation rates

The method of Section 4.1 will be utilized to calculate the present value of the change in life cycle costs.

A. Summary of Calculations and Assumptions

1. Air Comfort Project

The size of the U.S. rail transit car fleet is approximately 11,000 vehicles (Table 3-2). Assume that 1/30 of these vehicles are replaced each year and that 30% of the vehicles are equipped with air conditioning

$$N = 11{,}000\ (\frac{1}{30})\ (.3) = 110 \text{ units/year.}$$

Ten percent of the transit vehicle price is attributable to air conditioning. Only 3% of the 10% is for the air conditioning equipment, the remaining 7% is for duct work and installation.* One potential benefit of the air comfort project, is that the use of modular air conditioning may reduce duct work cost. It will be assumed that the air comfort project will lead to a 35% reduction in these installation costs. Throughout these calculations, a 1979 planning year cost of $700,000 per 75 foot rail transit vehicle, and $500,000 for a shorter 55 foot vehicle is used. An average rail car cost of $550,000 is assumed.

$$\Delta C = (.35)\ (.07)\ (\$550{,}000) = \$13{,}975$$

Table 3-10 identifies the portion of car maintenance costs associated with air conditioning. These are:

AC compressor	1.5%
AC condensor	1.0
AC evaporator	1.7
AC filters	.7
Total	4.9%

It will be assumed that the air comfort project will reduce air conditioning maintenance costs by 30%.

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*Subway Environment Engineering Handbook, pg. 4-77.

Table 3-5 lists the maintenance of equipment cost per vehicle, 1979 dollars, for several rail transit systems. There is variation in costs among the systems, but the bulk of the vehicles represented require \$20,000 per year, per vehicle, for car maintenance. It will be assumed that 25% of the car maintenance cost is fixed and 75% variable.

The expected maintenance cost savings of the air comfort project are:

$$M = (.30)\ (.049)\ (.75)\ (\$20{,}000) = \$220 \text{ per car year.}$$

The air comfort system project also offers potential for reducing the transit cars energy consumption.

The energy consumption per car mile as noted in Table 3-11, and repeated below is:

Function	Power Consumption	Percent
Traction	5.0 kWh/car mile	72
Air Conditioning	1.06	15
Heating	.30	4
Lighting	.08	1
Air Compressor	.16	2
Motor Generator	.27	4
	6.87	100

There is a very high probability that the air comfort project could successfully develop a system that would utilize the heat from dynamic braking to provide passenger comfort heating during cold weather. The operating cost savings of such a development per car, using 1979 power costs of 4¢ per kWh, a 90% reduction in heating power requirements, and 50,000 miles of travel per car per year, are:

$$\Delta M_h = (.9)\ (.30)\ (.04)\ (50{,}000) = \$540 \text{ per car year.}$$

Use of dynamic braking heat for passenger comfort heating will increase the capital cost of the car comfort system. Ducting, temperature sensors, and heat storage devices will be required to ensure a temperature environment that is uniform with respect to time. It is difficult to estimate the increase in capital cost without conducting a preliminary design. As noted earlier in this section, 7% of the cost of the car can be attributed to air comfort system duct work and installation costs. It will be assumed that the dynamic heating feature will increase this cost by 10%.

$$\Delta C_h = -(.10)\ (.07)\ (\$550,000) = \$3850 \text{ per car.}$$

The heating power reduction aspects of this project are likely to have wider acceptance than those related to modularization. It will be assumed that 75% of new car orders utilize the heating energy features of this project.

$$N = \frac{1}{30}\ (11,000)\ (.75) = 275 \text{ cars/year.}$$

The energy consumption of the air conditioning system is large, and may offer, potential for significant cost savings. Some reduction can be achieved by a more precise use of reheat, where the air is overcooled then warmed to reduce excessive humidity or to reduce cycling of compressors. Transit cars do not have humidity sensing devices and use temperatures as an approximate guide when applying reheat. Processes other than the traditional freon vapor cycle air conditioning also offer the potential of reducing energy consumption or even using the available dynamic braking energy to power air conditioning. However, due to limited information, the low probability of these features being effectuated, and the ability to justify the air comfort project on the previously enumerated savings, these additional energy savings will not be included in this analysis.

The present value of the air comfort improvement project will be calculated on the basis of the data in the tables shown below, which indicates an optimistic and pessimistic case in addition to the nominal case. Two cases are shown; in one, the impact of the modularization aspects of this project are quantified, in the second table, the impacts of the heating energy savings are quantified. The present value of the overall project is their sum.

Table 5-6. Air Comfort Improvement Project,
Modular Effect Only

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (years)	30	30	15
k (%)	10	10	10
g (%)	2	0	0
N (cars/year)	150	110	70
F (years)	2	5	7
Δ C $/car	20,000	13,500	5000
Δ M $/car year	500	220	200
Present Value	$ 28.5m	$ 9.33m	$1.06m

Table 5-7. Air Comfort Improvement Project,
Heat Energy Effect Only

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (years)	30	30	15
k (%)	10	10	10
g (%)	2	0	0
N (cars/year)	300	275	100
F (years)	2	5	7
Δ C $/car	-1,000	-3,900	-6000
ΔM_h /car year	540	540	450
Present Value	$ 9.4m	.22m	-1.26m

The sum of both the modular and heating effects are:

	Optimistic	Nominal	Pessimistic
Present Value	$37.9 million	$9.55m	-$0.20m

2. Auxiliary Power Supply - Static Inverter

The size of the cost savings attributable to the development of a static inverter for auxiliary power depends on the systems presently in use. Most of the U.S. transit industry powers the larger auxiliary loads with high voltage DC. The lower voltage subsystems are supplied either by a motor generator or a converter. Transit systems utilizing this system have made the decision that the increased maintenance costs of working with DC instead of ac motors, and restrictions associated with the use of the less standardized DC vs. AC powered air conditioning are less than the added costs and unreliabilities associated with the use of a motor alternator to supply AC instead of DC power.

A small segment of the U.S. transit industry (primarily CTA and BART) have been utilizing motor alternators in their recent car purchases, to provide AC auxiliary power.

To estimate the cost savings of a static inverter project, the savings relevant to the two predominant practices in the industry will be computed separately and added.

As noted in Table 3-2, the size of the U.S. rail transit fleet is approximately 11,000 vehicles. The CTA and BART fleets total 1482 vehicles. Assuming that these systems will continue to utilize motor alternators that the remainder of the industry will continue to utilize DC powered auxiliaries, and that the life of these subsystems is 30 years, then the market for the inverter project is:

$$N_{ACx} = \frac{1}{30} (1482) = 50 \text{ units/year}$$

$$N_{DCx} = \frac{1}{30} (9039) = 300 \text{ units/year}$$

Where N_{ACx} represents number of inverters replacing AC powered auxiliary units per year, and DCx represents the number replacing DC powered auxiliary units per year.

For the DC auxiliary system the estimated capital cost for 9 DC motors and an 8 kW motor generator is:

C (DC aux) = \$17,800

The AC auxiliary requires 9 AC motors costing \$1000, and a 42 kW motor alternator costing \$20,000, for a total:

C (AC aux) = \$21,000

Informal industrial estimates indicate that the price of a 42 kW static inverter to replace the motor alternator is \$30,000 and the cost of 9 AC motors is \$1000 yielding:

C (static auxiliary inverter) = \$31,000

The maintenance costs for each system will be estimated by assuming they are a percentage of capital costs. Substitution of the typical car parameters discussed here into the component cost equations contained in the previously cited report* and comparison with Table 3-10 indicates that for traction car motors the annual maintenance costs are approximately 10% of capital costs and for motor generators they are 5% of capital costs. The reference used was written before motor alternators were widely deployed and does not provide any direct maintenance costs estimates. With the foregoing as a guide, it will be assumed that

Annual maintenance costs DC auxiliary equipment = 10% Capital Cost
Annual maintenance costs AC auxiliary equipment = 5% Capital Cost
Annual maintenance cost of AC & solid state auxiliary equipment = 5% Capital Cost

Therefore,

M (DC aux) = \$1780
M (MA + AC aux) = \$2050
M (static inverter) = \$1550

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*Huss, op cit.

For a system similar to CTA, the following information would lead the change in life cycle costs due to replacing motor alternators by solid state inverters.

N = 50 units/year
ΔC = \$10,000/car
ΔM = \$500/car year
F = 5 years to first delivery
L = 30 years
ℓ = 30 years
k = 10% discount rate
g = % escalation rate

For systems where a static inverter would replace DC auxiliary power, the following revised values would be entered into the previous data set.

N = 300 units/year
ΔC = -\$13,200/car
ΔM = \$230/car year

The following tables calculate the life cycle cost associated with replacing either the DC auxiliary or the motor alternator set with a static inverter under a range of parameters.

Table 5-8. Replacing Motor Alternator with Static Inverter

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ,L (years)	30	30	15
k (%)	10	10	10
g (%)	2	0	0
N (cars/years)	100	50	25
F (years)	2	5	7
ΔC \$/car	-8000	-10,000	-10,000
ΔM \$/car year	1000	500	500
Present Value \$	1.25 million	-1.76 m	-.56 m

Table 5-9. Replacing DC Auxiliary with Static Inverter

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (year)	30	30	15
k (%)	10	10	10
g (%)	2	0	0
N (cars/year)	300	300	150
F (years)	2	5	7
ΔC $	-11,000	-13,200	-13,200
ΔM ($)	500	230	230
Present Value $	-14.6m	-19.3m	-5.1m

It is evident from these calculations that the static inverter project cannot be justified on the savings in maintenance cost of electrical equipment. The prime benefit of the static inverter is that it will facilitate the widespread adoption of AC powered air conditioning, which is more adaptable to the modular air conditioning concept than DC powered equipment.

The previous section identified certain costs related to air conditioning and conservatively estimated partial reduction in these costs associated with an air comfort improvement project. It would not be proper to count these benefits twice, once for the air comfort project and once for the static inverter project.

One solution could be to consider these as joint projects in that although managed separately, they would either both be funded or neither funded. Another solution would be to ascribe part of the potential benefit of the air comfort project to the static inverter project. This is reasonable as long as double counting is avoided.

It was prevously estimated that 7% of the cost of a new car was due to installation and duct work for air conditioning. It was assumed in the previous section that the air comfort project could reduce this cost by 35%, lending to a capital cost reduction per car of $13,500. It was also assumed that only 30% of new vehicles were equipped with the improved air comfort system.

The availability of a reliable source of AC auxiliary power makes it reasonable to expect that 50% of the remaining 70% (or 35% additional) of new transit car purchases will be equipped with the improved air comfort system plus solid state auxiliary power system.

The following new vehicle deployment values would be used in the static inverter present value equation.

$$N = 11{,}000 \left(\frac{1}{30}\right) (.35) = 130$$

ΔC (DC auxiliary & standard air conditioning replaced by static inverter and modular air conditioning) = -\$13,200 + \$13,500 = +300

Table 5-10 indicates the effect of varying the parameters to determine the optimistic, and pessimistic case in addition to the nominal.

Table 5-10. Improved Air Comfort System Plus Static Inverter Replacing DC Auxiliary

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (years)	30	30	15
k (%)	10	10	10
g (%)	2	0	0
N (cars/year)	200	130	100
F (years)	2	5	7
Δ C $/car	+2300	$300	-1700
Δ M $/car year	500	230	230
Present Values ($)	10.8 million	$ 1.5m	-.28m

3. Door System Design

Door systems account for only a small part of the capital and maintenance cost of a car. However, they do have a significant impact on the reliability of the entire transit system. The project evaluation method utilized in this report stresses the impact of research and development on hard dollars, that is those that are spent directly for capital, maintenance or operating costs associated with the subsystem. Indirect costs, such as impact on schedules, effect on car availability, or effect on under car temperatures are not included at this stage of the model. Such a process is likely to lead to an under valuing of the importance of door system R&D.

Door systems have been estimated to represent 3% of new car costs. Table 3-10 indicates that they account for 2% of car maintenance costs. Using the data base of the previous section leads to:

$$C\ (\text{doors}) = (.03)\ (550{,}000) = \$16{,}500/\text{car}$$

$$M\ (\text{doors}) = (.02)\ (20{,}000) = \$400/\text{car year.}$$

Assuming the R&D project could result in a 25% reduction in maintenance costs then:

$$\Delta M = (.25)\ (400) = \$100/\text{car year.}$$

It will be assumed that 85% of new cars employ the improved door system developed within this project.

$$N = (.85)\ \frac{1}{30}\ (11{,}000) = 312\ \text{cars/year.}$$

The following table indicates the calculated present value for a nominal, optimistic, and pessimistic estimate of the door systems life cycle costs.

Table 5-11. Improved Door System Direct Costs

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (year)	30	30	15
k (%)	10	10	10
g (%)	0	0	0
N (cost/year)	312	312	200
F (years)	2	5	7
ΔC ($)	1000	0	0
ΔM ($)	200	100	50
Present Value ($)	$6.93 million	.13m	.08m

Even this limited analysis of the direct costs indicates that the potential life cycle cost savings can justify a small research and development project.

A more extensive model, such as the multiattribute decision model discussed in Section 4.7, would consider other factors such as the impact on reliability, train dwell times at stations, car availability, and patronage.

A survey of several North American transit properties indicated that four properties report that 10% of their train delays are due to doors, two systems report that over 30% are due to doors, and one system reports less than 5%. London Transport for 1977 reported one train delay greater than 2 minutes due to doors for every 36,000 train miles. U.S. transit systems had reported door problem delays at a rate several times higher than that for London Transport.

Observations of several transit lines with a nominal schedule of 30 trains per hour indicate that normally a flow rate of less than 27 trains per hour is reached due to various delays. This is a net 10% reduction in the capacity of the transit line. If 20% of these delays were due to door problems, the reduction in system capacity due to doors would be 2%. Although a small number, it indicates that 2% of the multibillion dollar investment in a transit line can be lost due to door system problems.

This cursory analysis indicates the indirect importance of door systems on the operations of the transit systems in spite of their minimal impact on direct capital and maintenance costs. It also indicates the need for a more general project evaluation model.

Door system problems might be corrected by revised maintenance procedures or new equipment designs. The variation in door-caused delay among the properties encourages the expectation that maintenance procedure revisions might result in improved performance. To achieve even greater performance, or to lower equipment sensitivity to maintenance requirements may require new door designs.

4. Escalators

There are nearly 1000 escalators in use at transit properties in North America. Most of these are on the newer (WMATA, BART) systems, which often have 3-7 escalators per station. The older (NYCTA, CTA, SEPTA) systems have one escalator for every 3 to 5 stations. As a result of recent federal regulations concerning the elderly and handicapped, it can be expected that the number of escalators in U.S. transit stations will increase substantially.

These escalators represent a substantial capital investment that must be maintained and completely refurbished at least every 30 years.

There have been recent proposed and implemented innovations in escalator technology that require more detailed investigation. The mmore prominent among these is the use of extra flat steps and tredle operated escalators. Older esclators had 1.75 flat steps at their landings. A predominant practice has been to specify newer escalators with 2-4 flat steps at landings. It was thought that the extra flat steps would increase safety and passenger flow, particularly on high rise escalators. This anticipated benefit has not been proven, and a prime purpose of an escalator research and development project would be to determine the value of this design feature. Extra flat steps have increased the cost of escalators by 30%. If they prove to be unnecessary, a major cost reduction could result.

Tredle-operated escalators have been proposed as a means of reducing escalator energy consumption and maintenance cost. There have been claims that the frequent starts and stops due to tredles may actually increase escalator maintenance requirements. This must be examined carefully, especially in the light of the potential use of solid state power electronics to provide gradual starts and stops.

There are other escalator issues that warrant investigation; however other than for flat steps, it is very difficult to estimate their potential impact on life cycle costs.

The number of units that might benefit from the outputs of transit escalator research and development is:

$$N = \frac{1}{30} (1000) = 33 \text{ units per year}$$

The capital cost of an escalator is $5000 per foot. A typical height for a transit escalator would be 30 feet.

Since there is a reasonable chance that the study, although successful, will continue to recommend use of the high cost extra flat steps, it will be assumed that the cost saving for the actual project is one-half the potential.

$$\Delta C = \tfrac{1}{2} (.30) (30) (\$5000) = \$22{,}500/\text{unit}$$

The average maintenance cost for transit escalators is:

$$M = \$6000/\text{unit year}$$
$$\Delta M = 0$$

Using the above in the life cycle cost equations result in the following table:

Table 5-12. Escalator R&D Cost Savings

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ, L (years)	30	30	15
k (%)	10	10	10
g (%)	0	0	0
N (units/year)	50	30	10
f (years)	2	5	7
ΔC (\$)	45,000	22,500	5000
ΔM (\$)	0	0	0
Present Value (\$)	\$17.38m	\$ 3.79m	\$.135m

5. Fare Collection

Capital costs for fare collection systems are significant, but are much smaller than their operating costs. This is due to the cost of the station attendant, who plays an active role in the fare collection process in most transit systems.

Newer transit systems have adopted graduated fares to increase revenues. These have been implemented by magnetically encoded card accepting gates or coin accepting turnstiles. Older systems have been stretching the capabilities of their fare collection equipment to implement new fare policies to encourage patronage and benefit the elderly and handicapped.

Problems have developed with the capital, operating cost and reliability of graduated fare collection systems. Industry-wide issues exist on how to develop the most appropriate fare structure for a region and match that fare structure to equipment capabilities. The best design approaches to achieve these capabilities must also be determined. There is also a perceived need to achieve greater standardization of fare collection equipment specifications with the objective of lowering capital cost.

A series of projects or an entire fare collection research and development program is required to address these problems. An estimate of reasonable capital and operating cost savings that might result from such a program follows.

Data from several properties was readily available on the number and types of fare collection equipment in use. It can be used to estimate industry-wide equipment requirements, and the number of units of equipment purchased each year. Capital cost estimates will be developed for three types of fare collection systems: flat fare attended, flat fare unattended, and graduated.

Requirements for the flat fare attended systems can be estimated from the following data reported by NYCTA and CTA.

Table 5-13. Flat Fare Attended Stations - Selected Fare Collection Equipment and Capital Requirements per Station

	No. Stations	Type	Number	Unit Cost	Total Cost	Equipment Cost per Station
NYCTA	463	Turnstiles	2777	$ 2,100	$ 5,800,000	
		Bullet-proof Booths	508	40,000	20,300,000	
					$26,100,000	$56,400
CTA	142	Coin Turnstiles	442	10,000	4,420,000	
		Agent Turnstiles	292	15,000	4,400,000	
					$ 8,820,000	$62,000

The remaining systems in this category are MBTA, SEPTA, and CTS. According to Table 3-2 they contain 125 stations.

It will be assumed that their fare collection equipment investment per station is $55,000, and that they contain 5 turnstiles per station.

Capital Cost Fare Collection (MBTA+SEPTA+CTS) = 125x55,000 = $6,875,000
Number Turnstiles (MBTA+SEPTA+CTS) = 125x5 = 625

There are two unattended flat fare systems, PATH and MARTA.

In addition to coin accepting turnstiles, PATH has approximately two changemakers ($2000 capital cost) at each station. PATH is a small system (13 stations) with three very large terminals. The turnstiles per station will be larger than the average previously calculated, assume it is 7.

Capital Cost Fare collection (PATH);

(turnstiles)	13x7x10,000 =	$910,000
(changemakers)	13x2x 2,000 =	$ 56,000
		$966,000

Number Turnstiles (PATH) = 7x13 = 91

MARTA utilizes turnstiles that accept passes and monthly passes. They perform additional functions and have a higher cost ($22,000). Assume six turnstiles per station.

Capital Cost Fare Collection (MARTA) = 41x6x22,000 = $5,412,000
Number Gates (MARTA) = 41x6 = 246

The graduated fare rapid rail transit systems are BART, WMATA, and PATCO.

The fare collection equipment for all 34 stations of the BART system is listed in the following table.

Table 5-14. BART Fare Collection Equipment Costs

Type	Number	Number Station	Unit Cost	Item Cost
Gates	362	10.6	$22,000	$ 7,964,000
Ticket Vendors & Addfares	285	8.4	28,000	7,980,000
Data Acquisition & Display	34	1	10,000	340,000
				$16,284,000
			Cost per station	$ 478,000

The fare collection equipment in use or on order for the first 60 miles and 61 stations of the 101 mile WMATA system is listed below.

Table 5-15. WMATA Fare Collection Equipment Costs

Type	Number	Number Station	Unit Cost	Item Cost
Gates				
Reversible	309		$28,000	$ 8,652,000
Exit	75		20,000	1,500,000
Entry	75		19,000	1,425,000
End A	60		7,500	450,000
End B	60		7,500	450,000
	609	10.		$12,477,000
Fare Card Vendor	355	5.8	29,000	10,295,000
Add Fare	146	2.4	27,000	3,942,000
Data Acquisition and Displays	73	1.2	14,000	1,002,000
Fare Card Readers	3		29,000	81,000
High Speed Fare Card Encoders	3		29,000	81,000
				$27,878,000
			Cost per station:	$ 457,000

The experience on the first 34 mile section of the WMATA system is that equipment requirements per station were higher than the average for the 60 mile system. This is due to the first stations having higher patronage because of their downtown location, and several stations having two mezzanines. It is also partly due to the lower than expected performance of the equipment.

The PATCO system is similar to BART and WMATA but simpler. The PATCO fare card vendor is simplified by its selling preencoded tickets rather than encoding and printing them as sold. It will be assumed that this reduces the vendor cost by 2/3. The add fare system on PATCO utilizes a centrally monitored telephone and television system, rather than an automated add fare machine.

It will be assumed that there are 10 gates per station and 8 ticket vendors per station, and that the cost per station is:

Capital Cost Fare Collection (PATCO) = $300,000

This completes the estimate of the capital costs for fare collection equipment on U.S. rail rapid transit lines. Cost for items such as change room equipment and money containers have not been included.

The following table summarizes the estimates.

Table 5-16. Estimated Capital Cost For
U.S. Rail Transit Systems Fare Collection Equipment

System	Equipment Types	Number/ Station	Cost/ Station	Number of Station	Cost
Flat Fare Attended					
NYCTA	Turnstiles	6			
	Bullet-proof booths	1.1			
			56,400	463	$26,100,000
CTA	Coin Turnstiles	3.1			
	Agent Turnstiles	2.1			
			62,000	142	8,820,000
MBTA + SEPTA + CTS	Turnstiles	5			
			55,000	125	6,825,000
					$41,745,000
Flat Fare Unattended					
PATH	Turnstiles	7			
	Changemaker	2			
			74,000	13	966,000
MARTA	Gates	6	132,000	41	5,412,000
					$ 6,378,000
Graduated Fare					
BART	Gates	10.6			
	Ticket Vendor & Add Fare	8.4			
	DADS	1			
			$478,000	34	$16,284,000
WMATA	Gates	10			
	Fare Card Vendor	5.8			
	Add Fare	2.4			
	DADS	1.2			
			$457,000	61	27,878,000
PATCO					
	Gates	10			
	Vendors	8			
			$300,000	12	3,600,000
				891	$47,762,000

As a reasonable estimate of the capital cost savings that can result from a fare collection research and development program, it will be assumed that the cost of fare card vendors and add fares could be reduced by 50%.

Number of vendors and add fares in service : 787
Service line : 20 years

Number of vendors and add fare replaced per year: 40

ΔC (fare collection) = (1/2) (28,000) = $14,000 per vendor

The set of fare card vendors and add fares in service is relatively new. It is reasonable to expect operating agencies to utilize their existing investment for as long as it is economical. It will be assumed that the capital cost savings benefits of this project do not begin to occur for 8 years.

Data on the operating cost of fare collection equipment is not readily available. The following table lists operating costs as a percent of revenue collected for five transit systems. Salaries for station attendants, revenue collection agents, maintenance personnel, and replacement parts are included in these costs.

Table 5-17. Fare Collection Operating Costs

System		% of Operating Revenue
Flat fare		
Attended	NYCTA	19%
Unattended	PATH	8%
Graduated Fare		
Attended	BART	31%
	WMATA	21%
Unattended	PATCO	7%

The wide variation in operating costs leads to the expectation of a substantial saving if the reliability of fare collection equipment is improved. More reliable ticket vendors and gates will reduce but not eliminate the level of station attendant coverage and maintenance personnel in the graduated fare systems. Similarly, effective and reliable token vendors and pass readers could benefit the flat fare systems.

It will be assumed that industry-wide reduction of 1% in fare collection operating costs could be achieved by fare collection R&D. This cost savings reduction will be achieved as equipment on existing stations is replaced with the improved equipment. It will be assumed that this takes place over a period of 20 years.

$$\text{Number of Stations Reequipped} = \frac{891}{23} = 45/\text{year}$$

$$\Delta M \text{ (fare collection)} = \frac{(.01)\ (700{,}000{,}000)}{891} = \$7900 \text{ year}$$

The units used to estimate capital cost savings were ticket vendors while the units used for operating savings were stations. This difference prohibits mixing those savings in the same equation. The benefits must be calculated separately and added.

Table 5-18. Fare Collection R&D Cost Savings
Capital Costs Only

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ,L (years)	20	20	20
k (%)	10	10	10
g (%)	0	0	0
N (vendors/year)	60	40	10
F (years)	3	8	12
ΔC ($/vendor)	21,000	14,000	7,000
ΔM ($/year)	0	0	0
	7.58m	$ 1.77m	.12m

Table 5-19. Fare Collection R&D Cost Savings
Operating Costs Only

	Optimistic Case	Nominal Case	Pessimistic Case
ℓ,L (years)	20	20	20
k (%)	10	10	10
g (%)	0	0	0
N (stations/year)	45	45	45
F (years)	3	8	12
ΔC ($/station)	0	0	0
ΔM ($/station year)	16,000	7,900	4,000
	24.90m	$6.06m	$ .92m
Total	$32.48	7.83m	1.04m

B. Closure

These five illustrative examples have demonstrated the capabilities and limitations of the analysis methods. The techniques consider the rate of benefit deployment, the first year of deployment, technological life of the product, relative escalation rates, the discount rate, changes in annual maintenance costs and capital costs. By varying these parameters, a wide variety of complex deployment situations can be readily analyzed. Each of these enumerated factors can have a large impact on the benefit of a research and development project. The method would be improved if it could also account for the impact of the projects on transit service in addition to capital and maintenance costs.

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APPENDIX A

Table A-1
NEW YORK CITY TRANSIT AUTHORITY(7)
Comparative Statement of Operating Expenses by Function
For Fiscal Year Ended June 10, 1976 and 1975

Fiscal Year Ended	June 30		% Change
	1976	1975	from 1975
MAINTENANCE OF WAY AND STRUCTURES:			
Superintendence - Salaries and Expenses	$18,739,034	$19,299,882	(2.9)
Ballast	91,484	95,834	(4.5)
Ties	1,428,986	741,845	92.6
Rails:			
Running Rails	2,545,401	1,263,042	101.5
Guard Rails	244,498	116,810	109.3
Rail Fastenings and Joints	2,004,573	1,088,460	84.2
Special Work	642,376	292,930	119.3
Roadway and Track Labor:			
Trackmen	16,974,708	16,648,858	2.0
Other Labor	4,740,154	5,074,682	(6.6)
Miscellaneous Roadway and Track Expenses	5,489,412	4,965,536	10.6
Cleaning and Sanding Track	718,413	842,974	(14.8)
Removal of Snow, Ice and Sand	166,335	78,741	111.2
Repairs of Tunnels:			
Repairs	410,647	429,381	(4.4)
Painting	25,660	40,434	(36.5)
Drainage	2,356,551	2,450,177	(3.8)
Ventilation	732,956	847,026	(13.5)
Lighting System	1,337,190	1,355,505	(1.4)
Repairs of Elevated Structures and Foundations:			
Repairs	2,082,768	1,855,245	12.3
Painting	99,665	969,821	(89.7)
Repairs of Bridges, Trestles & Culverts	76,174	41,011	85.7
Repairs of Crossings, Fences & Signs	122,786	159,443	(23.0)
Repairs of Signal & Interlocking Systems	11,439,111	10,937,614	4.6
Repairs of Fire Protective Equipment	170,008	166,548	2.1
Telephone and Telegraph Repairs	1,224,141	1,223,654	(0.4)
Other Miscellaneous Way Expenses	4,094,340	3,061,113	33.8
Pole and Fixture Repairs	26,774	25,033	7.0
Underground Conduit Repairs	249,453	217,047	14.9
Transmission System Repairs	619,667	508,907	21.8
Distribution System Repairs:			
Underground Feeders	429,828	528,122	(18.6)
D.C. Feeders	733,032	608,117	20.5
Track Bonding	316,829	284,231	11.5
Third Rail and Fixtures	3,234,127	3,394,140	(4.7)
Miscellaneous Electric Line Expenses	178,019	152,712	16.6
Repairs of Building and Structures:			
Sub-Stations	339,509	327,911	3.5
Car Houses, Repair Shops and Inspection Shops	964,809	722,729	33.5
Stations, Waiting Rooms & Platforms	12,567,814	12,358,581	1.7
Other Buildings	748,158	745,068	0.4

Table A-1 (cont.)

NEW YORK CITY TRANSIT AUTHORITY

Comparative Statement of Operating Expenses by Function

For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change
	1976	1975	from 1975
Meal Allowance	65,710	108,662	(39.5)
Allowances:			
Vacations	7,461,833	6,946,869	7.4
Holidays	3,566,198	3,503,773	1.8
Sick Leaves	2,990,132	2,681,029	11.5
60% Sick Leaves	47,130	31,089	51.6
Jury Duty	184,645	270,422	(31.7)
Death in Family	90,141	90,330	(0.2)
Misc. Allowance	386,928	398,891	(3.0)
Differential Pay (Night)	2,451,044	1,703,243	43.9
Total Maint. of Way & Structures	$115,609,151	$109,658,472	5.4

Table A-1 (cont.)

NEW YORK CITY TRANSIT AUTHORITY

Comparative Statement of Operating Expenses by Function
For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change from 1975
	1976	1975	
MAINTENANCE OF EQUIPMENT:			
Superintendence - Salaries and Expenses	$12,632,313	$13,419,151	(5.9)
Repairs of Revenue Cars:			
Bodies (Incl. Fittings)	4,553,316	6,226,461	(26.9)
Painting and Varnishing	1,345,553	1,874,153	(28.2)
Repairs of Sub-Stations Equipment	1,993,328	1,918,988	3.9
Car Trucks:			
Wheels and Axles	2,781,884	2,407,883	15.5
Other Repairs	6,206,205	5,795,131	7.1
Car Brakes	6,437,976	6,801,448	(5.3)
Repairs of Locomotives	121,988	83,650	45.8
Repairs of Service Cars	218,074	246,043	(11.4)
Repairs of Service Automotive Equipment	655,948	474,236	38.3
Repairs of Electric Equipment of Cars:			
Control Apparatus and Wiring	10,578,507	10,473,631	1.0
Motors	8,377,910	8,927,825	(6.2)
Storage Batteries	167,337	420,350	(60.2)
Air Compressors and Governors	1,480,693	1,348,115	9.8
Light, Heat and Fan Circuits	538,820	464,720	15.9
Radio Equipment & Accessories	559,435	521,714	7.2
Air Conditioning Equipment Accessories	1,049,788	947,975	10.7
Repairs of Shop Machinery and Tools	1,203,220	1,178,253	2.1
Shop Expenses:			
Light and Power	1,756,016	1,715,771	2.4
Labor	3,748,274	3,395,780	10.4
Other Expenses	6,598,154	7,030,470	(6.2)
Other Miscellaneous Equipment Expenses	9,149	6,892	32.3
Inspection Labor	19,598,234	19,735,075	(0.7)
Maintenance Trainee Program:			
Undistributed Expenses	287,408	271,221	6.0
Meal Allowance	75,763	194,872	(61.1)
Allowances:			
Vacations	6,679,395	6,652,056	0.4
Holidays	3,019,458	3,053,283	(1.1)
Sick Leaves	2,462,289	2,361,544	4.3
60% Sick Leaves	66,804	76,629	(12.8)
Jury Duty	178,751	249,779	(28.4)
Death in Family	90,755	100,118	(9.4)
Misc. Allowance	92,551	154,703	(40.2)
Differential Pay (Night)	1,444,650	1,139,152	26.3
Total Maintenance of Equipment	$107,009,946	$109,667,072	(2.4)

Table A-1 (cont.)

NEW YORK CITY TRANSIT AUTHORITY

Comparative Statement of Operating Expenses by Function

For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change from 1975
	1976	1975	
POWER:			
Superintendence - Salaries & Expenses ..	$ 1,671,703	$ 1,676,334	(0.3)
Sub-Station Labor	8,171,972	8,032,378	1.7
Sub-Station Supplies & Expenses	508,387	419,650	21.1
Power Purchased	83,504,076	85,930,972	(2.8)
Meal Allowance	17,689	36,878	(52.0)
Allowances:			
Vacations	1,243,540	1,172,461	6.1
Holidays	595,444	547,920	8.7
Sick Leaves	312,653	317,626	(1.6)
60% Sick Leaves	5,594	3,723	50.3
Jury Duty	30,655	61,584	(50.2)
Death in Family	13,701	12,966	5.7
Misc. Allowance	9,074	36,685	(75.3)
Differential Pay (Night)	411,758	288,381	42.8
Total Power	$96,496,246	$98,573,558	(2.1)

Table A-1 (cont.)

NEW YORK CITY TRANSIT AUTHORITY
Comparative Statement of Operating Expenses by Function
For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change
	1976	1975	from 1975
OPERATION OF CARS:			
Superintendence - Salaries & Expenses ..	$24,490,421	$23,667,330	(0.7)
Passenger Motormen	30,400,606	31,072,664	(2.2)
Passenger Conductors	24,430,641	24,181,823	1.0
Miscellaneous Car Service Employees	12,641,074	10,684,143	18.3
Miscellaneous Car Service Expenses:			
Lubricants and Waste	111,153	118,589	(6.3)
Light	61,449	103,264	(40.5)
Car Cleaning Supplies	505,284	780,196	(35.2)
Cost of Tickets Used	133,559	146,513	(8.8)
Other Supplies and Expenses	212,349	225,356	(5.8)
Station Employees:			
Railroad Clerks	43,788,994	43,126,508	1.5
Platform Men	7,112,079	7,245,170	(1.8)
Porters and Watchmen	10,879,020	10,680,962	1.9
Other Employees	540,489	481,880	12.2
Station Supplies and Expenses	4,781,760	3,976,429	20.3
Special Patrolmen	62,663,482	66,201,062	(5.3)
Car House Employees	6,791,395	7,911,555	(14.2)
Operation of Signal & Interlocking System:			
Towermen	7,269,033	7,223,772	0.6
Other Expenses	5,803,183	5,461,310	6.3
Other Transportation Expenses	1,287,808	1,047,130	23.0
Meal Allowance	31,345	44,168	(29.0)
Allowances:			
Vacations	15,006,568	14,126,315	6.2
Holidays	6,756,078	9,028,686	(25.2)
Sick Leaves	5,966,141	5,650,278	5.6
60% Sick Leaves	239,857	218,770	9.6
Jury Duty	381,153	597,224	(36.2)
Death in Family	184,076	179,933	2.3
Misc. Allowance	155,592	223,762	(30.5)
Differential Pay (Night)	9,138,396	6,430,838	42.1
Total Operation of Cars	$280,762,985	$280,835,630	--

Table A-1 (cont.)
NEW YORK CITY TRANSIT AUTHORITY
Comparative Statement of Operating Expenses by Function
For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change from 1975
	1976	1975	
INJURIES AND DAMAGES:			
Injuries to Employees:			
Compensation Bureau:			
Salaries	$ 255,949	$ 250,124	2.3
Expenses	1,569	1,691	(7.2)
Medical Department:			
Salaries and Fees	514,795	507,873	1.4
Supplies and Expenses	43,786	57,518	(23.9)
Fees of Outside Doctors	49,163	146,158	(66.4)
Hospitalization	202,970	275,062	(26.2)
Provisions for Workmen's Comp. (a)	3,207,284	3,572,875	(10.2)
Wage Allowances over Comp. Payments	452,754	554,666	(18.4)
Miscellaneous	577,384	510,197	9.2
Other Injuries and Damages:			
Claim Department:			
Salaries	310,743	316,457	(1.8)
Expenses	9,929	10,795	(8.0)
Medical Department:			
Fees of Outside Doctors	2,995	3,990	(24.9)
Provision for Public Liability (b)	6,163,000	5,250,001	17.4
Law Expenses in Commection with Damages:			
Salaries of Attorneys	202,286	198,495	1.9
Salaries of Other Employees - (Investigators, Clerks, etc.)	369,105	365,131	1.1
Expenses - (Incl. Attorney's and Investigators' Expenses and Other General Expense of Department)	15,380	15,132	1.6
Court Costs and Expenses - (Witness Fees, Minutes, etc.)	94,173	106,154	(11.3)
Total Injuries and Damages	$12,453,265	$12,142,319	2.6

Table A-1 (cont.)
NEW YORK CITY TRANSIT AUTHORITY
Comparative Statement of Operating Expenses by Function
For Fiscal Year Ended June 10, 1976 and 1975

	Fiscal Year Ended June 30		% Change from 1975
	1976	1975	
GENERAL AND MISCELLANEOUS:			
Salaries & Expenses of General Officers.	$ 243,825	$ 189,269	28.8
Salaries & Expenses-Gen'l. Office Clerks	15,008,458	13,035,380	15.1
Gen'l. Office Supplies & Expenses	4,360,557	3,899,270	11.8
Provisions for Payments to Retirees and Beneficiaries	10,187,604	7,739,966	31.6
General Law Expenses	329,435	416,012	(20.8)
Insurance	382,969	392,704	(2.5)
Social Security-Employer's Contribution.	24,955,762	23,925,500	4.3
Contributions to New York City Employees' Retirement System	122,353,343	118,457,870	3.3
Health & Welfare Benefits	33,221,628	28,155,126	18.0
General Stationery & Printing	277,927	453,306	(38.7)
General Stores Expenses	4,044,588	3,782,185	6.9
Miscellaneous General Expenses	4,015,050	3,240,180	23.9
Undistributed Adjustments:			
Cash Discounts	CR. 220,364	CR. 156,014	41.3
Inventory Adjustments	545,337	CR. 161,391	--
Other	4,468,312	88,752	--
Supervision Credits	CR.5,534,294	CR.3,302,553	62.1
Advertising	11,621	87,017	(86.6)
Meal Allowance	12,555	22,785	(44.9)
Allowances:			
Military Duty	629,198	555,337	13.3
Provisions for Vacation & Sick Leave Benefits	601,360	3,130,328	(80.8)
Vacations	1,580,964	1,599,122	(1.1)
Holidays	668,787	642,880	4.0
Sick Leaves	536,596	496,628	8.0
60% Sick Leaves	1,196	192	--
Jury Duty	32,028	54,057	(40.8)
Death in Family	84,407	48,501	74.0
Misc. Allowance	7,079	9,331	(24.1)
Differential Pay (Night)	149,040	105,009	41.9
General and Miscellaneous	$223,134,968	$206,906,749	7.8
Credit from City for Transit Police Services	CR.100,495,433	103,642,946	(3.0)
Credit from City for CETA Program	CR. 2,794,478	1,174,504	137.9
Total Operating Expenses	$732,176,650	$712,930.350	2.7
(a) Comprising:			
Payments under Workmen's Comp. Act ...	$ 1,406,631	$ 1,290,800	9.0
Net Amount Carried to Reserve	1,800,653	2,282,075	(21.1)
(b) Comprising:			
Payments for Public Liability Claims..	$ 4,099,421	$ 4,154,348	(1.3)
Net Amount Carried to Reserve	2,063,579	1,059,653	88.3

APPENDIX B

Table B-1
San Francisco Bay Area Rapid Transit District
R5 Vehicle Component Repair & Vehicle Electronics
Program Expense by Work Order

		YEAR TO DATE (6-30-79)	
	DESCRIPTION	HOURS	DOLLARS
R501	VEHICLE COMPONENT REPAIR:		
	Traction Motor	1,515	56,953
	Line Switch Box Assembly	1,410	35,855
	Brake Grid Assembly-24 Tube R/H	1,550	36,308
	Brake Grid Assembly-36 Tube L/H	235	13,132
	Motor Reactor	5	72
	Line Filter Reactor	1	34
	Current Collector Assembly	334	12,824
	Motor Control Box	3,479	91,581
	Brake Control Unit	2,645	55,662
	Parking Brake Control Unit	2,300	136,812
	Hydraulic Power Unit	3,676	65,832
	Caliper Assembly	2,520	76,152
	Condenser Assembly	372	6,700
	A/C Compressor	9,047	276,892
	Evaporator Assembly	698	14,455
	Air Compressor	493	11,156
	Air Suspension Control Panel X-End	214	5,151
	Leveling Valve Assembly	846	18,477
	Motor Alternator	119	2,795
	Auxiliary Box Assembly	90	4,204
	Blower & Air Filter Assembly	3	45
	Light Assembly	0	75
	Retractable Coupler	1,254	27,592
	Door Operators	1,216	29,865
	Door Control Relay Panel	134	3,078
	Vehicle Doors	154	4,203
	Battery Assembly	6	97
	Windshield Wiper Assembly	159	2,615
	Sun Visor	68	1,920
	Defroster Assembly	31	554
	Run Number Sign Assembly	2	42
	Attendants Foot Rest	18	529
	Documentation & Miscellaneous	195	4,411
	ATO Equipment	1,444	34,659
	Semi-Conductor Box	4,868	198,392
	Truck Assembly	287	5,491
	Built Component Test Equipment	925	20,506
	Harness Repair	594	15,818
	Special Assignments	4,759	87,200
	Upholstery Repair	2,139	78,905
	Carpet Repair	0	33
	Parts Testing/New & Warranty	20	378
	Parts Cleaning	3,181	46,554
	Motor Assemblies	289	11,128

Table B-1 (cont.)
San Francisco Bay Area Rapid Transit District
R5 Vehicle Component Repair & Vehicle Electronics
Program Expense by Work Order

		YEAR TO DATE (6-30-79)	
	DESCRIPTION	HOURS	DOLLARS
	Vehicle Cab & Equipment	551	8,798
	Maintenance Emergency Equipment	0	426
	Electrical/Mechanical Shop Set-Up	0	953
R502	VEHICLE ELECTRONICS & COMMUNICATIONS MAINTENANCE:		
	Track Signal Antenna-Fabrication	55	1,881
	Plating PC Boards	240	3,626
	Revenue Vehicle E&C Maintenance	0	11
	Special Assignments	4,690	79,976
	Revenue Vehicle E&C Repair	15,468	349,430
	PC Board Artwork Repair	195	3,063
	ATO Manufacturing	48	764
	Propulsion Manufacturing	420	11,164
	AFC Manufacturing	17	414
R501 & R502 SUBPROGRAM TOTALS		74,979	1,955,643