NATIONAL COOPERATIVE TRANSIT RESEARCH & DEVELOPMENT PROGRAM

Report 3

Reduction of Peak-Power Demand For Electric Rail Transit Systems

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NATIONAL COOPERATIVE TRANSIT RESEARCH & DEVELOPMENT PROGRAM

Report 3

Reduction of Peak-Power Demand For Electric Rail Transit Systems

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  Administration
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NATIONAL COOPERATIVE TRANSIT RESEARCH & DEVELOPMENT PROGRAM

Administrators, engineers, and many others in the transit industry are faced with a multitude of complex problems that range between local, regional, and national in their prevalence. How they might be solved is open to a variety of approaches; however, it is an established fact that a highly effective approach to problems of widespread commonality is one in which operating agencies join cooperatively to support, both in financial and other participatory respects, systematic research that is well designed, practically oriented, and carried out by highly competent researchers. As problems grow rapidly in number and escalate in complexity, the value of an orderly, high-quality cooperative endeavor likewise escalates.

Recognizing this in light of the many needs of the transit industry at large, the Urban Mass Transportation Administration, U.S. Department of Transportation, got under way in 1980 the National Cooperative Transit Research & Development Program (NCTRP). This is an objective national program that provides a mechanism by which UMTA's principal client groups across the nation can join cooperatively in an attempt to solve near-term public transportation problems through applied research, development, test, and evaluation. The client groups thereby have a channel through which they can directly influence a portion of UMTA's annual activities in transit technology development and deployment. Although present funding of the NCTRP is entirely from UMTA's Section 6 funds, the planning leading to inception of the Program envisioned that UMTA's client groups would join ultimately in providing additional support, thereby enabling the Program to address a large number of problems each year.

The NCTRP operates by means of agreements between UMTA as the sponsor and (1) the National Academy of Sciences, a private, nonprofit institution, as the Primary Technical Contractor (PTC) responsible for administrative and technical services, (2) the American Public Transit Association, responsible for operation of a Technical Steering Group (TSG) comprised of representatives of transit operators, local government officials, State DOT officials, and officials from UMTA's Office of Technology Development and Deployment, and (3) the Urban Consortium for Technology Initiatives/Public Technology, Inc., responsible for providing the local government officials for the Technical Steering Group.

Research Programs for the NCTRP are developed annually by the Technical Steering Group, which identifies key problems, ranks them in order of priority, and establishes programs of projects for UMTA approval. Once approved, they are referred to the National Academy of Sciences for acceptance and administration through the Transportation Research Board.

Research projects addressing the problems referred from UMTA are defined by panels of experts established by the Board to provide technical guidance and counsel in the problem areas. The projects are advertised widely for proposals, and qualified agencies are selected on the basis of research plans offering the greatest probabilities of success. The research is carried out by these agencies under contract to the Academy, and administration and surveillance of the contract work are the responsibilities of the Academy and Board.

The needs for transit research are many, and the National Cooperative Transit Research & Development Program is a mechanism for deriving timely solutions for transportation problems of mutual concern to many responsible groups. In doing so, the Program operates complementary to, rather than as a substitute for or duplicate of, other transit research programs.

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FOREWORD

By Staff
Transportation
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Electric rail transit managers will find this report very useful in assessing energy costs for operation of electric rail systems. The energy cost reduction guidelines included in Appendix I contain step-by-step procedures for energy load management by reduction of the peak-power demand component of energy use. A key analysis tool used in the load management program is the Energy Management Model (EMM), a series of computer simulation programs developed by the Rail Systems Center of Carnegie-Mellon University. These programs have applications also in overall rail system management.

Rapidly increasing electric energy costs have resulted in a dramatic increase in operating expenses of transit agencies operating electric rail systems. The peak demand component of electric rates is directly associated with the cost of electric energy generation, transmission, and distribution facilities. If transit agencies improve the management of peak demand on their systems, a significant reduction in energy costs can be achieved. The objective of this research effort was to provide guidelines for transit agencies to lower peak electric power demand and, thereby, reduce electric energy costs.

The research conducted by the Rail Systems Center involved identification of factors that contribute to peak power demand, examination of energy-related data and policies, simulation of energy use patterns, and development of guidelines for reducing peak-power demand that will result in energy cost savings. Data were collected and analyzed from four transit agencies as a part of the research activities. The sensitivity of factors that influence power demand on these four electric rail systems was determined by using the EMM simulation programs previously developed by the researchers.

The general findings of the study are that (1) reduction of the peak-power demand component (load management) of the electric rate structure can be cost effective for transit agencies desiring to reduce energy costs, (2) the costs and benefits of load management are site specific, and (3) load management should be a part of an overall energy management effort. Vehicle performance modification strategies, such as top-speed reduction and coasting, can produce energy savings, are rather easily and quickly implemented, and are not costly to implement. However, more sophisticated strategies may be desirable for optimum cost reduction. Because load management reduces peak demand, the burden of the utility company cost allocation is shifted to other customers. Careful negotiation will be necessary to avoid higher rates in future years.

The energy cost reduction management guidelines contained in Appendix I of this report consist of a step-by-step procedure for making an energy management audit and for developing energy cost reduction strategies for an individual transit system. The use of information collected from four operating transit agencies and reviewed during presentations of the findings at seven rail transit agencies has shown that the guidelines are suitable for immediate implementation.

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PART I

PART II

NCTRP TECHNICAL STEERING GROUP

Annual research programs for the NCTRP are recommended to UMTA by the NCTRP Technical Steering Group (TSG). Under contract to UMTA, the American Public Transit Association, supported by the Urban Consortium for Technology Initiatives/Public Technology, Inc., is responsible for operation of the TSG, the membership of which is as follows.

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Reduction of Peak-Power Demand For Electric Rail Transit Systems

SUMMARY

Energy costs represent 8 to 16 percent of the operating cost of electric rail transit in the United States. Because tight energy supplies have forced electric utilities to seek substantial annual rate increases, energy will represent a larger portion of operating cost in the future. Opportunities exist for energy cost reduction for relatively small investments.

Factors which determine electrical energy cost are related not only to variables of equipment and system design and operating practices (sometimes referred to as the energy use pattern), but also to the power rate structure of the electric utilities that serve the system. The cost of electricity on transit systems is made up of facilities, power demand, and energy use components. Facility charges are fixed, while power demand and energy use vary with modes of operation. Power demand is the capacity reserved by the electric utility for transit operation, while energy use represents actual power used over time. A typical electric bill for transit in the United States is 50 percent power demand.

The objective of this research effort was the identification of systematic methods and procedures by which rail transit systems can lower the power demand component of the electric bill. This is generally known as load management, which consists of the monitoring, prediction, and control of power demand. Load management can also lower the energy use component of the power bill.

Four rail transit systems were selected to examine energy-related data and policies, to simulate the energy use pattern, and to develop more general guidelines for energy management on rail transit agencies. These organizations were the Washington Metropolitan Area Transit Authority; the Port Authority Transit Corporation of Lindenwold, New Jersey; the Greater Cleveland Regional Transit Authority; and the New York City Transit Authority. The sensitivity of key factors that influence power demand was tested on these sample rail systems, by using the Energy Management Model, a package of simulation programs previously developed at Carnegie-Mellon University to study power distribution in electric rail transit.

Load management techniques appropriate to rail transit were identified. This was accomplished through a survey of non-U.S. transit authorities and by investigating the consequences of these monitoring methods: real time, batch processing of detailed metering information, and electric bill analysis, all of which apply to rail transit. Using the four sample transit systems, energy conservation strategies were assessed according to their effectiveness for reducing power demand (and energy use), their degradation of system performance and their capability to work with power demand monitoring methods.

Estimates of overall cost and effectiveness of load management were made. Opportunities for further reduction of energy cost, which result from the ability to negotiate a more favorable power rate structure as a result of load management, were also investigated.

The findings indicate that most of the rail transit systems in the United States have a demand component to energy cost that is quite different from system to system. The demand interval varies from 15 min to 1 h, and electric meter readings are grouped both coincidently and noncoincidently for billing purposes. The length of the

demand interval allows load management to be an effective tool in reducing energy cost because there is time to respond to predictions of high levels of demand.

Of the nine non-U.S. transit organizations which responded to the survey, most have active energy conservation programs. Two have load management systems, where power for support services is reduced either on-board the trains or in the fixed facilities, in response to a predicted high demand level. The effectiveness of these load management systems was not determined.

Peak-power demand on U.S. transit agencies is generally determined by abnormal conditions of operation, following either train delays or other unusual conditions of high energy consumption over a demand interval.

Of the load management systems investigated, those that have real-time power-demand monitoring as their base represent the best opportunity to reduce peak-power demand cost while causing least reduction of the performance of the system. As might be expected, the initial investment to acquire such systems is the highest; however, payback periods in energy cost savings of 1 to 3 years may be realized. Energy conservation strategies, appropriate to load management with real-time monitoring systems, are vehicle performance reduction, including top speed reduction, coasting or optimum performance modification and support service reduction, either on board the vehicle or in the stations. These same strategies can also be used as part of overall energy use reduction.

For those transit authorities who cannot afford the initial investment of real-time power-demand monitoring and who may be able to take more degradation of system performance to achieve energy savings, batch processing of metering information or electric bill analysis may be used as a monitoring scheme. Load management using these monitoring procedures will involve response with a demand reduction strategy that lags the event that caused the peak demand charge by a few months while the information is being analyzed. In contrast to systems with real-time monitoring, these monitoring procedures require that the strategies be applied over longer periods of time, resulting in more degradation of performance. For those transit systems whose serving electric utilities have detailed information on metering (energy readings for each demand interval), more effective response is possible using batch processing of this information rather than electric bill analysis.

The reduction of peak-power demand through load management may be counteracted by an increase in the power demand rate as a response by the electric utility in order to obtain its rate of return on the investment allocated to the transit agency. In order to avoid this situation, the transit authority must maintain a knowledgeable representation at rate case hearings. In addition to the magnitude of the reduction of peak demand, other factors that can influence the response are: the fraction of peak demand attributable to the transit system as a member of its customer class and fraction of the customer class to the total; time of transit peak demand to utility peak demand; exclusive use facilities; and the ratio of peak demand to other cost components of the electric bill.

There is an inducement for all customers of the electric utility to conserve energy if one member of the group does because the burden of cost will shift to other customers. Load management is useful under this circumstance. It is also useful for a transit agency when it is expanding its service, because peak demand can be held constant or slowly increase, while no action would be taken by the utility.

This study has shown that the cost benefit of applying a load management system is extremely site specific. A series of guidelines that define an overall energy management program were produced and are included in Appendix I of this report.

The results of this investigation indicate that future work should be directed toward establishing a load management system on a transit agency. The steps in this development as well as their validation have been outlined.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

Although energy costs represent a small portion (8 to 16 percent) of the operating cost of electric rail transit, there are several conservation methods that yield large savings for the investment required to implement them. In recent years, many conservation strategies were proposed by the rail transit industry in order to reduce the electric bill of rapid and light rail operation. These strategies have been discussed in recent industry meetings, seminars, and publications (*1, 2, 3, 4, 5, 6, 7, 8*).

The application of energy cost reduction through structural, operational and institutional changes in a system is part of a discipline that has become known as energy management. Energy management is a process to understand the factors that determine system energy cost and to use this knowledge to determine the cost-benefit and overall effectiveness of energy cost reduction. The factors that determine electric energy cost are related not only to variables of equipment and system design and operating practices (sometimes referred to as the energy use pattern), but also to the power rate structure of the electric utilities that serve the system (*9*).

The energy use pattern is controllable within limits by transit management. The power rate structure, which sets the schedule for electric facility, energy consumption, and power demand charges, may be a matter of negotiation between the transit authority and the electric utilities.

PROBLEM STATEMENT

The cost of electricity on rail transit systems is made up of facilities, power demand, and energy consumption components. The facilities charges are fixed and cannot be controlled by transit management. The energy consumption and power demand components result from operating the system. Energy consumption is the actual use of power integrated over time, and it is measured by electric meters in units of kilowatt-hours (kWh). Power demand represents the generation, transmission, and distribution facilities, which the electric utility reserves for its large customers, and is determined using the electric meter readings together with a complex mathematical formula. Power demand has units of kilowatts (kW). A typical electric bill for a rail transit operation in the United States is 50 percent demand.

During the past several years, there were many studies concerned with reducing the energy consumption component on rail transit systems. Few of these studies considered the reduction of power demand and its relation to energy cost reduction. The research reported here was directed toward the identification of systematic methods and procedures by which rail transit systems can lower the power demand component of the electric bill.

PRESENT KNOWLEDGE

The maximum demand for billing purposes generally occurs during the peak operating hours of the transit system. These peak hours occur twice each weekday, typically from 6 to 10 AM (morning rush) and 3 to 7 PM (evening rush). Special events, such as sporting attractions, concerts, etc., within the transit district can be responsible for creating the maximum demand in periods other than the morning and evening rush.

The value of reducing maximum demand was recognized at the New York City Transit Authority in the late 1960's and early 1970's, when they initiated work on an energy storage system for peak load shaving (*10*). In this proposed storage system, which is battery based, some of the required peak energy is supplied from storage devices that are charged during off-peak operating times.

There are energy conservation strategies that can be applied to transit systems and that result in both a reduction of energy consumption and power demand. The advent of the solid state propulsion control systems, such as choppers with DC traction motors in the mid-1960's, allowed trains of self-propelled transit cars to regenerate electrical energy (*11, 12, 13*). This energy could be returned to the line to be used by auxiliaries in the same train or as traction and auxiliary power in other trains on the system. Other schemes would allow the regenerated braking energy to be stored on the transit vehicle or in storage devices along the right of way, or to be returned to the electric utility's distribution and transmission system by using inverter substations. In the United States, chopper rail cars are now operating in Atlanta, Boston, Cleveland, Philadelphia, and San Francisco. They will be operating in the near future in Baltimore, Buffalo, Miami, Pittsburgh, and Washington.

Two R32 cars were equipped with on-board storage capability using chopper control with high-speed flywheels. These cars were tested for 6 months on the New York City subway system with a measured energy consumption savings of 30 percent (*14*). No wayside storage devices or inverter substations have yet been built for rapid transit operation, although some feasibility and economic studies were conducted (*15, 16*).

There are operational energy conservation strategies that can reduce both the power demand and energy consumption components of the power bill at the expense of a slight increase in running time. These conservation methods are sometimes called performance modification strategies because they involve reducing the performance of the cars in order to save energy. Among them are top speed reduction, coasting, and optimum performance modification (*17*).

Another class of operational strategies that are useful in reducing energy consumption (and in some instances power demand) is passenger load factor improvement. Among these strategies are running shorter trains in non-peak periods and turning trains at intermediate stations during peak periods. The former method would have no effect on power demand, whereas the latter, in some cases, may increase it while reducing the energy consumption component.

All of these energy conservation strategies can be applied on a continuous basis on a system, and result in a reduction of both the energy consumption and power demand components of the electric bill.

OBJECTIVES AND SCOPE OF ASSIGNED RESEARCH

The primary objective of this research effort is to reduce the peak power demand charge by load management, which consists of monitoring, predicting, and controlling power demand during the peak operating periods of the transit system.

APPROACH TO SOLVE PROBLEM

In order to meet the objective of the research effort, a research plan was developed which involved examining energy-related data and policies on four transit agencies: Washington Metropolitan Area Transit Authority (WMATA), Port Authority Transit Corporation (PATCO), Greater Cleveland Regional Transit Authority (GCRTA), and New York City Transit Authority (NYCTA). Utility metering information was examined to determine the key factors influencing power demand.

The basis of energy management is the ability to monitor power. Three monitoring methods were examined in terms of their effectiveness: real time, batch processing of utility metering information, and electric bill analysis. The first monitoring method is appropriate to load management where quick response is required, while the latter two methods would be used as part of an energy audit with longer term response.

The key factors influencing power demand, which are under management control, were tested for sensitivity using the Energy Management Model (EMM), a package of simulation programs developed at Carnegie-Mellon University to study power in electric rail transit systems. At the same time, degradation of transit system performance was identified and estimated.

Load management techniques appropriate to rail transit were identified. Questionnaires were sent to non-U.S. rail transit agencies, which included London, Toronto, Montreal, Sao Paulo, Rio de Janeiro, Paris, Munich, Stockholm, Vienna, Brussels, and Tokyo, to determine their programs. Several energy conservation methods such as performance reduction (reduced acceleration, lower top speed, and the application of coasting) and regeneration of braking energy were selectively tested using the EMM on each of the four sample transit systems. The techniques for conservation of traction energy were assessed according to their ability to reduce power demand and energy consumption, degradation of system performance, and capability to work with demand monitoring techniques.

Estimates of the overall cost and effectiveness of load management were attempted using the four sample rail agencies. Costs which were included were monitoring and resulting performance reduction, while effectiveness was measured in terms of power bill reduction.

Opportunities for further reduction of energy cost, which resulted from the ability to negotiate a more favorable power rate structure as a result of load management, were explored.

Management guidelines to establish load management on general electric rail agencies in the United States were developed. These guidelines include data requirements, methods of analyses, unit costs of monitoring, descriptions of key factors to be considered and cost/effectiveness analysis techniques.

A preliminary validation and demonstration plan for the management guidelines developed in this effort was formulated. The plan includes experimental methodology, required measurements, and generic equipment lists (*1* through *19*).

ABBREVIATIONS

ACE	Atlantic City Electric Company
ATC	Automatic Train Control
ATO	Automatic Train Operator
ATP	Automatic Train Protection
ATS	Automatic Train Supervisor
COE	Central Office Equipment
C-MU	Carnegie-Mellon University
EMM	Energy Management Model
ENS	Electric Network Simulator
GCRTA	Greater Cleveland Regional Transit Authority
LRV	Light Rail Vehicle
MDCTA	Metropolitan Dade County Transportation Administration
NYCTA	New York City Transit Authority
P	Power Level
PASNY	Power Authority of the State of New York
PATCO	Port Authority Transit Corporation
PCC	President's Conference Committee
PE	Philadelphia Electric Company
PEPCO	Potomac Electric Power Company
PL	Performance Level
PSE&G	Public Service Electric and Gas Company
RSC	Rail Systems Center
RTU	Remote Transmitting Unit
SEPTA	Southeastern Pennsylvania Transit Authority
TPS	Train Performance Simulator
VEPCO	Virginia Electric Power Company
WMATA	Washington Metropolitan Area Transit Authority

CHAPTER TWO

FINDINGS

POWER DEMAND COMPONENT OF THE ELECTRIC BILL

The formula used by the electric utilities to compute the power demand component of the electric bill for rail transit systems in the United States can be generalized to five basic elements.

1. Specification of a *demand interval,* which is a time interval measured in minutes over which electric power as recorded on the meters is averaged.
2. A method of *demand consolidation,* which is a way to combine the recordings of several meters for computing maximum demand. *Maximum demand* is determined *coincidentally* when in a given customer class and/or jurisdiction,* it is the maximum of the sum of the average powers recorded on all electric meters in the same demand interval; and, *noncoincidentally,* when it is the sum of the maximum average powers recorded on all electric meters in any demand interval.
3. Computation of the *monthly demand,* which is the maximum demand as determined using the demand consolidation method in a monthly billing period.
4. A *ratchet demand,* simply called *ratchet,* calculated by a predetermined formula, which represents a minimum demand level for billing purposes.
5. Computation of the *billing demand* which is the maximum of the monthly demand and the ratchet.

A survey of the power rate structure of ten rapid transit agencies in the United States (*9*) has shown that the demand interval varies from 15 min to 60 min. In this same survey, it was found that there are 28 rates under which U.S. rapid rail transit systems are billed for power furnished by 15 electric utilities in 11 states. All of the transit agencies have some form of contract with the supplying utilities.

SUMMARY OF NON-U.S. RAIL TRANSIT SURVEY

A questionnaire was sent to 12 non-U.S. rail transit systems to identify energy conservation programs and load management techniques now being applied. The detailed responses to this survey, together with a copy of the questionnaire, are contained in Appendix F.

Questionnaires were sent to London, Toronto, Montreal, Sao Paulo, Rio de Janeiro, Paris, Munich, Hamburg, Stockholm, Vienna, Brussels, and Tokyo. Nine responses were received and energy statistics from the rail agencies that responded are given in Table 1. Of particular interest was the energy conservation and load management efforts at these agencies.

Toronto is in the process of converting existing mercury arc rectifiers to solid state. This is expected to improve efficiency from 92 percent to 94 percent. The budget for this improvement is $2.4 million with an annual energy savings goal of $245,000. All new vehicles are equipped with regenerative braking. Load management is identified in a future energy conservation program.

Montreal has taken some positive steps toward energy conservation. Fan operation and floor heaters are curtailed during peak hours. New traction equipment has regenerative braking, and one regenerative substation has been installed for assured receptivity of regenerated power. They are considering other regenerative substations. Tunnel profiles are designed for gravity assisted acceleration and braking (accelerate down-hill, brake up-hill). A load management system is already in place. The demand meter reading is projected over the demand interval, and if this projection is above a critical value, the tunnel ventilation fans and passenger station floor heaters (in winter) are turned off. Fans and floor heaters are restored after the peak hour of transit operation.

Sao Paulo trains have regenerative braking that saves 20 percent in energy use. They have found that power demand is proportional to the number of trains in service, so that control of demand is based on controlling the number of trains in service. Consideration has been given to offsetting train departures to maximize receptivity under regeneration and reducing the accelerating rate in the case of electrical system failures. The latter strategy interferes with revenue operation.

The RATP in Paris has conducted an energy management program for the past several years. The program was responsible for energy savings of 10 percent and involved regeneration in rolling stock and lighting, ventilation, and escalator reduction. Power can be controlled remotely from a central location where it is monitored and supervised.

Munich is investigating three-phase induction motor drives that will regenerate braking energy. Reduction of station lighting is also considered as part of an energy management program. A demand monitoring system is in place; however, the details were not included in the survey response.

The Hamburg subway system (S-Bahn) uses a form of coasting

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*The jurisdiction is the regulatory body which governs the setting of rates by the electric utility. The customer class is a category used by the utility to classify the customer according to his electricity usage pattern. For example, residential and industrial users are in different customer classes.

Table 1. **Summary of data response from non-U.S. transit agencies.**

RAIL TRANSIT SYSTEM	ANNUAL ELECTRIC POWER COST (US $M)	BREAK DOWN OF ANNUAL ENERGY COST (%) POWER DEMAND	ENERGY USE	ENERGY COST AS % OF OPERATING COST
London				ND[b]
Toronto	12.2	24	76	4.3
Montreal	7.4	45	55	7.0
Sao Paulo	2.1	50	50	5.0
Paris	40.0	20-25	75-80	4.0
Munich	7.9	ND	ND	17.0
Hamburg	1.9	0	100	8.2
Stockholm	11.5	17[c]	33[c]	26.0
Vienna	9.8	0	100	14.3

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[b] ND=No Data

[c] Facilities charges account for the remainder.

on its approach to a station. Power is cut off and the train is allowed to coast from its maximum speed to platform approach speed. In the urban railway (U-Bahn), if the demand is too high, certain auxiliaries aboard the trains, such as heating systems, are cut off for several minutes.

The Stockholm rail system also has an energy management program. The goal is to reduce energy consumption by 15,000 MWh in the period 1982–1987 and another 15,000 MWh in 1987–1992. The principal means to achieve these reductions are increasing the number of regenerative cars and vehicle performance modification during off-peak periods. There is no load management system.

There are no official energy conservation or load management programs in Vienna.

In the nine responses received from the non-U.S. transit agencies, energy management programs rely heavily on more regeneration of braking energy in the future by additional purchases of cars with solid state propulsion. Reduction of support power is also a popular way to reduce energy. Several load management systems exist with real-time monitoring, and the response generally is the reduction of support power either on or off-board the cars. No transit system survey reduces train performance as a response to a prediction of high peak demand.

BRIEF DESCRIPTION OF FOUR SAMPLE RAIL TRANSIT SYSTEMS

Four rail transit authorities were selected as sample systems for this research effort. Data from these systems were used as the basis for load management guidelines development. Table 2 summarizes the basic physical and operating characteristics that influence energy consumption on these properties. A brief description of each system is given here, while detailed information is presented in Appendixes A through D.

Washington Metropolitan Area Transit Authority (WMATA)

The Red Line (*18*) of the WMATA Metrorail was selected. The segment used included the double track operation between Dupont Circle and Silver Spring stations. Present use of cam-controlled switching of resistors to control DC series motors to propel the vehicles does not allow regeneration of braking energy.

Electric power service to Metrorail is provided by two electric utilities: the Potomac Electric Power Company (PEPCO) (85 percent), and the Virginia Electric Power Company (VEPCO) (15 percent). PEPCO service is governed by three jurisdictions: District of Columbia, Maryland, and the Rosslyn portion of Virginia. Metrorail is considered as a separate customer class in all three jurisdictions. For the balance of the rail system in Virginia, VEPCO supplies electricity under the Virginia State Rate Schedule, which is applicable to state agencies chartered in Virginia.

Port Authority Transit Corporation (PATCO)

The PATCO Lindenwold system operates from 16th Street, Center City, Philadelphia, to Lindenwold, New Jersey. The propulsion on the cars are cam switched resistors controlling DC series motors. No regeneration capability exists on these cars and no plans exist for future cars with regeneration.

Power is purchased from three electric utilities: the Philadelphia Electric Company (15 percent), the Public Service Electric and Gas Company (68 percent), and the Atlantic Electric Company (17 percent). There is also a tie to the Southeastern Pennsylvania Transit Authority (SEPTA) rail system in Philadelphia to be used in emergency situations. The power purchased from Philadelphia Electric Company is obtained through SEPTA.

Table 2. Summary of characteristics which influence energy consumption for the four sample transit systems used in study.

	WMATA	PATCO	GCRTA[a]	NYCTA
Segment Studied	Red Line	Total	Blue & Green Line	RR-Line
Segment Distance (mi)	9.9	14.2	9.2 9.7	17.7
Intermediate Stops	9	11	16 16	37
Operational Mode	Automatic	Automatic	Manual	Manual
Maximum Speed (MPH)	75	75	50	40
Peak Operation Headway (min)	5	3 - 8	8 8	2 - 5
Vehicle Weight Range (tons)	36 - 52.5	38.4 - 50.0	18.5 - 26.0	50.0 - 65.0
Propulsion Type	Resistor-DC Motors Chopper	Resistor-DC Motors Chopper	Resistor-DC Motors	Resistor-DC Motors
Peak Operation Cars/Train	6-8	6	1	8

[a] Light Rail System.

Greater Cleveland Regional Transit Authority (GCRTA)

The Blue and Green Lines of the GCRTA constitute a light rail system which is presently in transition from PCC cars to new, modern light rail vehicles. Only the PCC cars were considered in this effort. The segments of the system included in the study are from Union Terminal to Green on the Shaker Heights Line (Green), and from Union Terminal to Warrensville on the Van Aken Line (Blue). The Blue and Green lines share the same trackage from Union Terminal to Shaker Square. The propulsion system is switched resistors controlling DC series motors with no regeneration capability.

The Cleveland Electric Illuminating Company supplies all of the traction power and 89 percent of the support power for both the rapid rail (Red Line) and the light rail (Blue and Green Lines). They are governed by the Ohio Public Utilities Commission.

New York City Transit Authority (NYCTA)

The RR Line of the NYCTA was selected. It extends from Ditmars Boulevard Station, Queens, into Manhattan, south through Manhattan and into Brooklyn, ending at 95th Street Station. The R44 car was selected as the basic rail vehicle on the line. The NYCTA receives its electric power from the Power Authority of the State of New York (PASNY).

FACTORS INFLUENCING THE POWER DEMAND COMPONENT

The power demand component of energy cost is influenced by both the power rate structure of the utilities which provide the electric service, and the structural and operational characteristics of the transit system.

Power Rate Structure

The demand elements of the power rate structure of the four transit systems used for this study are quite different.

Under service from PEPCO, the WMATA has a 30-min demand interval and in each of the three jurisdictions of District of Columbia, Maryland, and Virginia, the maximum demand is determined coincidentally. The ratchet in the D.C. and Md. jurisdictions is the maximum of the past two monthly demands. In the Md. and Va. jurisdictions, the ratchet is the maximum of all previous monthly demands. Under service from VEPCO, there is no power demand component to the electric bill.

Under service from the Philadelphia Electric Company, the PATCO has a 30-min demand interval with noncoincident consolidation. In the months October through May, the ratchet is the maximum of 25 kW or 80 percent of the maximum monthly demand realized during the preceding June through September. Under service from the Public Service Electric and Gas Company, the demand interval is 15 min with noncoincident consolidation. The monthly demand is the average of the four greatest maximum demands on separate days or 75 percent of the maximum demand in the present month, whichever is greater. Under service from the Atlantic City Electric Company, the demand interval is 15 min with coincident consolidation. The monthly demand is the maximum demand for the present month, and the ratchet is 75 percent of the original contract capacity, 75 percent of the average monthly demand over the previous 12 months, or 1000 kW, whichever is greatest. However, for each kW of billing demand, PATCO is credited for 100 kWh of energy.

Under service from the Cleveland Electric Illuminating Company, the demand interval on the GCRTA for traction power is 60 min with noncoincident consolidation and, for support power, is 30 min with coincident consolidation. The monthly demand in both cases is the maximum demand in the present month.

Under service from PASNY, the NYCTA has a 30-min demand interval with coincident consolidation. The monthly demand is the maximum demand in the present month, while the ratchet is 75 percent of the largest monthly demand in the past 12 months.

Table 3 gives the demand interval, the headway during the peak operating hours, and the ratio of the demand interval to the minimum headway for ten rapid transit agencies in the United States. This ratio represents the number of times the meters will cycle. (Another way of expressing this is that the power cycle as seen through the meters is periodic with one headway interval being the period. The number of periods equals the ratio of the demand interval to headway. Of course, variation of passenger load factors, delays, and other operational changes can disturb these cycles.) With the exception of PATCO, this ratio is ten or greater. Thus, it is overall energy consumption rather than instantaneous peak power that will determine demand. As a result, any conservation strategy which reduces overall energy consumption during the peak operating period will also reduce peak demand.

A second important conclusion concerns the effect of the ratchet on the demand component savings that are realized by applying energy conservation strategies. For those properties with no ratchet, the energy savings that result from load management are realized immediately, while for those with a ratchet, the savings would not appear in the power bill until the ratchet decreases.

Structural and Operational Characteristics

It is convenient to express the power used during peak operating time by the formula:

$$P = P_0 + E_1(CM/H) \qquad (1)$$

where the quantity P_0 is the background power in kilowatts, the grouping CM/H represents the rate of accumulation of car-miles in car-miles/hour, and the coefficient E_1 symbolizes the energy per car-mile. This formula can be applied to a single electric utility meter, or a consolidation of meters, provided that the quantity, CM/H, is estimated properly. Since the power, P, is an average power over many cycles of the transit system, it can represent the power demand. The background power, P_0, is used for support functions and would be metered even if no trains were running.

The rate of accumulation of car-miles is determined by the size of trains, headways that are maintained, average speed, and turnaround times. Variation in this rate can occur as a result of train delays and catch-up operation which is sometimes used to bring the system back to normal operation after delays. To normal operation, the rate of accumulation of car-miles can either increase or decrease with train delays and catch-up operation depending on operational procedures.

The energy per car-mile depends primarily on car weight, type of propulsion system, maximum speed, interstation distances, and grades along the right of way. Secondary influences on energy per car-mile are dwell times, on-board auxiliary power, train cross sectional area train (train resistance), and number of cars per train.

Table 4 presents the energy per car mile as determined using the EMM and the rate of accumulation of car-miles for normal peak operation on the four transit lines considered in this study. Although the energy per car-mile is a result of computer simulation, it was verified to be within 3 percent of actual at WMATA and PATCO in previous studies (*3, 18*).

The energy use per car-mile varies from a low value of 4.04 on the Green and Blue lines of GCRTA, to a high of 8.90 for the RR Line of the NYCTA. The PCC car, running at the GCRTA is very light (18.5 tons) as compared to the remaining systems, and the top speed is relatively low and as a result has the lowest energy use. The R44 cars on the RR Line of the NYCTA have the highest energy consumption because the cars are heavy and the average interstation spacing is small.

The determination of the background power, P_0, requires that a detailed audit of energy use be conducted on a transit agency. An audit of this nature was conducted at WMATA. For Red Line traction energy, this background was found to be 1412 kW or 11 percent of the normal power during the peak operating periods. This background exists because of no-load losses of transformer-rectifier units; support services such as heating, lighting, and ventilation of substations; tunnel ventilation and lighting and switchpoint heating. WMATA is metered for traction power via traction substations and support power at the passenger station substations. For transit agencies whose traction and support power are metered together, the background power is expected to be much higher—at the level of 25 to 30 percent of demand during peak operation.

Figures 1 and 2 show statistical summaries of power metered by PEPCO for the AM peak operation for the WMATA Red Line during 1980 and the Atlantic City meter of PATCO for the year of 1981. This summary shows the average, standard deviation, and the maximum of traction power demand over half-hour demand intervals beginning each quarter hour on weekdays. On the WMATA Red Line the difference between the maximum to average power demand can be attributed to catch-up operation. In the case of PATCO, it was not possible to determine the cause because no detailed study was conducted. The power which may be saved by using a demand monitoring system is expected to be the difference between the maximum and one-standard deviation above the average power demand.

The maximum demand generally sets the demand charge. Because the empty car weight, type of propulsion system, interstation distances, grades along the right of way, and train cross-sectional area are fixed, the only energy per car-mile influences on variation in power demand are passenger loads, maximum speed dwell times, on-board auxiliary power, train delays, and use of catch-up operation. The effect of each of these can be determined by computing the quantity:

$$\frac{(\Delta E_1/E_1)}{(\Delta p/p)} \qquad (2)$$

where $\Delta E_1/E_1$ is the fractional change in energy used per car-mile and $\Delta p/p$ is the fractional increase in the parameter, p, which refers to one of four of the above mentioned influences on the variation of power demand. Table 5 gives these ratios for the four sample transit lines.

The large grades on the Red Line of WMATA account for the larger variation of energy with passenger load factor. However, even this value is rather small. For example, if over the half-hour demand interval of the Red Line of WMATA, the average passenger load factor increased by 10 percent, the coefficient E_1 would increase by 3.4 percent. Because of the contribution from the background and support power, the net effect on peak demand would even be lower (2.5 percent). In the case of the lines studied at PATCO, GCRTA, and NYCTA, the effect would be much smaller. Thus, it is expected that passenger load factor variation plays a relatively minor role in peak demand variation.

In fact, careful observation of Table 5 reveals that all parameter variation results in small changes in the energy per car-mile coefficient indicating small variation in peak demand. In the case of the influence of the maximum speed increase, there would generally be an increase in car-miles per hour as well, doubling the effect.

A second class of influences that cause variation of power demand is the variation of actual rate of accumulation of car-miles from day to day. This variation can be attributed to changing timetables, train delays, and use of catch-up operation. The variation in size of trains, headways, average speed, and

Table 3. Demand interval, minimum headway, and ratio of demand interval to minimum headway for ten rapid transit systems in the U.S.

AUTHORITY	DEMAND INTERVAL (Min)	MINIMUM HEADWAY (Min)	DEMAND INTERVAL / MINIMUM HEADWAY
San Francisco Bay Area Rapid Transit	30	2	15
Chicago Transit Authority	60	2.5	24
Greater Cleveland Regional Transit Authority	60	3	20
Metropolitan Atlanta Rapid Transit Authority	60	1.5	40
Massachusetts Bay Transportation Authority	30	2	15
New York City Transit Authority	30	2	15
Port Authority Transit Corporation (Lindenwold Line)	15	5	3
Port Authority Trans-Hudson Corporation	15	1.5	10
Southeastern Pennsylvania Transportation Authority	30	2	15
Washington Metropolitan Area Transit Authority	30	3	10

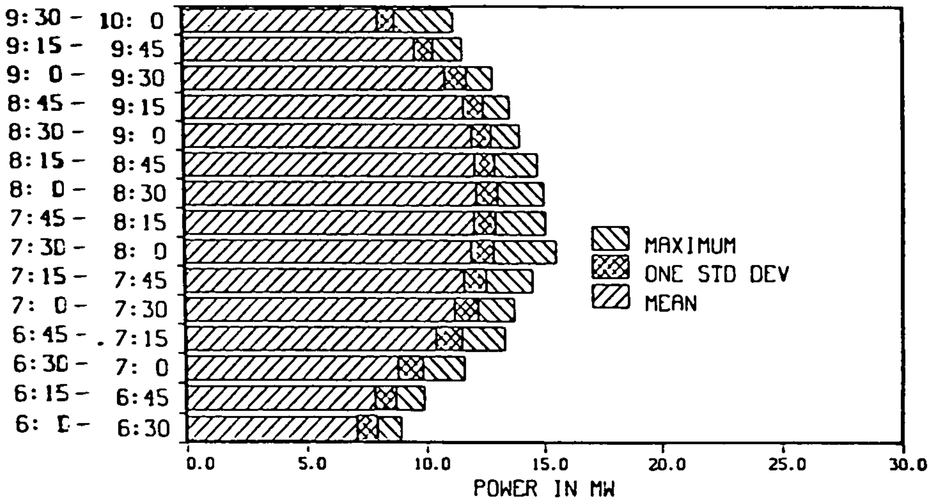

Figure 1. Summary statistics—WMATA Red Line, AM peak.

Table 4. Summary of energy use per car-mile and car-miles/h during the peak operating periods of the four sample transit systems.

	E_1(KWHPCM)	CM/H
WMATA (Red Line)	6.43	1644
PATCO	7.02	2415
GCRTA (Green & Blue Lines)	4.04	355
NYCTA (RR Line)	8.90	1339

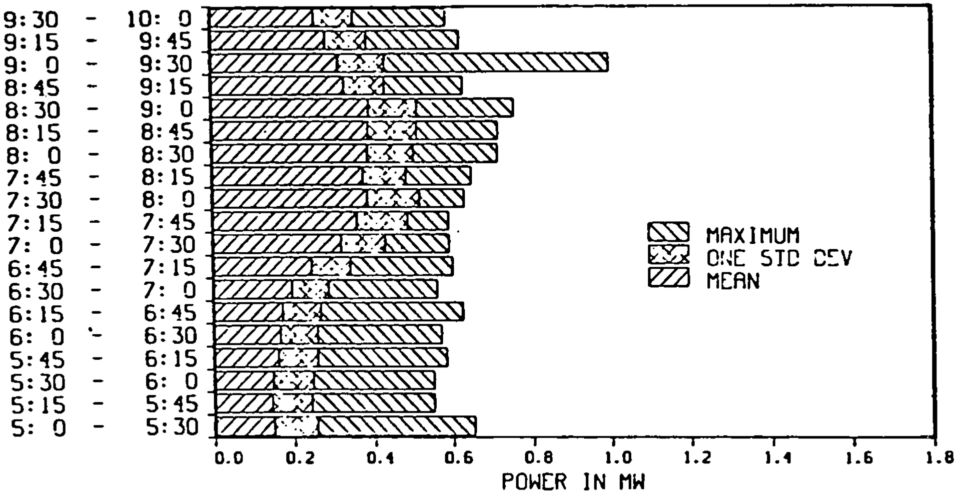

Figure 2. Summary statistics—Atlantic City meter.

Table 5. **Influences on energy use per car-mile of energy intensive parameters on four sample transit systems.**

DEMAND VARIATION INFLUENCE	PARAMETER (P)	$(\Delta E_1 E_1)$ / $(\Delta p/p)$			
		WMATA	PATCO	GCRTA	NYCTA
Passenger Load	Load Factor	0.34	0.04	0.05	0.05
Maximum Speed	Maximum Speed	0.27	0.47	0.20	0.07
Dwell Time	Average Dwell Time	0.02	0.02	0.01	0.04
On-board Auxiliary Power	Average Auxiliary Power	0.08	0.12	0.04	0.27

turnaround times causes changes in car-miles per hour, which in turn causes changes in power demand.

Ambient Temperature Effects

Because of heating and cooling equipment which is used aboard the vehicles and in the passenger stations, tunnels, maintenance shops, and office buildings, the average power as recorded by the meters will depend on ambient temperature. If power consumption is known as a function of time (by hour, day or month), the relation between consumption and average ambient temperature (hourly, daily, monthly—available from the Weather Bureau) can be determined using regression analysis.

Figure 3 shows the general form of average power dependence on average ambient temperature. The specific form of the curve depends on the nature of the heating and cooling equipment which are powered through the electric utility meter in question. For example, if no heating equipment were in the metered circuit, there would be no heating region. Likewise, T_{CO}, the temperature at which cooling equipment may begin to operate may be less than T_{HO}, the temperature at which heating equipment is fully off. This effect could occur when thermostatically controlled ventilation equipment begins operating at low values of ambient temperature.

Cooling equipment would include air conditioning and ventilation fans, while heating equipment could include equipment and space heaters. The use of regression analysis on power as a function of ambient temperature will pick up outside lighting (if turned off and on at nightfall and daybreak) as heating equipment.

Regression analyses were conducted on the average daily power recorded on three support meters of WMATA Metrorail. These meters recorded power at the office building and two Metrorail repair shops. In the case of the T-Street Repair Shop, a heating effect was observed because more power was used on colder days. In the Garden City Repair Shop the power used for heating at 20 F was 4.97 times larger than the minimum power. The office building shows a much higher power on hot days than on cold days. The detail of the theory and the results of these analyses are presented in Appendix E.

Three years (1979 through 1981) of electric bill information was obtained from the GCRTA. A regression analysis was conducted on average energy/month versus car-miles/month (Red, Green, and Blue Lines), and degree-days/month (ambient temperature). The results are given in Table 6. A very strong dependence on ambient temperature is observed. If the average monthly temperature changes by 1 F, the energy consumption will change by 58 MWh.

It is probably not practical to regress power against temperature on anything less than a daily average because of the delay between a temperature change in a confined structure and the outside ambient. If such information was available, it might be possible to conduct these regressions at time intervals of less than a day.

Coincident vs. Noncoincident Demand Consolidation

Noncoincident peak demands together with their times of occurrence are given in Table 7 for the meters supplying the Red Line of WMATA. The coincident peak demand is also shown in the table. The noncoincident peak demand is 30 percent larger than the coincident value.

The noncoincident peak demand is always larger than the coincident peak. The magnitude of the difference between the two depends on four major influences.

1. The variation in the passenger load factor with time on a local level as compared to the same variation over the whole line.
2. Abnormal operation (train delay and catch-up operation) which is more likely to occur on a local basis rather than on the whole line at any particular time.
3. Several of the meters, especially those associated with yards, shops, and storage tracks, can record peak power at nonpeak transit operating times. Since the power drawn from the substation is extremely sensitive to the feed voltage (higher voltage than nominal means larger power draw, reducing the power draw of adjacent substations), voltage variation can cause the maximum noncoincident demand to be higher than the coincident demand.
4. The voltage at which the utility supplies power, which can vary at each feed point.

The effect of voltage variation at the feed point is illustrated by using the EMM to simulate the WMATA Red Line operation. The results are given in Table 8. In the first case, a normal off-peak operation is simulated with all feed points at nominal voltage. In the second case, the voltage at the New York Avenue feed point has been increased by 1 percent relative to the other

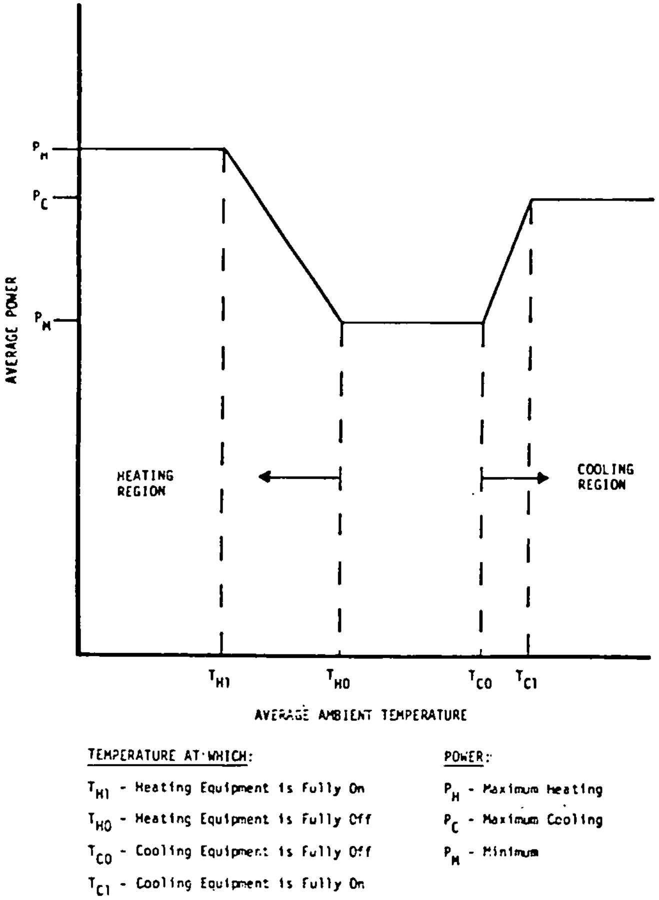

Figure 3. General form of average power dependence on average ambient temperature.

Table 6. Regression analysis results of energy vs. car-miles and ambient temperature for GCRTA on a monthly basis.

REGRESSION FORMULA:

$$E = E_0 + E_1(CM/M) + E_2(DD/M)$$

Values

E_0 (Background Energy)(MWH/Mo.)	517
E_1 (KWHPCM)	6.94
E_2 (MWHPDD)[a]	-58.2
Average Car-Miles per Month (CM/M)	363,300
Average Degree-Days per Month (DD/M)	0
Average Energy Use (MWH/Mo.)	3053

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[a] The number of degree days per day is (T-49) where T is the average daily temperature in (°F) and 49°F is the average temperature over the time period.

Table 7. Noncoincident and coincident peak power demand for traction meters on the WMATA Red Line.

		PEAK DEMAND
METER NAME	VALUE (kW)	TIME OF OCCURENCE
Farragut North	2399	17:00 - 17:30
Gallery Place	2441	17:00 - 17:30
Union Station	1741	17:30 - 18:00
New York Avenue	1831	16:45 - 17:15
Rhode Island Ave.	2200	17:45 - 18:15
Brookland Ave.	2961	17:45 - 18:15
New Hampshire Ave.	2506	17:15 - 17:45
Takoma Park	2252	17:30 - 18:00
Silver Spring	3542	9:15 - 9:45
TOTAL NON-COINCIDENT	21873	
COINCIDENT	16572	8:15 - 8:45

Table 8. Voltage variation influences on power.

	AVERAGE POWER (KW)		% CHANGE
METER NAME	NORMAL	INCREASED VOLTAGE*	
Farragut North	648	641	-1
Gallery Place	232	206	-11
Union Station	259	187	-28
New York Avenue	644	896	+39
Rhode Island Ave.	1236	1126	-9
Brookland Ave.	347	328	-5
New Hampshire Ave.	85	81	-5
Takoma Park	107	106	-1
Silver Spring	173	173	0
Coincident	3731	3743	+.3

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*The voltage at New York Avenue has been increased by 1%.

feed points. The resulting power draw from the New York Avenue substation has increased by nearly 40 percent, while the power draw from the adjacent substations has decreased.

Typically, the utility can guarantee the voltage to ± 5 percent and as a consequence, voltage variation at the feed points can create a situation where noncoincident peak demand can be much higher than coincident demand.

POWER DEMAND MONITORING

Three forms of power demand monitoring were considered in this investigation: real time, batch processing, and electric bill analysis.

Real Time Monitoring

Power demand monitoring in real time is required as part of a load management system. The basic objective is to monitor the demand trend over the early portions of the demand interval and predict the demand level for that interval. If it appears that the demand will exceed the desired maximum, a warning would be issued so that transit management could take precautions to reduce demand.

A generic demand monitoring system, which can monitor 16 meters, is shown in Figure 4. It can be expanded to handle up to 50 meters without difficulty. A number of these systems can be "ganged" together to further expand the monitoring capabilities.

The power consumption and supply voltage are monitored near the metering point. It may be possible, upon agreement with the electric utility, to use their potential and current transformers to monitor the demand. In the event that this would not be done, and depending on the magnitude of voltage and

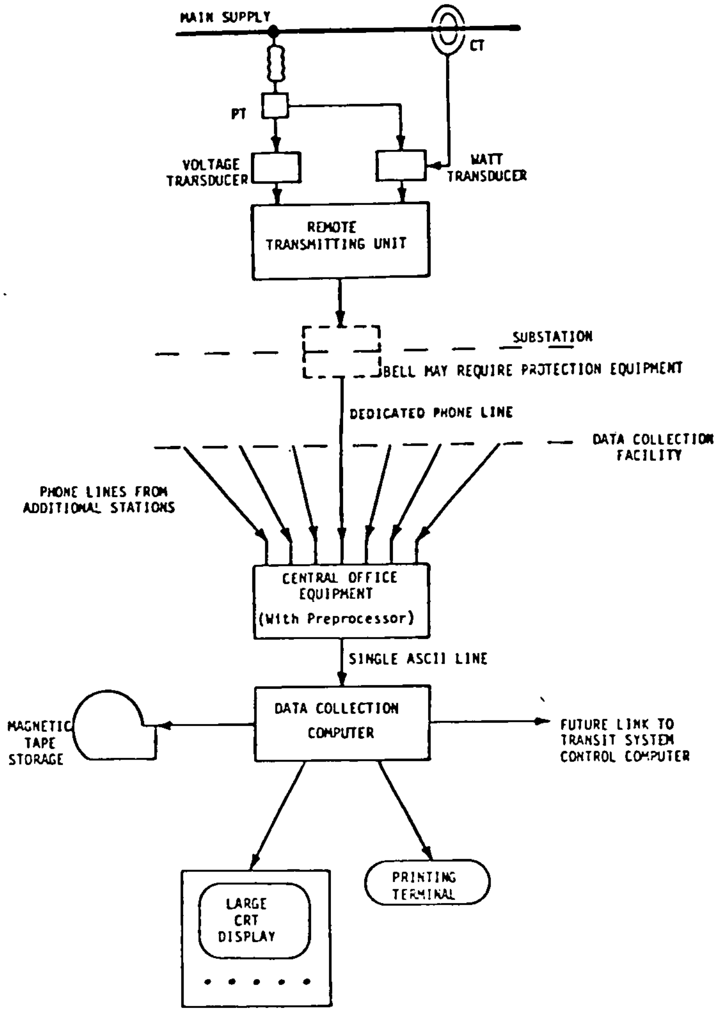

Figure 4. Real-time power-demand monitoring system.

current, one or two potential and current transformers will be required. The outputs of these are fed to the inputs of a multielement watt transducer producing an output proportional to the input. Likewise, the output of one of the potential transformers is fed through a voltage transducer to produce a signal proportional to the supply voltage.

The outputs of the transducers are connected to the inputs of Remote Transmitting Units (RTU) which convert them into a frequency domain, multiplexed FM signal suitable for transmission across voice grade telephone lines. Each of the RTU transmits its data along a single dedicated telephone line to the Central Office Equipment (COE) located at a data collection facility. The COE is capable of handling 50 RTU.

The COE separates and demodulates the two channels incoming from the RTU. Each signal is processed and filtered to give the time average of that parameter over the past 1-min time interval. The COE contains a microprocessor that is programmed to sample power and voltage once per minute and pass the digitized results to the main Data Collection Computer, on command, via a serial link.

In the main Data Collection Computer, the data from each meter is processed separately and examined over the demand interval. The appropriate meter consolidation is made by summing the individual meter powers into a total power curve. The slope and area under the power curve are evaluated over the early portion of the demand interval in order to predict the final demand for that interval. If a critical value of final demand is predicted, an alarm will sound, and those separate meters that are contributing the largest to that critical demand will be displayed on a monitor. In the case of an Automatic Train Control (ATC) transit system, there is a capability to pass the warning information to the train control computer which, in turn, can take automatic action to selectively modify train performance. Since some experience is required before proper control algorithms can be developed, initial installation on ATC properties will involve the operator shaving the load manually.

All of the data for a given demand interval is stored in a nonvolatile memory to prevent loss in the event of a power fluctuation at the data collection facility. At the end of each day, or other convenient time period, the data from the memory is archived on a tape cassette. The historical information developed by the monitoring systems can be used for electric bill monitoring and rate case development.

Batch Process Monitoring

Electric utilities serving some of the U.S. rail transit agencies record metering information on magnetic tape for electric bill processing purposes. In these cases, batch process monitoring, which consists of certain types of analyses of the information on these tapes, can be used to understand the nature of peak-power demand.

The first such analysis involves producing statistical summaries similar to that shown in Figure 1. This analysis will show how much larger the peak demand is than the average. Any correlation of the date-time of the peak with unusual events on the transit system, such as an increase in car-miles/hour train delays or catch-up operation should be noted.

The second type of analysis to be conducted is a regression analysis relating power to car-miles/hour in the form:

$$P = P_0 + E_1(CM/H)$$

where the quantity P_0 is the background power in kilowatts, the grouping CM/H represents the rate of accumulation of car-miles in car-miles/hour, and the coefficient E_1 stands for energy per car-mile. This will require gathering car-mile/hour data on a regular basis. Table 9 gives the background power and energy per car-mile coefficients for the meters on the Red Line of WMATA during the calendar year 1980.

The third type of analysis which can be completed using regression techniques is the determination of the background power dependence on ambient temperature. This can be done by finding P_0 as a function of temperature. Figure 5 shows an example of the results of this regression.

Batch process monitoring can also be used as a supplement to a real time monitoring system because the kind of detailed data that are needed is available.

Electric Bill Monitoring

For those transit agencies which cannot use batch process monitoring because they do not have the detailed information available, monitoring of electric bills is possible. Because the value, but not necessarily the time of peak demand, is presented on the electric bill, it is necessary to keep records of car-miles/

Table 9. Background power and energy per car-mile for the WMATA red line as obtained from regression analysis.

METER NAME	P_0 (KW)	E_1 (KWHPCM)
Farragut North	222	0.90
Gallery Place	134	0.88
Union Station	95	0.69
New York Ave.	217	0.75
Rhode Island Ave.	44	0.73
Brookland Ave.	261	1.00
New Hampshire Ave.	170	0.63
Takoma Park	71	0.82
Silver Spring	449	0.62
COINCIDENT RED LINE	1844	6.87

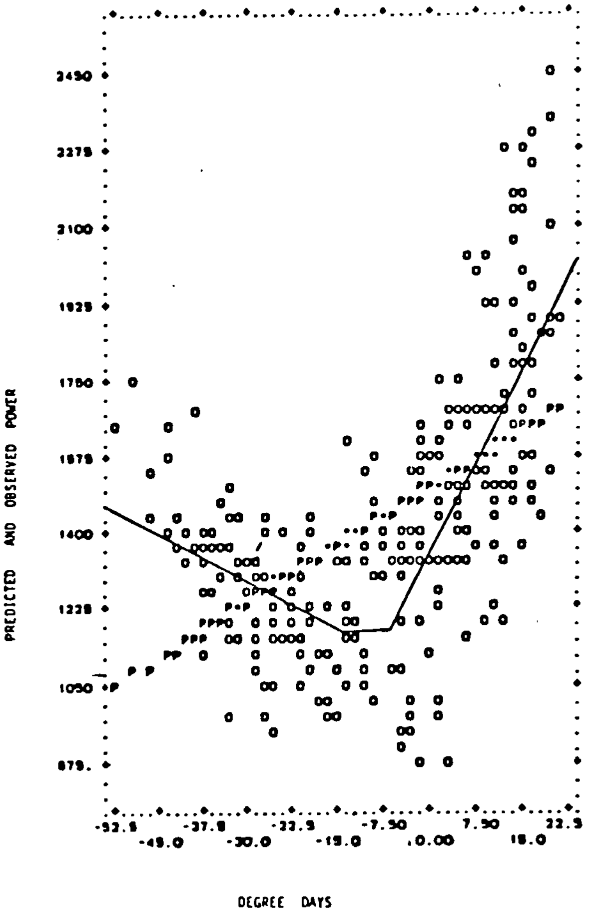

Figure 5. Average temperature dependence of the average power recorded at one support meter (office building) at WMATA.

hour and any abnormal operation to determine how this peak demand was achieved.

Regression analysis using ambient temperature can still be conducted, but only on the basis of average monthly temperature. Likewise, regression analysis to determine monthly energy consumption as it relates to car-miles/month can be carried out to determine the average monthly background power and the energy per car-mile.

POWER DEMAND REDUCTION OPPORTUNITIES

Strategies for energy conservation on rail transit systems can be applied on a real time basis (in conjunction with a real-time power-demand monitoring system), at preselected time intervals, when demand is known to be high or at all times as part of an overall energy conservation program. Structural strategies, such as regeneration, fall in the last category because once they are incorporated into the transit system, it is most cost-effective to use their energy savings capability at all times.

Two operational strategies, vehicle performance modification and passenger load factor management, can be applied on a real time basis, at preselected time intervals or at all times. Both of these strategies reduce the overall performance of the transit system.

Identification and Assessment of Strategies

Three general classes of traction energy conservation strategies were identified as appropriate to power demand reduction. These strategies are vehicle performance modification, passenger load factor management and regeneration of braking energy. Each of these classes of strategies has been assessed in terms of load management. In addition, support power reduction can also be used as a strategy in response to high demand prediction. These would be effective during cold and hot months where peak demand is excessive because of heating or cooling.

Performance Modification

Transit agencies use their equipment to minimize running time between stations, subject to the speed restrictions, grades, traffic interference, and other operational policies. In some cases, full performance is not used, but held in reserve for catch-up operation in case of train delays or other problems. In general, the minimum running time does not result in the minimum energy consumption.

Energy conservation by performance reduction can be illustrated using Figure 6. The accessible region is the area in the running time vs. energy consumption plane which can be realized by a given train with a fixed passenger load factor between two stations. Depending on how the traction equipment is operated, any point in this plane is accessible as the train moves between the stations.

The curve bordering the accessible region is called the noninferior curve. It represents the extremum of energy consumption for a fixed running time that is greater than the minimum running time. Within the accessible region is an operating region in which the train typically operates. Because of operational and equipment variances, most of the running times and energies will vary with the closed curve shown in the figure.

An energy conservation strategy is one which involves vehicle performance modification in the closed curve in the figure to move to the right and downward in the accessible region. This represents an increase in running time and a decrease in energy consumption. The quantity

% Energy Decrease/% Running Time Increase

can be defined. It is a measure of how well the employment of a particular vehicle performance modification strategy is expected to both reduce energy consumption and system performance in terms of schedule time increase. Several performance modification strategies can be used. Among the useful ones are coasting, top speed reduction, and optimum performance modification.

Coasting. Coasting is a proven method to reduce energy consumption with minimal increase in running time. There are several methods to apply the coasting strategy. In the first method, which is referred to as "anticipatory" coasting, the train accelerates to the speed limit, remains at the speed limit, and begins coasting in anticipation of a lower speed restriction or a station stop. In the second method, which is referred to as "sawtooth" coasting, the train accelerates within a speed band whose top speed is the speed limit.

The benefit of coasting can best be realized in ATC systems

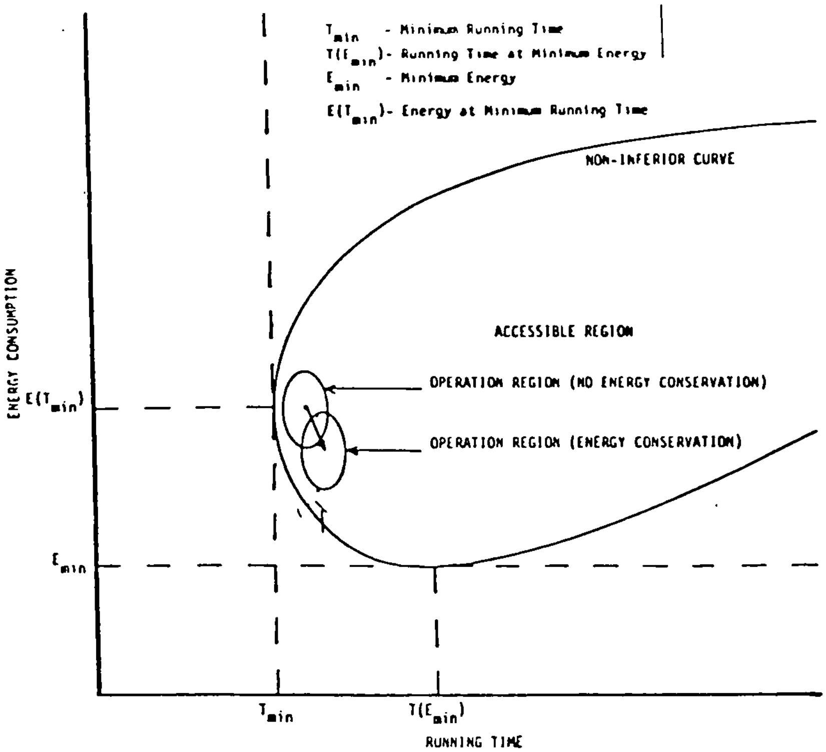

Figure 6. Energy-running time plane and accessible region.

(WMATA and PATCO) where the train operations were designed without considering energy savings. On manual systems, the timetable must be set for the slowest operators. Thus, it is expected that the average operator will already incorporate a large amount of coasting in his driving technique. As a result, enforced coasting as a policy may not yield much energy savings on a manually operated system.

The curves in Figure 7 show the percent change in energy per percent change in schedule time for anticipatory coasting for the four sample transit lines. Increased schedule times from 0 to 3 percent are probably not unreasonable in terms of performance modification.

The results show that the energy savings available by coasting on NYCTA, RR Line, and GCRTA are significantly higher than of WMATA and PATCO.

Top Speed Reduction. Although reduction of maximum speed is not as efficient as coasting in decreasing energy consumption with increasing schedule time, it is a strategy that can easily be implemented through operating rule or signal changes on a manual system or speed command changes on an ATC system.

The curves in Figure 8 show the percent decrease in energy as a function of the percent increase in schedule time as top speed is reduced on the four sample transit lines.

Top speed reduction for NYCTA is an appropriate strategy on the RR Line. This is explained by the fact that the top speed of 50 mph is seldom achieved on the RR Line. Refer to Figures D-7 and D-8 in Appendix D.

Optimum Performance Modification. An optimum performance modification strategy is one in which energy consumption is a minimum for a fixed increase in schedule time above the minimum schedule time. This strategy is accomplished by varying the tractive effort in a way that produces minimum energy consumption as the train moves along its route. The energy and schedule time would lie on the lower portion of the curve bounding the accessible region shown in Figure 6. This strategy can be found by using the technique of multiobjective optimization, which is briefly described below and in more detail in Appendix G.

Low energy consumption and minimum schedule time are conflicting objectives. Rail transit cars are used to their maximum performance capability so that minimum running time is achieved (T_{MIN} in Fig. 6). Use of full performance results in energy consumption (ET_{MIN} in Fig. 6), which is larger than the minimum energy (E_{MIN} in Fig. 6). The boundary of the accessible region is called the noninferior curve because it represents the best (worst) possible tradeoffs between the conflicting objectives.

The problem of finding the optimum performance modification strategy is to find those strategies that lie near the lower portion of the noninferior curve, so that given a small increase in schedule time, a maximum energy savings is possible. Two methods were used to find the optimized strategies: Monte Carlo, by which tractive effort was varied randomly and the best alternatives were selected, and steepest descent described in Appendix G.

This problem has been worked out and was applied to the WMATA Red Line. The results of top speed reduction, anticipatory coasting, sawtooth coasting, and optimum performance modification strategies are shown in Figure 9.

The results show that at a 2 percent increase in schedule time, the optimum performance strategy results in 75 percent more energy savings than the coasting strategies.

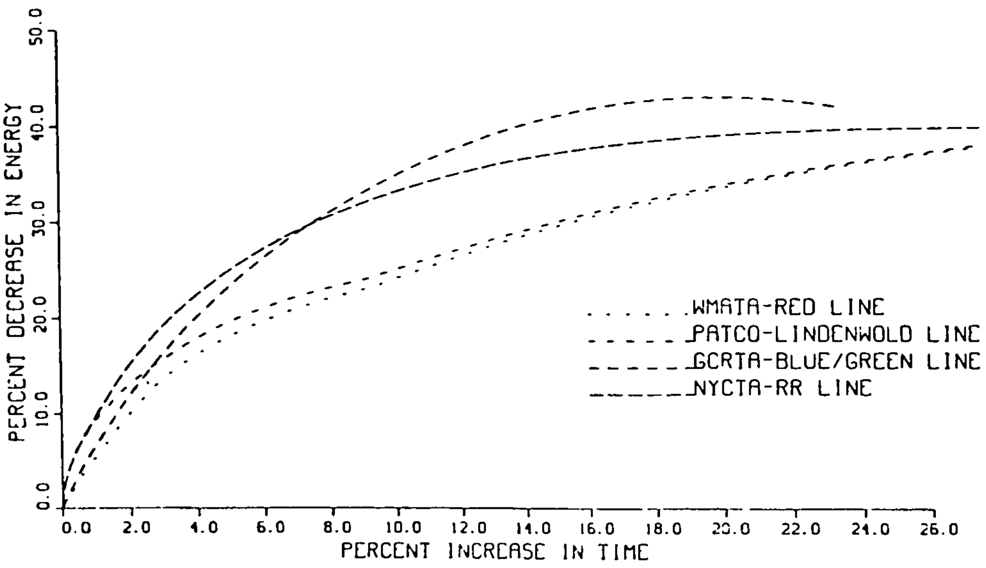

Figure 7. Energy savings—anticipatory coasting.

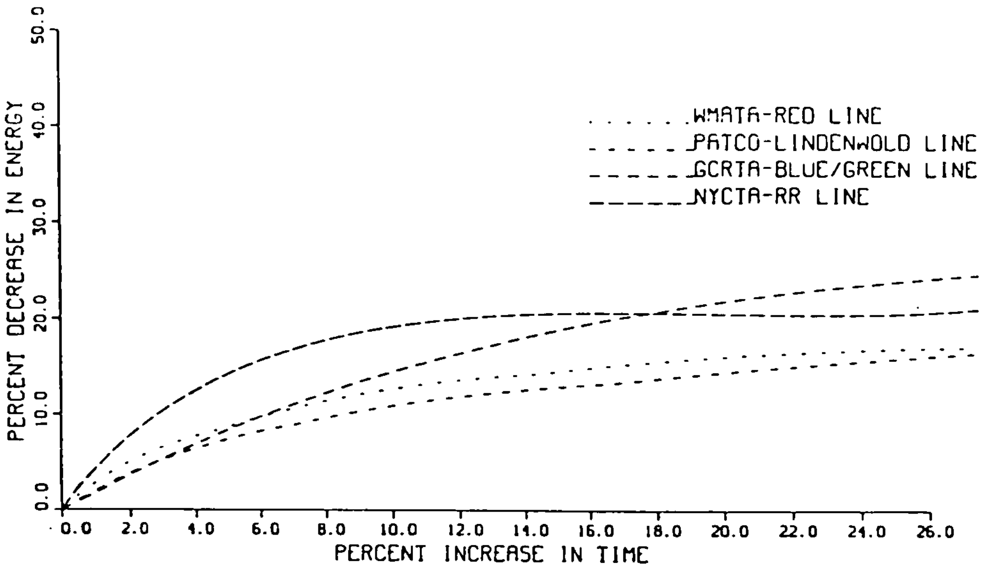

Figure 8. Energy savings—top speed reduction.

Passenger Load Factor Improvement

Passenger load factors can be improved by running shorter and/or less trains in off-peak hours and turning trains at intermediate stations during peak and off-peak hours. Both strategies reduce the rate of accumulation of car-miles, and as a result, the energy consumption. The energy use per car-mile is expected to increase because of heavier cars, train resistance effects, and, in the case of turning trains at intermediate stations, because of a change in the length of the profile. This increase is expected to be small compared to the decrease of the rate of accumulation of car-miles.

During the peak hours of train operation, it only makes sense to turn trains at intermediate stations. This strategy must be carefully considered before implementation because of difficulties which may be encountered with scheduling and traffic interference. To be most effective, a match between car-miles/hour and passenger-miles/hour between stations would be required in a practical operational way.

Regeneration of Braking Energy

Regeneration of braking energy has a large potential for energy savings on modern rail transit systems. In order to accomplish this savings, however, it is necessary that the cars be equipped with solid state propulsion control, either choppers controlling DC motors or inverters controlling three-phase AC induction motors.

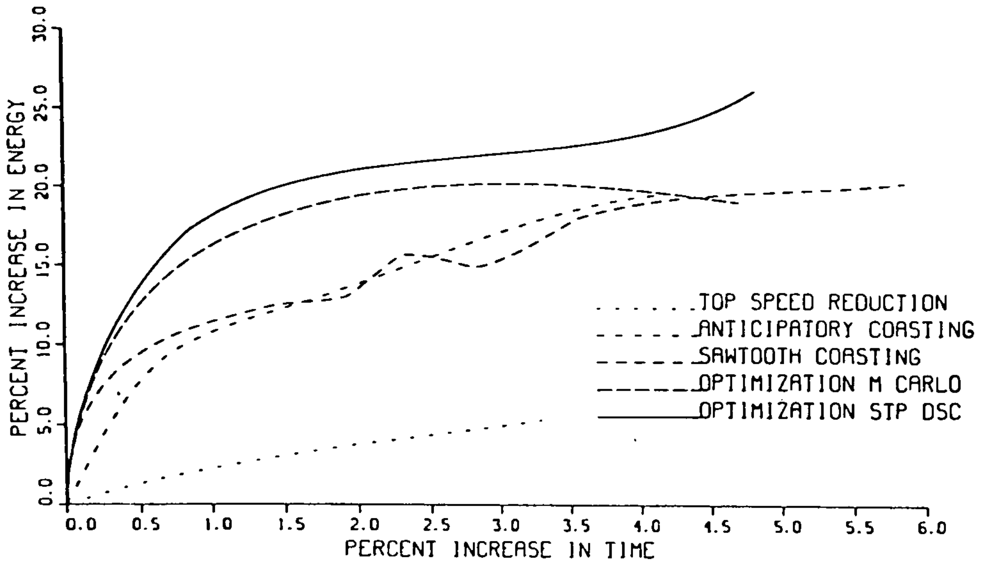

Figure 9. Performance modification results—WMATA Red Line outbound.

Only regeneration with natural receptivity, in which all of the cars that made up the train were chopper cars and the only receptors of regenerated brake energy were other trains on the line, was considered in this effort.

Using the EMM, regeneration with natural receptivity was simulated for peak periods on the WMATA Red Line, PATCO, and GCRTA. The results show a reduction in energy used per car-mile of 2.01 kWh per car-mile for WMATA, 2.19 kWh per car-mile for PATCO, and 1.07 kWh per car-mile for GCRTA.

Since regeneration is a structural strategy, it will reduce energy at all times. Thus, both power demand during the peak period and energy use will be diminished.

Strategy Implementation Cost Factors

Part of the cost to implement a load management system at a rail transit agency is the implementation costs of the energy conservation strategies. The remainder of the cost is incurred in power demand monitoring. Strategy implementation costs cannot be determined unless a detailed energy cost reduction study is completed at the transit agency. One such study has been completed at WMATA (*18*), and the results are used here for illustration purposes in the discussion of cost factors of the various strategies.

Performance Modification Strategies

The cost of performance modification strategy implementation is very site specific and dependent on the type of operation (manual or ATC).

Top speed reduction could be incorporated into the operating rules on manual rail transit systems and as a consequence the cost would be minimal. On ATC systems, the speed commands given to the trains through wayside transmitters must be changed. Of the ATC systems studied, WMATA has the capability of changing the speed commands, whereas PATCO does not. However, PATCO does have the capability of running in manual operation, so that top speed reduction could be implemented in this mode.

The more efficient performance modification strategy of coasting requires expenditures in both manual and ATC modes. In the manual mode, the principal cost would lie in operator training and wayside coasting signposts. In ATC systems, coasting could be achieved by modification of the speed regulator aboard the car, so that braking does not occur until a lower speed margin is reached. At WMATA, it was estimated that the cost to modify the fleet of cars was $100 per head end unit. This modification would result in sawtooth rather than anticipatory coasting.

Optimum performance modification would require an additional control on the cars that had the capability of programming the tractive effort as a function of position along the right-of-way. It is estimated that a microprocessor-based device of this sort may cost in the range of $1,000 to $2,000 per head end unit. In manual systems, it may be possible to approach optimum performance reduction with signposts and operator training.

Passenger Load Factor Improvement Strategies

Turning trains at intermediate stations is the only passenger load factor improvement strategy that would reduce power demand during the peak operating period. Without specific examples, the incurred operational cost is not possible to estimate. However, among the considerations in such a cost estimate are the additional operators that may be required and any additional station personnel at the intermediate stations. This strategy cannot be used with real time demand monitoring because of the logistics and the resulting response time. In other words, it would not be practical to implement this strategy in response to reduced demand in one demand interval.

Regeneration Strategies

It is probably not cost-effective to change the propulsion system of an existing rail transit car from cam-control to chopper control in order to just effect energy savings. Thus, the only way regeneration can be implemented is through a new car purchase or a major overhaul, under which the propulsion equipment is purchased. For transit cars that are the size of the cars used at WMATA, NYCTA(R44), and PATCO, the cost difference between chopper and cam-control is expected to range between $25,000 to $30,000 per car. In the case of light rail vehicles, the range would be $20,000 to $25,000 per car.

LOAD MANAGEMENT COST AND EFFECTIVENESS

As used in this context, load management will involve power demand monitoring and the ability to respond to a projected high peak demand by changing operating procedures. The power demand monitoring may be on a real time basis, batch processing of metering information, and/or analysis of electric bills, while changing operating procedures could mean exercising performance modification, passenger load factor improvement, and/or support power reduction strategies. In each case, there is a cost and an effectiveness involved. Effectiveness is generally measured as the savings in the demand component of the electric bill. The costs will involve both initial investment (capital) and recurring costs (operating).

Cost Information

Budgetary estimates were made for the three classes of monitoring methods. Table 10 presents the power demand monitoring cost components for real time, batch process and electric bill monitoring.

For real time monitoring, a 16 metering point system was designed for the purpose of determining costs. Details of the initial investment are presented in Appendix I. A large investment item for the real time monitoring system is the potential and current transformers for isolation of the power and volt meters to obtain the necessary data. If the electric utility's transformers can be used for this purpose, the initial investment is substantially reduced. The monitoring technician would represent one person working full time over the peak transit operating periods, independent of the number of meters being monitored.

In batch process monitoring, the initial investment would be the purchase and/or development of computer programs necessary to translate and analyze the magnetic tapes submitted by the electric utility. Recurring costs include the computer time and manpower necessary to interpret the analyses. This would also include the deciphering of the events that led to the creation of this peak demand so that steps could be taken to avoid them in the future.

The cost for implementing sawtooth coasting on trains with ATC was estimated at $100 to $200 per head end unit, whereas a microprocessor-based device capable of developing an optimum performance trajectory would range from $1,000 to $2,000 per head end unit.

In using a performance reduction strategy, an intangible cost is the reduction of system transportation capacity, just at the time it is needed the most, namely, during the peak transit operating time. If done in response to a real time monitoring warning, the effect can be minimal. With batch processing monitoring, it may be necessary to use performance reduction strategies over longer periods of time because of uncertainties in operational procedures.

Reduction of support power could mean reducing air conditioning or heating aboard vehicles or in passenger stations. Actual costs for automatic systems to accomplish this are very site specific and were not estimated here.

Effectiveness

One objective of a real time monitoring system would be that maximum peak demand be limited to no more than the average demand plus one standard deviation (refer to Fig. 1). Such a goal is probably attainable at most rail transit systems; however, detailed site specific investigations are required to verify this hypothesis.

Examples of Cost/Effectiveness of Real Time Monitoring

Because a detailed energy study was completed for WMATA Metrorail, it was possible to use this system as the basis for a cost/effectiveness evaluation of a real time power demand monitoring and control system. Because the demand interval at WMATA is 30 min, peak demand reduction was estimated for reactions at 10, 15, and 20 min into the demand interval (i.e., the performance modification strategy was initiated after 10, 15, and 20 min into the demand interval). It was also assumed that catch-up operation was responsible for creation of the abnormal peak demand. Two strategies were considered: first, initiation of coasting for the remainder of the demand interval, and second, reverting back to normal operation. The energy cost savings are given in Table 11. In the case of catch-up operation with coasting, the increase in schedule time was 2.5 percent on the Red Line and less than 0.5 percent on the Blue and Orange Lines.

The previous estimates on energy savings were based on a simple application of performance modification, namely, reducing the performance of the whole system. Because of the nature (microprocessor-based) of the demand monitoring, it would be possible to apply performance modification on a local basis where it might be most effective in reducing energy use per minimal increase in schedule time.

Table 12 summarizes the cost of the demand monitoring and control system using the unit costs of Table 10. Use of the catch-up operation with coasting strategy requires a fleet modification to the speed regulator in the on-board ATO equipment. This modification was estimated at $40,000.

A summary of the cost effectiveness of real-time power-demand monitoring and control at WMATA is given in Table 13. Normally, if the investment required is not too large, a pay-back period of less than 3 years is acceptable in the rail transit industry. Observation of Table 13 reveals that the pay-back period is very sensitive to the time in the demand interval when the correction strategy is initiated. The lower this time, the

Table 10. Power demand monitoring cost components.

Real Time Monitoring

Initial Investment	$24,560/metering point ($11,690/metering point less high voltage equipment.)
Recurring Cost	
Telephone Lines	$32/month/metering point
Monitoring Technician	$50,000/man-year
(Independent of number of meters monitored)	

The initial investment is based on a sixteen metering point system:

Hardware Cost (Less High Voltage Equipment)	$107,000
High Voltage Equipment	$206,000
Engineering Labor (1 man year)	$ 80,000
Total	$393,000

Batch Process Monitoring

Initial Investment	
Computer Programs	$20,000
Recurring Cost	
Computer Time	$500/month
Engineering Time (1/4 MY/Y)	$1670/month

Electric Bill Monitoring

No Initial Investment	
Recurring Cost	
Engineering Time (1/10 MY/Y)	$670/month

Table 11. Energy cost savings of real-time power-demand monitoring and control for WMATA.

STRATEGY	($K/MONTH) STRATEGY INITIATED AFTER 10 MIN	 15 MIN	 20 MIN•[†]
Catch-up Operation with Coasting	74.4	55.9	37.3
Revert Back to Normal Operation	62.3	47.6	31.2

DEMAND REDUCTION (MW)

JURISDICTION	CATCH-UP WITH COASTING			REVERT BACK TO NORMAL OPERATION		
	10 MIN	15 MIN	20 MIN	10MIN	15 MIN	20 MIN•
DC	4.9	3.7	2.5	4.5	3.4	2.3
MD	1.1	0.8	0.5	0.5	0.4	0.2
VA	0.8	0.6	0.4	0.6	0.5	0.3

[†] •Time into demand interval during which strategy is initiated.

Table 12. Summary of costs for real-time demand monitoring and control for WMATA Metrorail.

INITIAL INVESTMENT (72 metering points) ($M)	
With High Voltage Equipment	1.77
Without High Voltage Equipment	0.84
Coasting Modification to Fleet	0.04
RECURRING COST ($K/month)	
Telephone Lines	2.3
Monitoring Technician	4.2

Table 13. Summary of cost/effectiveness analysis for real-time power-demand monitoring and control at WMATA Metrorail.

	CONTROL STRATEGY	
	REVERT TO NORMAL OPERATION	CATCH UP WITH COASTING
Initial Investment ($M)	1.77 (0.84)	1.81 (0.84)
Monthly Cost ($K)	6.5	6.5
Monthly Savings ($K)		
10 min*[a]	62.3	74.4
15 min*	47.6	55.9
20 min*	31.2	37.3
Payback Period(years)		
10 min*	2.6 (1.3)	2.2 (1.1)
15 min*	3.6 (1.7)	2.7 (1.3)
20 min*	6.0 (2.8)	4.9 (2.4)

( ) Without high voltage equipment.

Payback Period = Initial investment divided by Net Savings/year.

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[a] *Time into demand interval at which strategy is initiated.

higher the penalty to be suffered in reduced performance during the peak transit operating period.

WMATA already has a system where the power consumption information is brought to a central location. Therefore, the cost of a power demand monitoring and control system is expected to be much less if the present system can be used.

LOAD MANAGEMENT AND POWER RATE STRUCTURE NEGOTIATION

Another aspect of rail transit energy management is the design of the power rate structure. This aspect has become important as a result of the rapid escalation of power costs and the higher frequency of rate increases being sought by the electric utilities. Proper design of the power rate structure can also reduce energy cost. Rail transit energy management is most effective in reducing energy cost when the "double-barrel" approach of the energy-use-pattern changes, established by employing conservation policies, are used as the basis for a more favorable power rate structure during a rate change.

Principles of Power Rate Structure Negotiation

Two fundamental guidelines are followed to reduce energy cost through improvements in the power rate structure. The first is knowledgeable representation at rate case hearings and/or negotiations. The second is the inclusion of changed energy use patterns fostered by the energy conservation policies of the transit authority into rate design through the appropriate cost of service analysis.

The objective of representation at rate case hearings is to secure a power rate structure which, given the energy use pattern of the transit system, will result in lowest energy cost consistent with the cost of serving the system. Because of the adverse nature of rate proceedings, regulatory agencies tend to believe that a customer or customer class not represented at the hearings is satisfied with the result. A transit agency, as a member of a customer class, can influence both the size of the general increase granted to the utility and the share of that increase which is borne by it as a customer class. Its degree of influence, given equal representation by all customers of the class, would in some sense be proportional to its contribution to total utility revenues as it relates to that of the customer class members. If it is the only customer in the class, it carries all of the influence of that class.

As an electric utility customer, the transit agency sees two major areas of issues in rate proceedings. The requirements for revenue and rate of return on investment by the utility refer to the area of general increase in the rates and are open only to general debate to the agency as one of the utility's customers. The second area of issues, which is more under the influence of the agency, concerns the division of the general increase among the customer classes. Representation by the transit agency at the rate case hearing is likely to be most effective here.

The basic principle of rate design, generally accepted by the industry, is that rates charged to customers should be based on cost of serving. In line with this principle, cost of service allocation is broken down by the three major functions: power production, transmission and distribution among the three major categories of customer, and demand and energy charges. This is shown schematically in Figure 10. In many cases, other func-

FOR EACH CUSTOMER CLASS: INDUSTRIAL, RESIDENTIAL, PUBLIC USE, ETC.

Cost Is Allocated By:

Major Plant Function:	Major Category:		
	Customer	Demand	Energy
PRODUCTION	$	$	$
TRANSMISSION	$	$	$
DISTRIBUTION	$	$	$

Production: Generation and Power Purchase
Transmission: Bulk Power Transmission Facilities
Distribution: Local Delivery of Power

Customer: Vary with Number of Customers and Class of Service
Demand: Capacity Allocation
Energy: KWH Produced

Figure 10. Cost allocation.

tions are sometimes included, the most popular being sales expense and accounting.

There are several methods of cost of service allocation that are used among the electric utility industry. These are summarized together with the data requirements for cost of service studies in a document entitled, *Electric Utility Cost Allocation Manual,* by the National Association of Regulatory Utility Commissioners.

The opportunities for reducing energy cost to the transit property through representation at rate case hearings will principally involve the cost of service allocation. Specific arguments are:

1. More favorable peak demand interval with smaller time interval for resetting.
2. Exclusion of taxes as a cost attributable to the transit agency because of its tax exempt status.
3. Use of the relation of transit system peak demand to utility peak demand as a point of favorable argument for rate relief.
4. Obtaining a separate customer class for the transit system.

To take maximum advantage of these opportunities, it is necessary to have general management support, detailed knowledge of the specifics of the regulatory process for the transit agency and credible, expert witnesses to support the presentation of the transit agency.

Negotiation With Load Management

Once a knowledgeable representation at rate case hearings is established by the transit agency, techniques can be developed to incorporate arguments for rate relief because of the change of energy use patterns that result from load management.

Reduction of peak demand will shift the burden of rate increase toward the other customer classes serviced by the utility. The degree to which this shift occurs depends on many factors, in addition to the degree of peak demand reduction attainable.

1. The fraction of peak demand attributable to the transit system as a member of his customer class.
2. The fraction of peak demand attributable to the customer class of which the transit system is a member.
3. The relation of the time of peak demand of the agency to utility peak demand.
4. Facilities set aside for exclusive use of transit.
5. The ratio of peak demand to energy plus customer components in cost categories.

All of these factors must be incorporated into a new cost of service study that would be carried out by the transit agency in order to strengthen its position.

The degree to which rate relief can actually be realized is not certain. Since any rate relief realized by the transit agency increases the rate burden of customers in other classes, there is an inducement for them to initiate conservation of policies to shed this burden and equalize the situation.

One strong argument for initiating energy conservation and load management is that other customer classes of the utility will conserve energy, shifting the cost burden to the transit system. Under these circumstances, energy conservation would become a purely defensive measure.

Load management is particularly useful, without any repercussions from the utility in the form of a rate increase, wherever service (car-miles/hour) is increased. If demand can be held at the preexpanded service level, the utility has no basis for initiating a rate increase.

The cost effectiveness of load management is dependent on the ratio of the demand/energy use component of the electric bill. As the electric bill becomes more demand determined, load management is more desirable.

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

INTERPRETATION

In the context of this research, load management is defined as the monitoring, prediction and control of the demand component of electrical energy cost. It can be a powerful tool as part of an overall energy management program which begins with an understanding of the energy use pattern and power rate structure of the transit agency.

The use of four real transit agencies in the development of this work has shown that both the energy use pattern and power rate structure of transit systems can differ widely, so that estimates of the cost and effectiveness of load management must be conducted on a site-specific basis. In developing such estimates, simulation is a beneficial and low-cost method to investigate the energy use pattern on a system under actual operating conditions. Thus, demand control strategies such as passenger load factor improvement and vehicle performance modification can be simulated before testing to ascertain their effectiveness. Once the best strategies are selected, they can be verified by test, resulting in a lower cost investigation than outright testing of all strategies.

Power demand monitoring is an important aspect of load management. It can be accomplished in real time, by batch processing of metering information that has been previously generated, and/or by analysis of electric bills. The most expensive monitoring is real time; however, it develops complete information and provides a capability to respond quickly to reduce power demand cost. Gathering of real time power demand information also allows a complete understanding of the energy use pattern under dynamic conditions, as it changes from day to day operation and as a function of ambient conditions.

A second monitoring scheme that is less expensive than real time and allows response to be made over longer periods of time (on a monthly level) is batch processing of metering information. This avenue is only open to transit agencies whose serving electric utilities collect metering information on time scales of the same order as the demand interval, and are willing to make it available to their customers. Under these circumstances, abnormal events that lead to the creation of peak demand can be recorded and correlated with the metering information. As a consequence, steps can be taken by transit management to minimize the energy effects of abnormal operation in the future.

Finally, the least expensive and least effective power demand information scheme is analysis of electric bills. If the day and time of peak demand are recorded on the bill, some attempt can be made to correlate it to abnormal operation. However, because the statistics of demand are not available, it is difficult to determine what steps are necessary to minimize the effects of similar events in the future.

Once power demand has been monitored, several energy conservation strategies can be called upon to reduce predictions of abnormally high demand. With real time monitoring systems that require quick response, the performance modification strategies are appropriate. Three classes that were analyzed and summarized on the four sample agencies were top speed reduction, coasting and optimum performance modification. The effectiveness of any of these strategies is very site specific, so that a transit agency desiring strategy options must investigate them in detail as was done for the four sample agencies in this study.

Performance modification strategies, together with passenger load factor improvement in peak transit operating periods, are appropriate with the longer term demand monitoring schemes of batch processing and electric bill analysis. It would be necessary to incorporate them into operating policy which would be subject to considerations other than energy.

Both the performance modification and passenger load factor improvement energy conservation methods require expenditures that offset the savings. The tangible expenditures are easy to estimate, such as initial equipment changes in the case of performance modification and increased manpower requirements for passenger load factor improvement (turning trains at intermediate stations). There are also intangible expenses. The strategies in both of these classes reduce transit system performance. In the case of performance modification, schedule time is increased resulting in lower system transportation capacity. However, limiting this increase to 2 to 3 percent is generally within the noise level of transit operation, will not generate a requirement for an additional train, and can generally be made up by reducing turnaround times at terminals and dwell times in low passenger volume areas. In the case of passenger load factor improvement by turning trains at intermediate stations, service frequency will be reduced for some customers. This must be considered carefully.

Regeneration of braking energy is not a strategy that would be used to reduce the demand component of energy cost alone, but rather, as a structural change to reduce overall energy cost (demand and energy based components). It is based on modern, solid state propulsion control, with proven high reliability (*19*), and other considerations, such as reduction of maintenance cost, would play a vital role in decisions to incorporate regeneration.

An overall energy management program at any transit agency should also incorporate power rate structure negotiation as a component. Reduction of peak demand through load management reduces the burden of electric utility cost allocation to the transit agency but increases it to other customer classes of the utility. If the transit agency is a large customer, the rate may be expected to increase in the long run, unless steps are taken through knowledgeable negotiation.

APPRAISAL

This research was directed at reducing energy cost at rail transit authorities. Energy cost is one component of operating cost, typically (8 to 16 percent). Although energy cost is small, there are two factors that make it a target in any cost reduction program conducted by transit management.

- Energy cost is expected to increase in the future as it has done in the recent past. As a result, it will become a larger component of operating cost.
- Energy can be controlled on a technical and operating basis. Reduction of maintenance cost, a second component of operating cost, generally involves reduction of manpower, and consequently an adversary relationship between transit labor and management. However, energy cost reduction may slightly increase manpower, providing a beneficiary relationship between transit labor and management.

In the example of cost-effectiveness of load management illustrated in the findings, a pay-back period of 2 to 3 years was estimated on an expenditure of less than $1 million. This kind of pay-back on investment makes good economic sense. However, because of technical risk, and an expenditure of nearly $1 million, initiating such a program must be considered carefully. This is the reason that a step-by-step approach must be used, and at each step the program should be evaluated on a cost and effectiveness basis.

One uncertainty will always be the future direction of energy cost trends. If the trend is toward making the demand component larger than the energy component of total cost, load management becomes more lucrative. If the trend is in the other direction, the reverse is true. It is difficult to assess this trend in the long run. On the one hand, failure to increase electrical generating capacity, as evidenced by reduction in new plant orders, would tend to put demand at a premium, while on the other hand, increasing fuel costs tend to put energy at a premium.

If load management with real time monitoring of demand is not cost effective, an overall energy management program should be considered which incorporates strategies both during peak, off-peak and nonrevenue service times. These will reduce both peak demand and energy use and there will be no requirement for demand monitoring.

APPLICATION

Application of load management to a rapid or light rail transit system involves six steps in progressive order. Appendix H details the steps that are summarized in the following description. The first four steps constitute an energy management study.

Step 1—Energy Audit

Through the use of audit type procedures, the actual energy use pattern of the transit agency should be determined in detail. This audit may take the form of detailed analysis of metering information over successive demand intervals over a long period of time (a year or more) or a detailed estimate of energy end use expected to flow through each meter. The audit must include both traction and support energy.

At the same time, the power rate structure should be outlined in detail, so that the major components of energy cost as determined from the marriage of the energy use pattern to the power rate structure can be understood. Future trends in the power rate structure should be estimated. An active program in power rate structure negotiation should be established if not already present.

The energy audit will require a certain amount of data from the transit agency and the electric utility, and the ease of gathering and the form of these data will determine the cost of this step.

Step 2—Simulation of Normal Operation

Energy flows from daily operation of the transit system should be simulated in order to understand energy end use. Estimates of metering information as gathered by the electric utilities should be made. These estimates should include both traction and support power.

To conduct such a simulation, much information on the structural and operational parameters that determine energy consumption is required. The EMM, developed at the RSC and available to the transit industry, is the ideal tool for such estimates.

The cost of this step is principally determined by the magnitude and availability of data and the simulation costs.

Step 3—Verification of Normal Operation

In order to provide a framework for the estimates of cost effectiveness of the application of energy conservation strategies, it is essential that the estimates of metering information be verified by comparing simulated data, as obtained in Step 2, with actual data, as obtained in Step 1. This verification will lend credence to the steps that follow.

Step 4—Energy Reduction Cost/Effectiveness Study

Once the verification of simulated energy consumption is complete, energy conservation strategies can be tested for effectiveness using simulation. The EMM is particularly useful at this stage.

Strategies that should be simulated are:

- Vehicle Performance Modification
  - Top speed reduction
  - Coasting
  - Optimized performance modification
- Passenger Load Factor Improvement
  - Turning trains at intermediate stations during peak periods
  - Shorter trains during off-peak periods
- Reduction of Auxiliary Power Aboard Cars During Storage

- Reduction of Support Power During Operating and Nonoperating Periods
- Regeneration of Braking Energy
  - Natural receptivity
  - Assured receptivity

Because this study was directed more toward load management (power demand component), energy conserving strategies that concentrated on the energy use component, such as running shorter trains and reduction of auxiliary and support power during off-peak periods, were not considered. It may be desirable for some transit agencies to consider regeneration with assured receptivity, either using on-board or off-board storage devices or regenerative substations.

Energy savings from all of these strategy applications can be tabulated as well as the cost (both initial and recurring). Those strategies whose application have short pay-back periods (typically less than 2 or 3 years) should be considered further on the basis of initial cost, pay-back period, and risk.

The cost of a load management system should be determined which consists of both the power demand monitoring and strategy application (vehicle performance modification, passenger load factor improvement, and/or reduction of support power during peak operating periods) portions. Estimates of effectiveness should be made at the same time. If a load management system appears desirable, it should be considered along with all other energy conservation strategies that can reduce both power demand and energy use components of cost.

Step 5—Prototype Operation and Verification Testing

After completion of the energy cost reduction study, contained in Steps 1 through 4, a decision must be made on selection of the energy conservation program. At this point all of the estimates should be available to transit management.

This step involves a prototype testing and verification of the strategies selected. A low-cost experiment should be conducted during which both the energy savings and performance changes can be measured and compared with the simulation predictions.

Step 6—Full Implementation and Monitoring

The verification of the program in Step 5 should reduce the risk of implementation on a systemwide basis. Monitoring of the energy consumption and any performance changes should continue to assure that the savings are real.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

Although load management must be investigated and applied on each specific rail transit system, there are a few principles that are general enough to apply to any system. The conclusions drawn from the results of this research are noted as follows. Specific areas for research have also been identified.

CONCLUSIONS

Load management using real time power demand monitoring can be cost effective. For those transit authorities who do want to reduce energy cost, but do not want performance changed by much, it may be a good alternative.

Load management mainly affects the power demand component of energy cost and this is determined by the power rate structure, structural and operating characteristics, ambient temperature, and the method of demand consolidation. Rapid and light rail transit agencies should advance toward coincident demand for three basic reasons:

- Generally, the DC distribution system is interconnected and is then a subtransmission system even though it is fed and metered at many points.
- The power draw through the meters is extremely sensitive to the electric utility voltage at the meter, higher voltage relative to adjacent meters meaning higher power draws. As a consequence peak demand may be determined by utility voltage in a noncoincident demand consolidation situation.
- Some meters may peak at times other than the peak transit operating periods, which means that noncoincident demand is higher than coincident.

Vehicle performance modification strategies are appropriate for use with real time demand monitoring because they can be initiated quickly. Although the least costly to implement, top speed reduction produces the least energy savings of the three classes of performance modification studied. Coasting seems the most cost effective; however, at additional expense optimum performance modification may prove to be highly cost effective.

The cost effectiveness of a load management system is sensitive to the demand/energy use ratio of the electric bill. As this ratio increases, the cost effectiveness of load management becomes better. Since these ratios are highly utility dependent, future trends should be assessed.

Any load management system must be part of an overall energy management effort, which includes a strong capability for negotiating rate structures with serving electric utilities. Because load management reduces peak demand, the burden of the utilities' cost allocation is shifted to other customer classes. Careful negotiation will be required to avoid higher demand rates in future years.

SUGGESTED RESEARCH

The results of this research effort were presented on an individual basis to the general manager's staff of 11 electric rail transit authorities. Chicago Transit Authority, Mass Transit Administration of Maryland (Baltimore), Massachusetts Bay Transportation Authority (Boston), Metropolitan Atlanta Rapid Transit Authority, Metropolitan Dade County Transportation Administration (Miami), New Jersey Transit, New York City Transit Authority, Port Authority Trans-Hudson Corporation, Port Authority Transit Corporation (Lindenwold Line, Philadelphia), Southeastern Pennsylvania Transportation Authority (Philadelphia), and Washington Metropolitan Area Transit Authority.

As a result of these presentations and subsequent discussions, it became clear that any real time demand monitoring and control system would be useful to a transit system which had a high premium on schedule performance and a large demand component of the electric bill. Such a demand monitoring and control system would be most efficient on a transit system with automatic train control.

Two candidate transit authorities were identified as potential rail systems for incorporating a prototype real time demand monitoring and control: The Washington Metropolitan Area Transit Authority (WMATA) and the Metropolitan Dade County Transportation Administration (MDCTA). Both systems have automatic train control, energy management studies, and an interest in developing such a system. WMATA already has the capability to monitor its meters from a central location.

The next logical sequence of events in the development of load management is to apply a small, prototype version of a real time demand monitoring and control system at one of these authorities. The demand monitoring system should be microprocessor based so that as new algorithms are developed with such a system, portions may be reprogrammed.

A real-time power-demand monitoring system requires that voltage as well as power be recorded, since the power draw of any substation is voltage dependent. Present simulation techniques can take this into account if some assumptions can be made on voltage drop as a function of load from the generator. However, the other customer loads are also important in the determination of the voltage. Algorithms should be developed to be included in simulation to take this into account after an investigation of this voltage variation is undertaken.

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APPENDIX A

APPLICATION OF EMM TO WMATA

A.1 GENERAL

When completed, the Washington Metrorail will consist of 100.84 miles of double track, rapid rail transit, with a total of 86 stations. The system operates in Maryland, Virginia, and the District of Columbia. Figure A-1 shows a map of the system and its present status.

For the purpose of this work, the Red Line Metro in operation which was in effect during most of 1980 was selected as the system to be studied.

A.2 SYSTEM OPERATING CHARACTERISTICS

Metrorail is operated by an automatic train control (ATC) system which consists of three subsystems and a computerized central control system. The three subsystems are:

1. Automatic Train Operation (ATO), which regulates speeds between stations, starts trains, and provides automatic station stopping.
2. Automatic Train Protection (ATP), which provides proper train separation and ensures that train doors open automatically only at stations, and on the side on which there is a platform.
3. Automatic Train Supervision (ATS), which selects routes through switches, dispatches trains, and provides means to make the trains responsive to supervisory commands from central control.

The car-borne ATC system has three operational modes: automatic, manual with ATP, and manual without ATP. Dwell time at passenger stations is under the control of the train attendant even under automatic operation.

The maximum speed on the system is 75 mph. Out of the various levels of operational performance which are possible, only two are considered in this study. They are normal operation, which is referred to by Metro operations as performance level two (PL2), and catch-up operation, which is referred to as performance level one (PL1). The latter performance level represents a decrease in running time of 10 percent over normal operation. All performance levels are controlled by setting maximum interstation speeds and by setting the power level in the propulsion equipment.

The 1980 timetable that was in effect from February through October 1980 is shown in Table A-1. The weekday was divided into five operating periods, Saturday was divided into two operating periods, and Sunday was divided into three operating periods, as shown in Table A-1. The operation during midday and evenings on weekdays, and midday on Saturdays and Sundays, is essentially the same, namely, the operating of six-car trains over 10-min headways on the Red Line.

The Red Line peak operation consisted of running both six- and eight-car trains on a headway of 5 min. Passenger load factors between stations were developed by using passenger origin-destination data from the spring 1980 Metrorail Survey (Phase IV) and the 1980 operating timetable. The origin-destination data consisted of station-to-station passenger counts on a weekday during four periods: AM peak, midday, PM peak and evening. Link-volumes between the stations were computed in the same four periods. The number of passenger spaces provided during these same four periods was estimated using the timetable information. The passenger load factor is the ratio of the number of passengers in the link-volume to the number of passenger spaces provided according to the timetable. The number of passenger spaces provided always refers to a crush loaded vehicle, and load factor is expressed on that basis. Graphs of the passenger load factors during the four weekday peak operating periods on the Red Line are shown in Figures A-2 through A-5. Dwell-time information was obtained empirically by having riders on the train time the interval between the stop and the start at each station. The statistics on dwell time showed no significant difference between the peak and non-peak periods, and inbound and outbound running of the train. The average values of the dwell times obtained during this time period are given in Table A-2 for the Red Line.

A.3 VEHICLE CHARACTERISTICS

A.3.1 Physical Characteristics

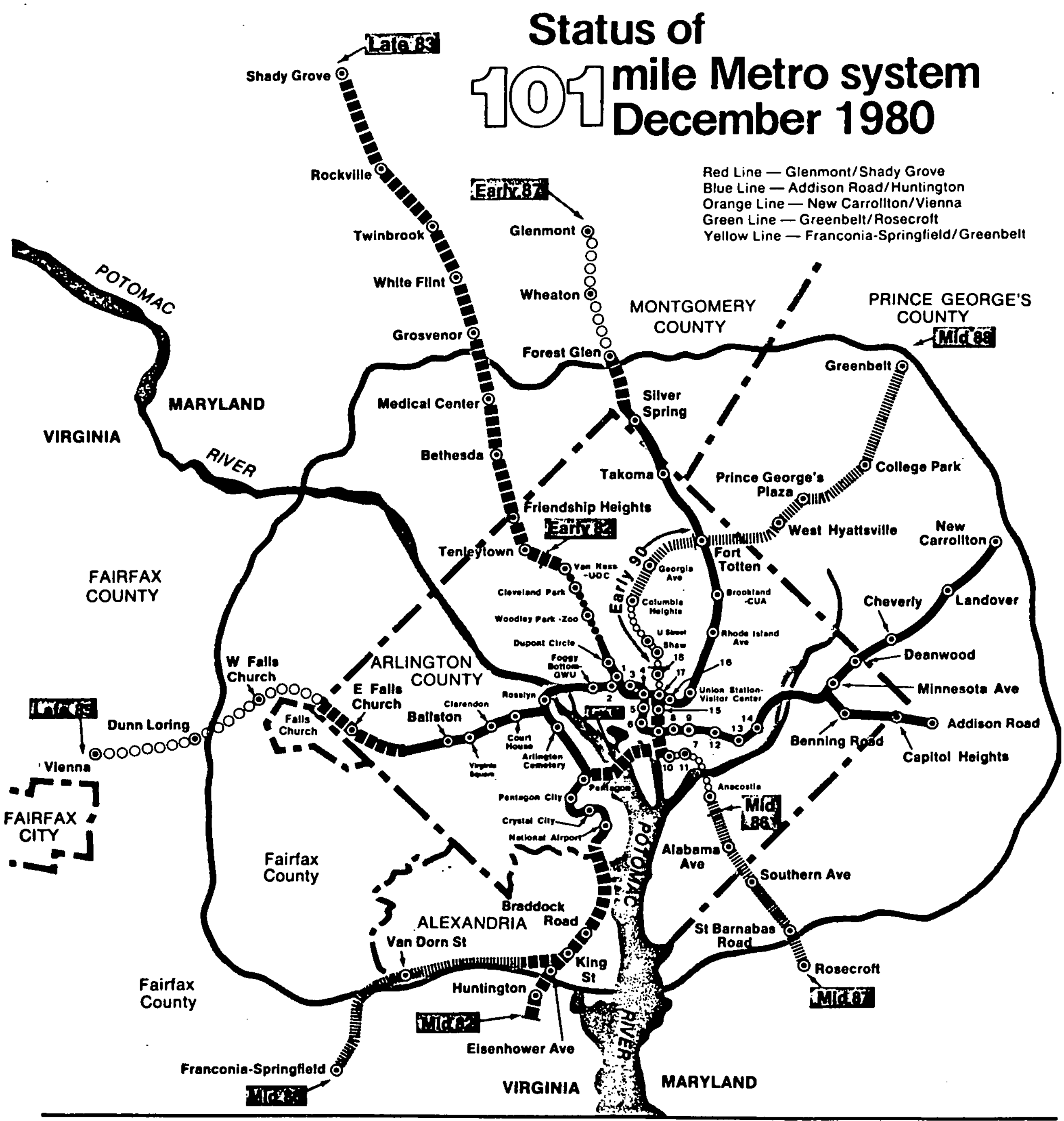
The vehicles which comprise the Metrorail fleet were assumed to have identical physical characteristics from the standpoint of train performance. Table A-3 provides a listing of these physical characteristics.

A Davis-type train resistance formula was used in order to characterize the train resistance of the consists for the purpose of the Train Performance Simulator (TPS). The coefficients of the Davis formula were selected to approximate the results of actual train resistance measurements that were made on the cars.

The average auxiliary power used on each car during revenue operation was given as 30 kW. This includes motor generator set control, train propulsion control, lighting, air conditioning, and heating.

A.3.2 Propulsion Characteristics

The Metrorail vehicle is a self-propelled rail transit car with four powered axles. The main propulsion characteristics are given in Table A-4. The power conditioning and control subsystem is presently cam-controlled resistor switching. One new car order includes 18 chopper-controlled cars which have the



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Contact Paul Willis—637-1047

LEGEND

━━━◉━━	Operating Lines	37.15 miles	41 stations
●●●●●◉●●●	Next opening Early '82	2.06 miles	3 stations
■■■■◉■■	Under Construction or Substantially Complete	27.16 miles	19 stations
○○○○◉○○	Under Final Design	14.43 miles	10 stations
▥▥▥◉▥▥	Remainder of System	20.04 miles	13 stations

Late 81 Projected start of operations for this segment based on approved schedule. Applies to all stations inbound from this point.
Note: Dates assume funding availability for completion of system by 1990.

Total mileage—100.84

Total stations—86

1. Farragut North
2. Farragut West
3. McPherson Square
4. Metro Center
5. Federal Triangle
6. Smithsonian
7. L'Enfant Plaza
8. Federal Center SW
9. Capitol South
10. Waterfront
11. Navy Yard
12. Eastern Market
13. Potomac Ave
14. Stadium-Armory
15. Archives
16. Judiciary Square
17. Gallery Place
18. Mt Vernon Sq-UDC

metro Washington Metropolitan Area Transit Authority
600 Fifth Street, N.W., Washington, D.C. 20001

Figure A-1. Status of 101 mile Metro system.

Table A-1. Summary of 1980 timetable for Metrorail operations (effective February–October 1980).

OPERATING PD	TIME SPAN	HEADWAY	CARS/TRAIN
Weekdays			
Midnight	12:00A - 6:00A	-	No Revenue Operation
AM Peak	6:00A - 9:30A	5	6 & 8
Midday	9:30A - 3:00P	10	6
PM Peak	3:00P - 6:30P	5	6 & 8
Evening	6:30P -12:00A	10	6
Saturday			
Midnight	12:00A - 8:00A	-	No Revenue Operation
Midday	8:00A -12:00M	10	6
Sunday			
Midnight	12:00A -10:00A	-	No Revenue Operation
Midday	10:00A - 6:00P	10	6
Evening	6:00P -12:00A	-	No Revenue Operation

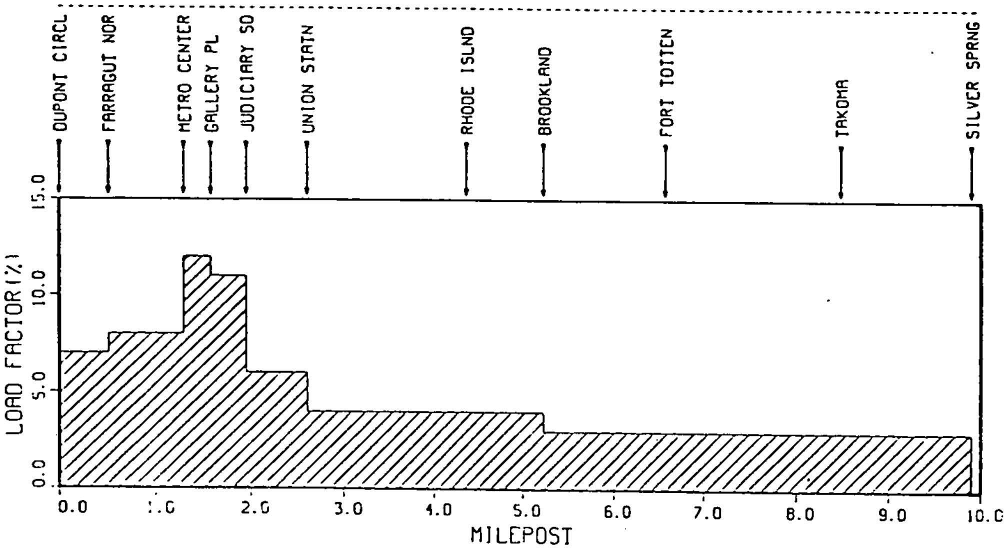

Figure A-2. Passenger load factor—Red Line (AM peak) Dupont Circle to Silver Spring.

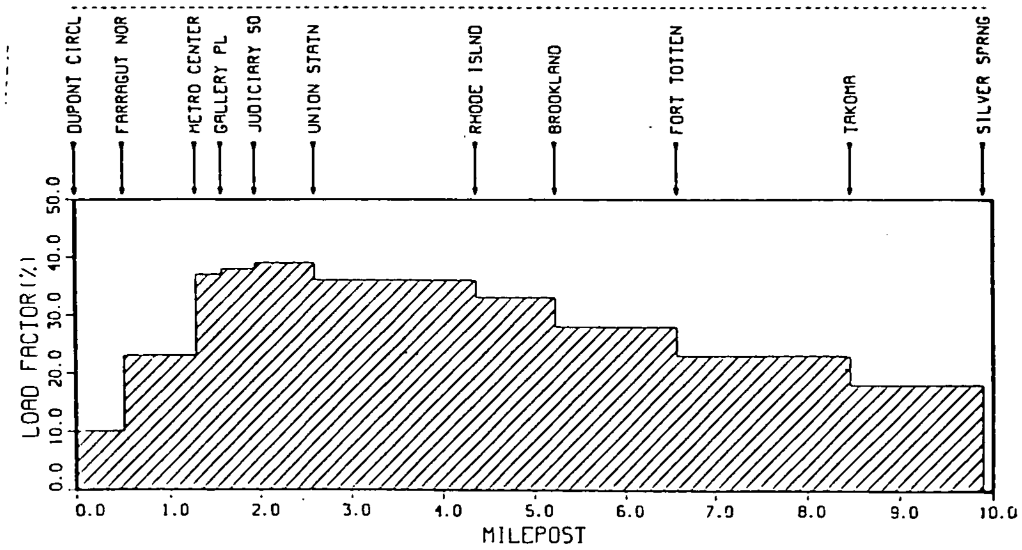

Figure A-3. Passenger load factor—Red Line (AM peak) Silver Spring to Dupont Circle.

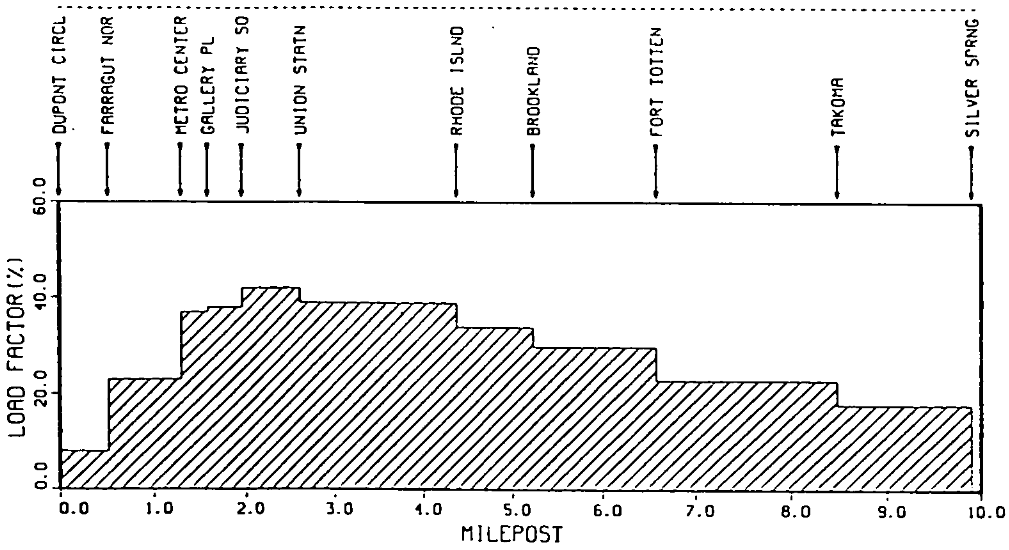

Figure A-4. Passenger load factor—Red Line (PM peak) Dupont Circle to Silver Spring.

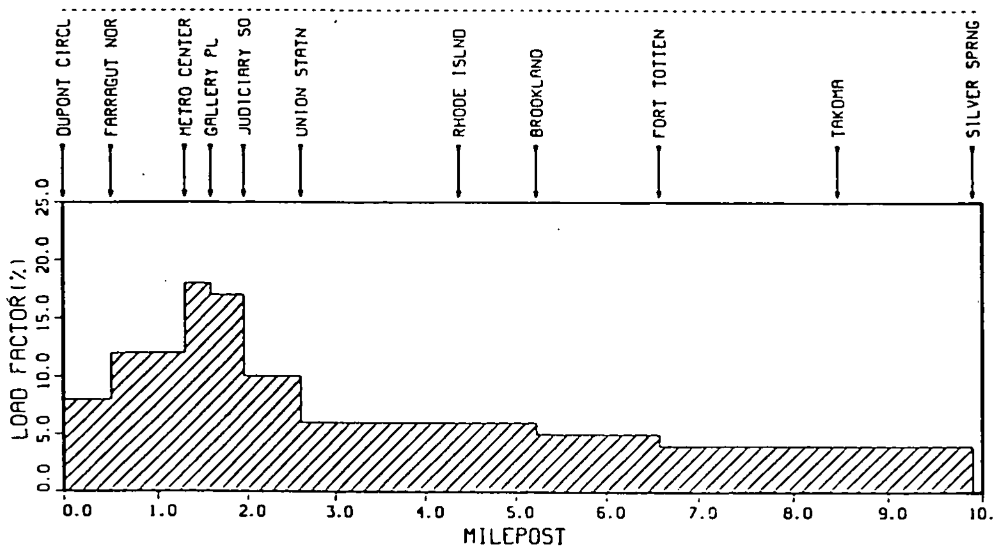

Figure A-5. Passenger load factor—Red Line (PM peak) Silver Spring to Dupont Circle.

capability to regenerate power back to the third rail. An option to that order provides for 200 chopper-controlled cars.

Five power levels, designated P5, P4, P3, P2, and P1, are available for Metrorail operation. These levels are achieved by limiting the control progression as shown in Table A-5. In automatic operation at performance levels PL2 (normal operation) and PL1 (catch-up operation), only the power level P5 is used. Thus, all of the propulsion characteristics used in this work were developed at power level P5.

A.3.2.1 Cam Control Resistor Switching

To control the motor circuit voltage in present cars, resistors are inserted between the line and motor circuit. Figure A-6 shows the tractive effort-speed curves at each of the motor circuit modes, designated 1 to 8 in Table A-5. These were calculated by requiring the line voltage to vary linearly with power drawn. The envelope of these curves represents the maximum tractive effort-speed capability of the car at power level P5. Because the car has load weighing capability, the tractive effort, at any time, will be adjusted by controlling the motor current so that acceleration never exceeds 3.0 mph per sec on level track.

The motor control philosophy, with cam-controlled switched resistors, is:

1. The motors are initially connected, four in series, with maximum resistance in the circuit at zero speed during acceleration.
2. As the speed increases, resistance is stepped out of the circuit until the speed reaches the point where no resistance is in series with the motor circuit.

Table A-2. Summary of empirical dwell time information.

STATION	AVERAGE DWELL TIME (in seconds)
Farragut North	30
Metro Center	35
Gallery Place	24
Judiciary Square	24
Union Station	31
Rhode Island Avenue	26
Brookland	27
Fort Totten	27
Takoma	31

Table A-3. Vehicle physical characteristics.

Empty Weight (tons)	36.0
Crush Load Weight (tons)	52.5*
Vehicle Length (ft.)	75.0
Cross Sectional Area (sq. ft.)	85.0
Measured Flange Coefficient (lbs/ton/mph)	0.071
Number of Axles (all powered)	4
Average Auxiliary Power (kW)	30
Wheel Diameter (inches)	28
Gear Ratio	5.414
Lead Vehicle Air Drag Coefficient (lbs/ton/mph^2)	0.0024
Trail Vehicle Air Drag Coefficient (lbs/ton/mph^2)	0.00034

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*Based on 220 150lb passengers in a crush loaded car.

Table A-4. Vehicle propulsion characteristics.

Motors per Vehicle	4
Motor Characteristics	(W) Type 1462
Control	Cam Resistor Switching (Present Operation) Chopper (Regeneration)
Maximum Accelerating Rate	3.0MPHPS
Wheel Diameter	28 inches
Gear Ratio	5.414
Maximum Speed	75mph
Nominal Line Voltage	750V
Maximum Line Voltage	860V
Minimum Line Voltage	600V

Table A-5. Metrorail propulsion power level definition.

MODE #	MOTOR CIRCUIT NUMBER OF MOTORS SERIES/PARALLEL		MOTOR FIELD STRENGTH (%)
1	4	1	100
2	4	1	70
3	4	1	60
4	4	1	40
5	2	2	100
6	2	2	70
7	2	2	60
8	2	2	40

Progression: Mode # 1 → 2 → 3 → 4 → 5 → 6 → 7 → 8

POWER LEVEL	ACCELERATING RATE (MPHPS)	PROGRESSION TO MODE	REMARKS
P5	3.0	8	Highest
P4	3.0	5	
P3	1.5	5	
P2	1.5	4	
P1	0.75	1	Lowest

3. The motor circuit is switched from four series to two series/two parallel, with the cam reset to place resistance back into the circuit in order to reduce the applied voltage to the motors to the value it had at the end of step 2.

4. As the speed further increases, the resistance is once again stepped out of the circuit until full line voltage appears across the motor circuit.

5. At this point, the motor field is gradually weakened until 40 percent of full field is reached. The tractive effort follows the mode 8 curve which is shown in Figure A-6.

6. Running at constant speed on the profile is accomplished by working the cam control and field shunt switches in such a manner that the tractive effort matches the train resistance under speed and grade conditions. Field shunts are used in preference to resistor control in the region beyond the mode 1 tractive effort curve in Figure A-6.

Figure A-7 presents graphs of the propulsion system efficiency as a function of both tractive effort and speed. The efficiency is the ratio of rail power to line power. Rail power is measured at the output of the wheels, and line power is measured at the third rail shoe.

A.3.2.2 Chopper Control

Metro has ordered a number of cars from BREDA with chopper control propulsion systems. Since one of the strategies

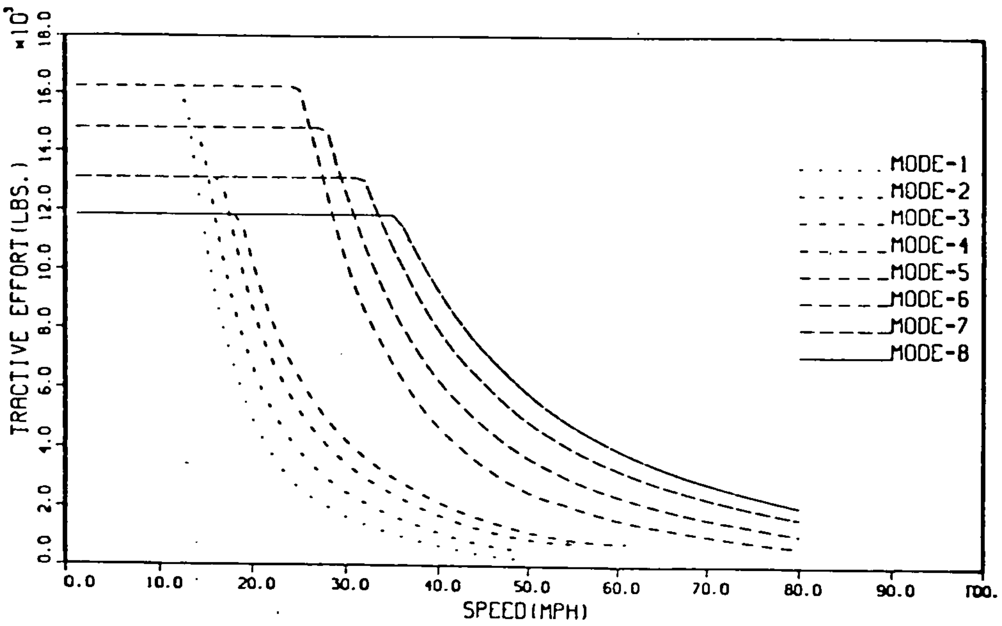


Figure A-6. Tractive effort-speed curve—WMATA car, cam control, P5 mode.

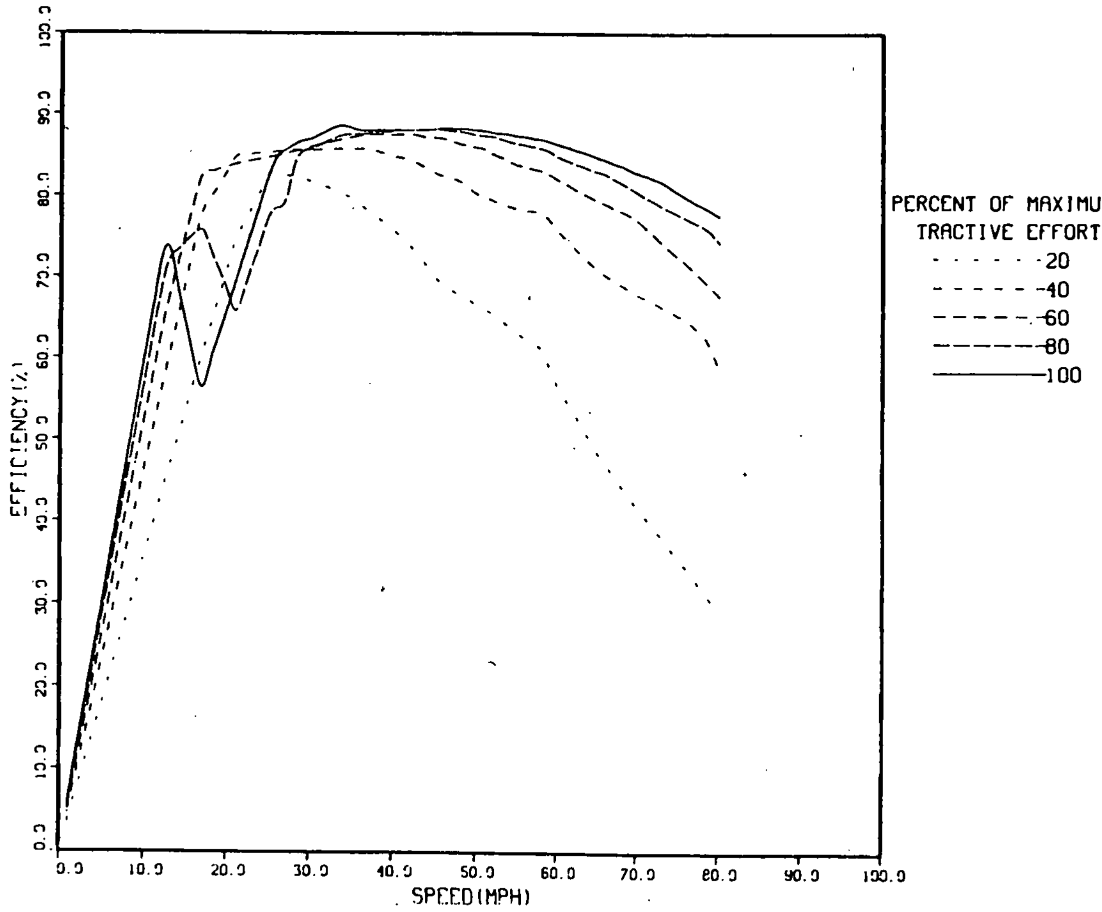


Figure A-7. Propulsion system efficiency—WMATA car, cam control, P5 mode.

to be investigated as part of this study is regeneration using chopper control, this method for varying the voltage to the motor circuit in power, and for stabilizing line voltage during regenerative braking, was also modeled. The parameters (obtained from the Transportation Division of Westinghouse Electric Corporation) used for this model are shown together with its description in Figure A-8.

Figure A-9 shows the tractive effort speed curves at each of the motor circuit modes (1-3) described in Table A-5. These curves were calculated by allowing the line voltage to vary linearly with the power drawn from the line (no power line voltage = 750 volts; maximum power line voltage = 600 volts). The envelope of these curves represents the maximum tractive effort speed capability of the car at the P5 power level. As in the case of resistor control, the load weighing capability limits the acceleration to 3.0 mph per sec on level track.

The motor control philosophy with chopper control is similar to that of the cam control. The chopper is used to vary the voltage to the motor, and in constant speed, running the field shunts are used in preference to chopper control for setting tractive effort to overcome train resistance. The efficiency in power is shown as a function of tractive effort and speed in Figure A-10.

Figure A-11 shows the electrical braking effort-speed characteristic used for regeneration with the chopper control. The decrease in electrical braking effort at high speed is referred to as the brake taper and represents the commutation limit of the motor. The cut off at low speed is due to the inability to "chop up" to line voltage.

In regeneration, the motors are permanently connected in a two series/two parallel circuit. The efficiency in regenerative electrical braking, plotted as a function of braking effort and speed, is shown in Figure A-12. This efficiency is the ratio of regenerated power at the line to power at the wheels.

A.3.3 Braking Characteristics

The brake rate has been set at 3.0 mph per sec. Except for the case of the chopper control with regeneration, all braking is achieved using friction and electric brake with the power developed by the latter being dissipated in resistors.

A.4 RIGHT-OF-WAY CHARACTERISTICS

The locations of the passenger stations on the Red Line is shown in Figure A-13. Both the station numbers, as defined by Metro, and the mileposts, as defined for use in the EMM, are shown in the figure. In the case of the Red Line, the Dupont Circle passenger station was taken as milepost 0.00.

The grades were obtained from the maintenance-of-way track charts. Maximum grades are 4 percent. Elevation profiles of the Red Line are shown in Figure A-14. The Red Line has a large elevation change between Metro Center Station and Silver Spring.

The speed restrictions for normal operation (PL2) are shown for the outbound and inbound directions of the Red Line in Figures A-15 and A-16. The speed restrictions for the catch-up (PL1) operation for the Red Line are shown in Figures A-17 and A-18. The speed profile of an empty six-car train, as simulated by the TPS, has been included in all of these figures. The speed profile is shown as an example of how a train would approach the speed restrictions.

A.5 POWER DISTRIBUTION SYSTEM

A.5.1 Network Description

The electrical network for the Red Line is shown in Figure A-19.

The nominal DC distribution voltage is 750 volts. The impedances are per unit values at unit power of 5000 kW and unit voltage of 750 volts.

From Dupont Circle to Silver Spring, the Red Line is served by ten traction substations, each of which is metered by PEPCO. In 1980 operation, which was used as the basis for this study, the meter designated MA2 (Belmont Road) was not operational.

The Red Line is a two-track system with tiestations whose breakers are normally closed connecting the lines between substations.

A.5.2 Substation Description

Table A-6 presents the substation characteristics appropriate to the Red Line. The transformer-rectifiers which were provided for each substation are 2000 kW units, and they each have a per unit impedance of 0.1986 with a no-load loss of 8.3 kW. Auxiliary transformers, which are used to run heaters and ventilation equipment, are provided in some of the substations. In some substations, the auxiliary transformers are used to power other equipment, such as in the yard at New Carrollton.

A.5.3 Line Impedance

The line impedances along the tracks were calculated from data provided by Metro, and are shown on the networks as per unit values. For two- and four-track systems, the resistance is the series resistance of contact rail plus the running rails acting in parallel shown below:

Two Tracks—0.324 ohms/mile
Four Tracks—0.265 ohms/mile.

A.6 POWER RATE STRUCTURE

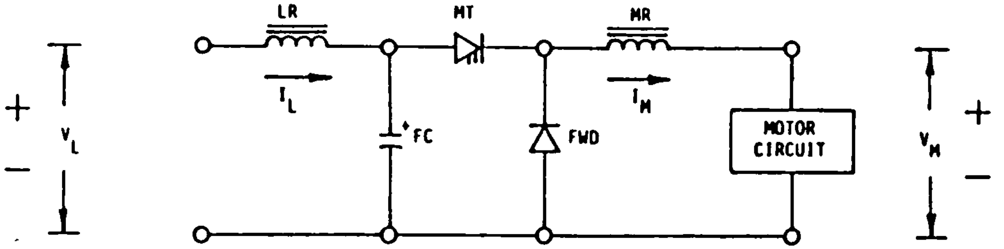
The PEPCO service to Metrorail has the same rate structure for traction and support delivery points. The rate structure design is similar for each of the three jurisdictions in which PEPCO serves Metro, but the rates (unit costs) vary in each jurisdiction. The rate structure is given in Table A-7.

The demand interval is 30 min. and the consolidation for demand purposes is coincident. The billing demand is the maximum of all monthly demands in the jurisdictions of Virginia and Maryland, and the maximum of the last three monthly demands, including the present month, in the DC jurisdiction. Thus, in the Virginia and Maryland jurisdictions, once a new peak demand is reached, it becomes the basis for demand cost from that period.

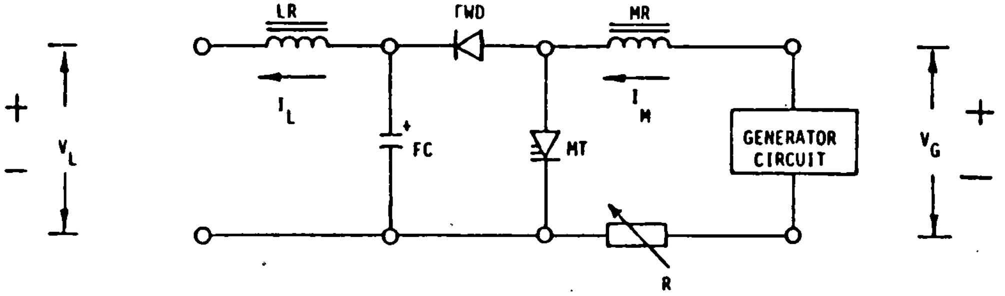
The VEPCO service to Metro for traction and nontraction power is based on a simple rate formula. There is no demand

CHOPPER PROPULSION MODEL

1. POWER



2. BRAKING



LR:	LINE REACTOR	R:	VOLTAGE REDUCING RESISTOR
MR:	MOTOR REACTOR	MT:	MAIN THYRISTOR
FC:	FILTER CAPACITOR	FWD:	FREE WHEELING DIODE

R_{LR} = 0.00185Ω

R_{MR} = 0.012Ω

R_{FC} = 0.0053Ω

V_{MT} = 1.45 V

V_{FWD} = 1.3 V

P_C = 2000 W

EQUATIONS PERTINENT TO CHOPPER CONTROL FOR PROPULSION

Definition of Symbols on Attached Figure

1. Power

   a. Voltage Drop from Line to Motor Circuit at Maximum Voltage on Motor (MT is fully conducting)

$$V_L - V_M = I_M (R_{LR} + R_{MR}) + V_{MT}$$

   b. Power Loss in Chopper

$$P_L = I^2_M (r^2 R_{LR} + R_{MR}) + I_M \left[r V_{MT} + (1-r) V_{FWD} + r(1-r) R_{FC} \right]$$

$$+ P_C$$

   where P_C represent constant losses in reactor and commutation circuitry and

$$r = \frac{V_M}{V_L}$$

2. Brake

   a. Voltage Drop from Generator Circuit to Line at Line Voltage with no resistance, R in circuit.

$$V_G - V_L = I_M (R_{LR} + R_{MR}) + V_{FWD} + r_t V_L$$

   b. Power Loss in Chopper ($V_G < V_L$; $R = 0$)

$$P_L = I^2_G (r^2 R_{LR} + R_{MR}) + I_G \left[r V_{FWD} + (1-r) V_{MT} + r(1-r) R_{FC} \right]$$

$$+ P_C$$

   where

$$r = \frac{V_G}{V_L}$$

$$r_t = \frac{\text{Commutation Time}}{\text{Period of Chopper}}$$

Figure A-8. Chopper propulsion model.

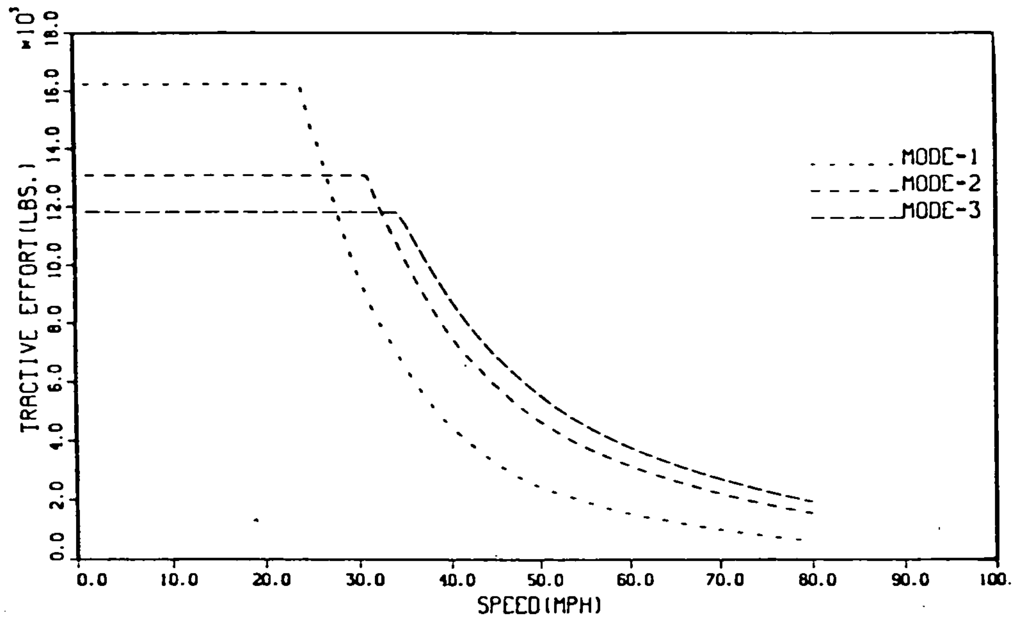


Figure A-9. Tractive effort-speed curve—WMATA car, chopper control, P5 mode.

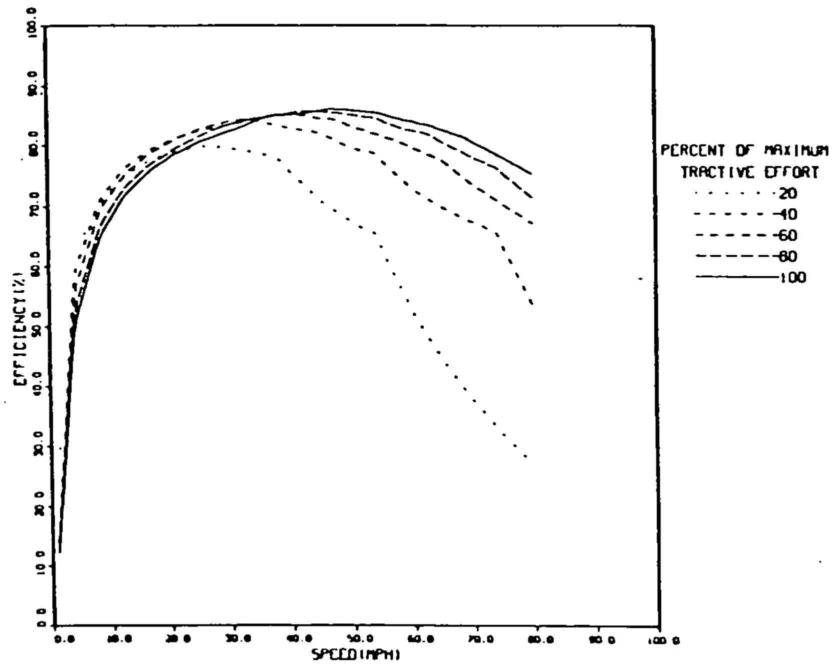


Figure A-10. Propulsion system efficiency—WMATA car, chopper control, P5 mode.

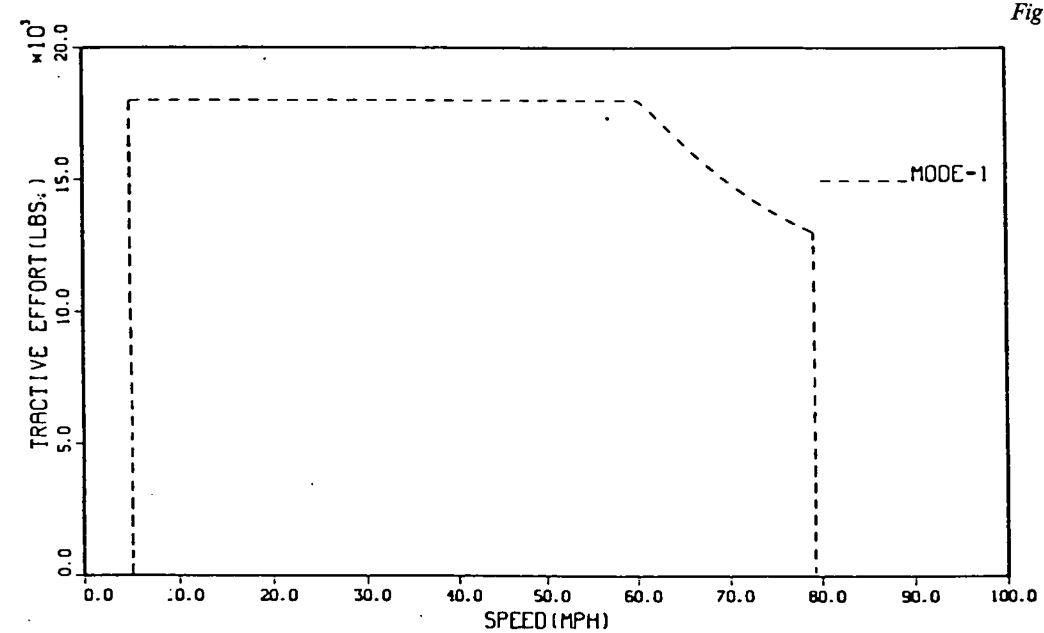


Figure A-11. Tractive effort-speed curve—WMATA car, chopper control, regenerative brake.

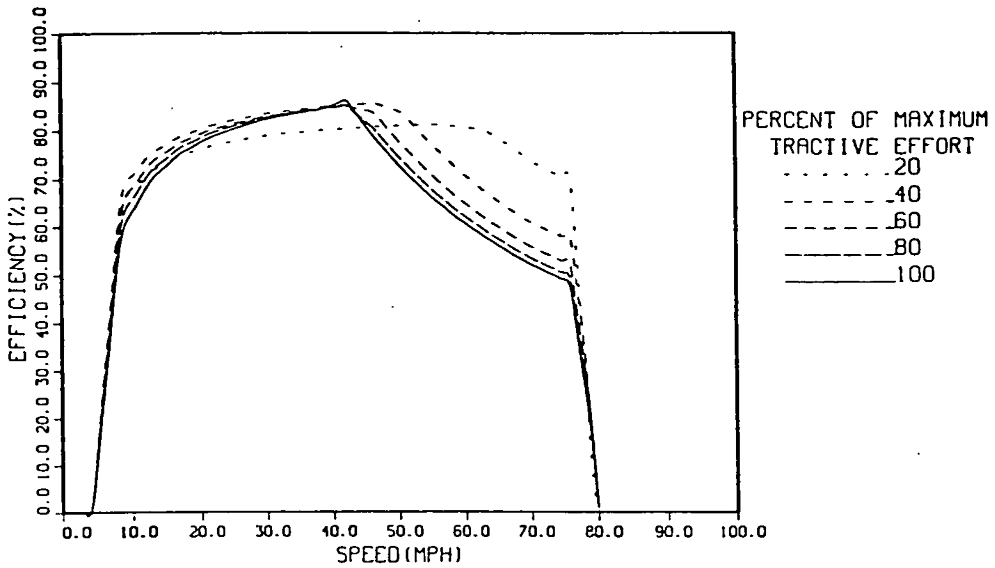


Figure A-12. Propulsion system efficiency—WMATA car, chopper control, regenerative brake.

charge, and the rates are (effective October 1980): \$.04/kWh for energy, and \$.0211/kWh for fuel adjustment.

These rates exclude excess facility charges which are not considered in this study.

A.7 SIMULATION FOR 1980 OPERATION

A.7.1 TPS Runs for Normal Operation

Using the 1980 timetable, the passenger load factors derived from the origin-destination passenger counts obtained from Metro, measured average dwell times, and the speed restrictions associated with PL2 operation, train performance simulations were conducted for weekday peak and off-peak periods on the Red Line. The energy and running times are summarized in Table A-8. The energy represents energy consumed at the line.

The principal variation among the energy consumption numbers of Table A-8 can be explained as follows:

- For a given line in a fixed direction of travel, the variation in energy is due to variation in passenger load factor. This is a relatively small variation.
- The relatively large increase in elevation on the outbound direction of the Red Line accounts for the energy difference between outbound and inbound operation. (The difference is about 1 kWh per car-mile.)

Figures A-20 and A-21 show the power profiles for an empty six-car train running on the Red Line in both directions. These power profiles were generated so that a profile of peak power regions could be identified.

A.7.2 ENS for Normal Operation

Using the electric distribution networks for the Red Line (Fig. A-20) and Metro's 1980 operational timetable, a summary of which is shown in Table A-1, peak operation was simulated using the ENS for the following time periods on a weekday:

SIMULATION TIME	TO REPRESENT
8:00–9:00A	AM Peak
4:30–5:30P	PM Peak

Table A-9 contains the results of the ENS for the Red Line. These results do not include the background or the effect of turnaround time at the terminals.

A.7.3 TPS Runs for Catch-up Operation

Using the 1980 timetable, the passenger load factors derived from origin-destination passenger counts obtained from Metro, measured average dwell times, and speed restrictions associated with PL1 operation, train performance simulations were conducted for weekdays, AM and PM peak periods, on the Red Line.

The energy and running times are summarized in Table A-10. The energy represents energy consumed at the line.

These runs were made in order to complete ENS for the catch-up operation, since this mode of operation could determine the peak power demand. These should be compared with the summary of the TPS in Table A-8 in order to ascertain the differences between PL1 and PL2 operation.

A.7.4 ENS Runs for Catch-up Operation

Table A-11 shows the results of the ENS for catch-up (PL1) operation during the peak operating period for the Red Line. The results should be compared with normal operation shown in Table A-9.

A.8 VERIFICATION OF SIMULATION

The two areas in which the results of the EMM for normal

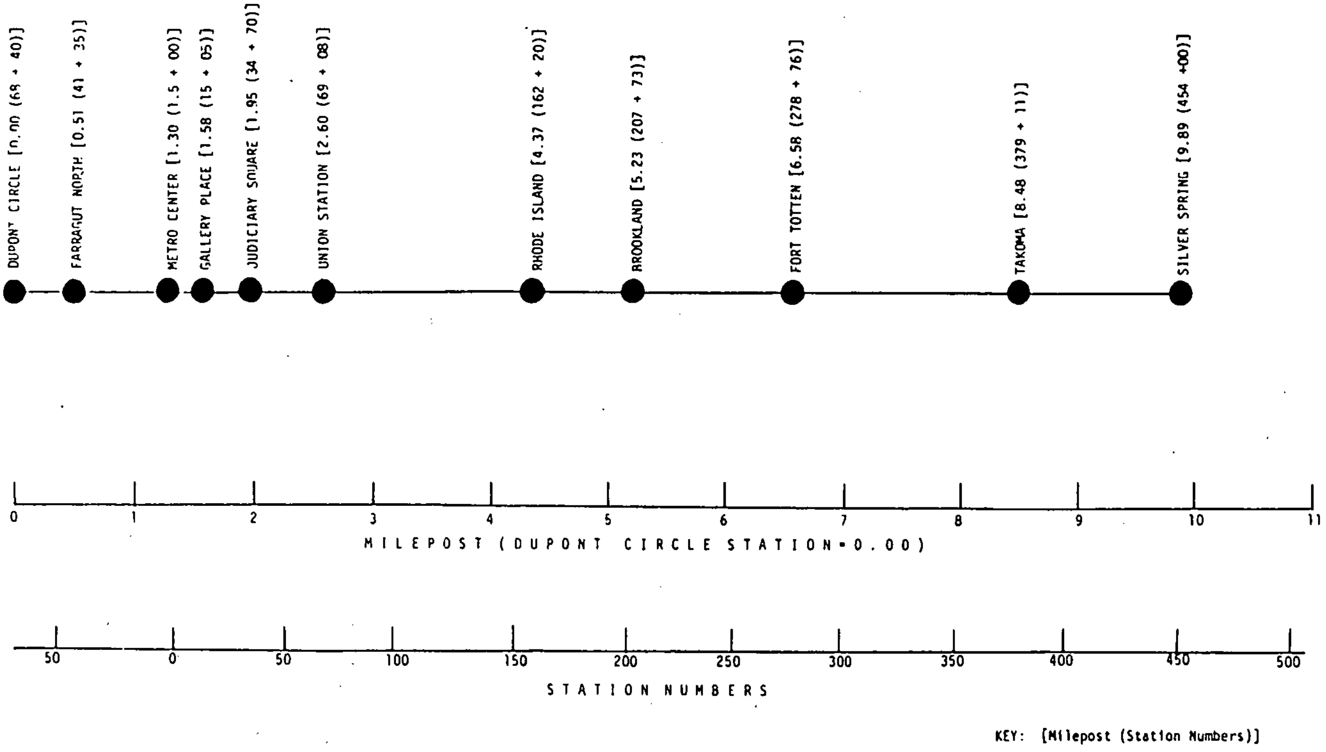


Figure A-13. Passenger station configuration—Red Line.

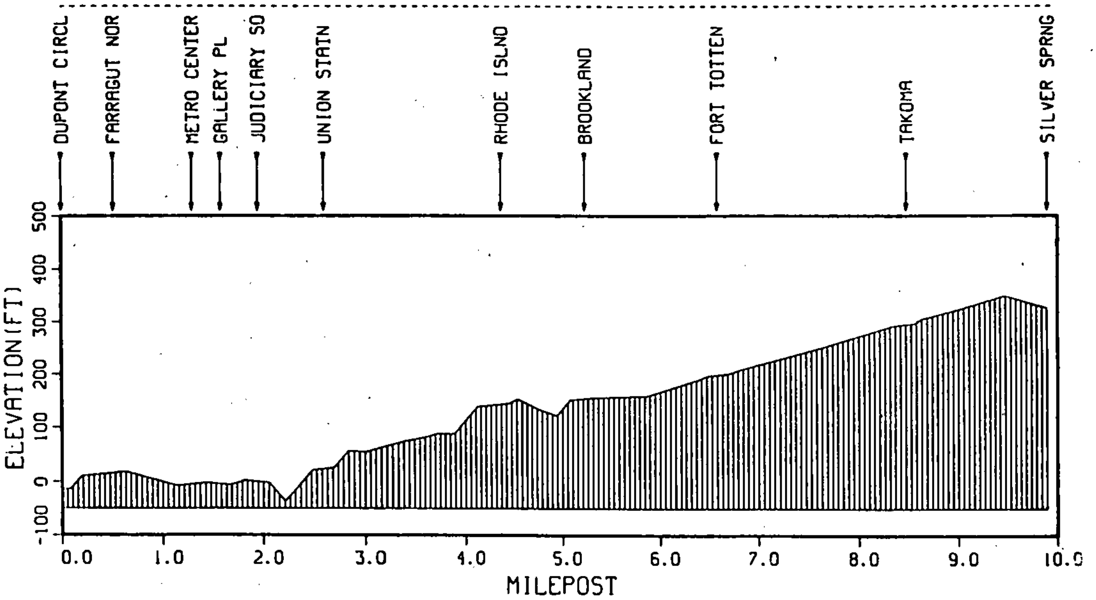


Figure A-14. Elevation Profile—WMATA Red Line.

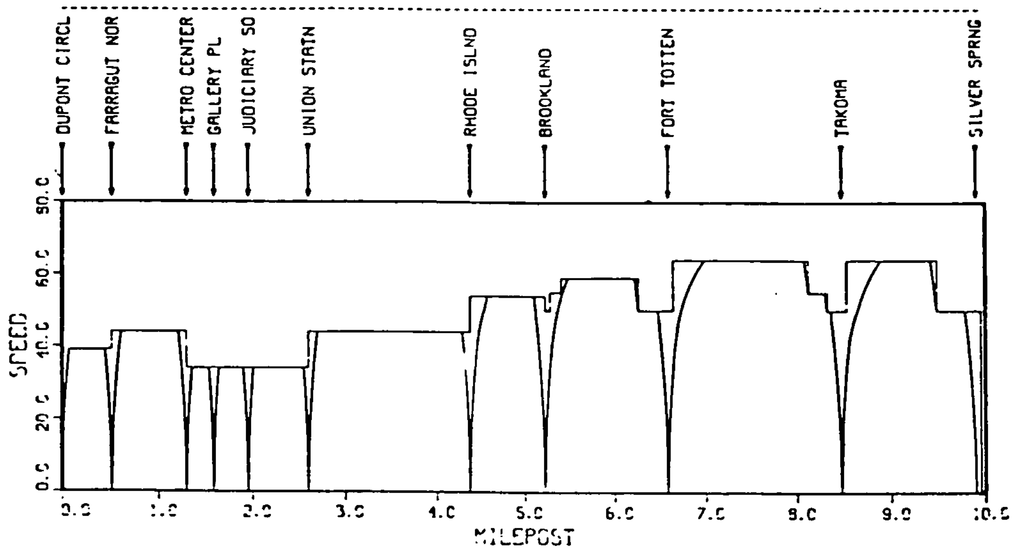


Figure A-15. Speed profile and restrictions—Red Line 6-car empty train outbound, PL2.

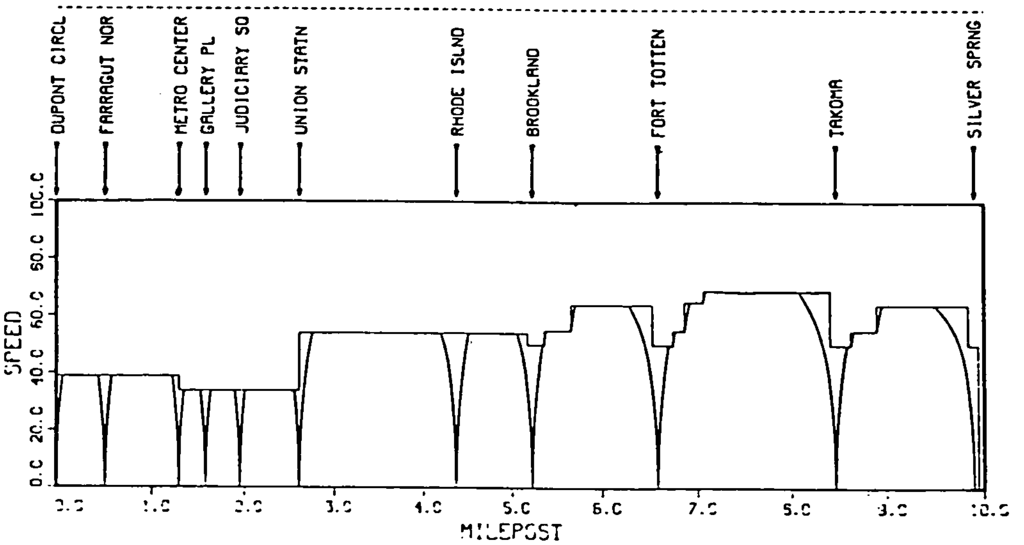


Figure A-16. Speed profile and restrictions—Red Line 6-car empty train-inbound, PL2.

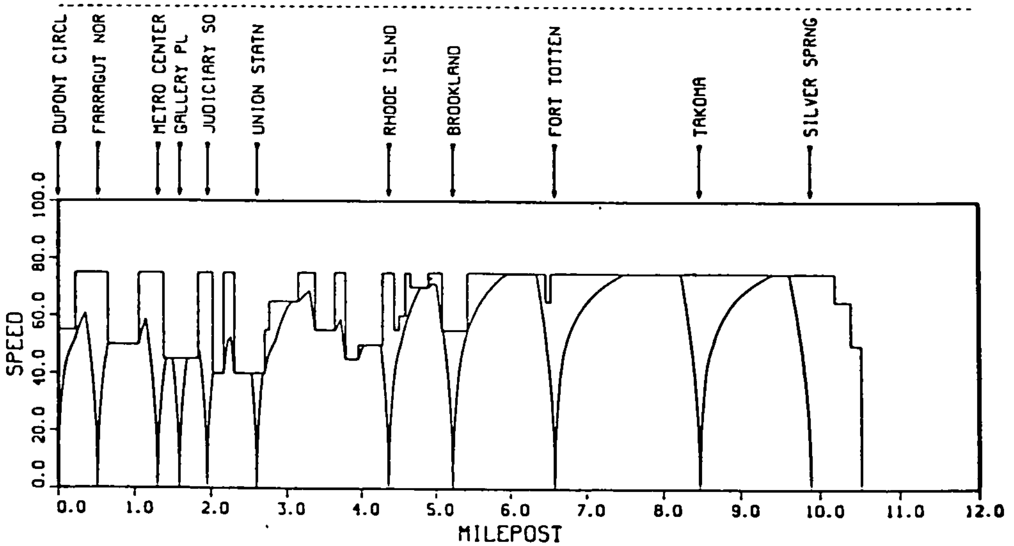


Figure A-17. Speed profile and restrictions—Red Line 6-car empty train outbound, PL1.

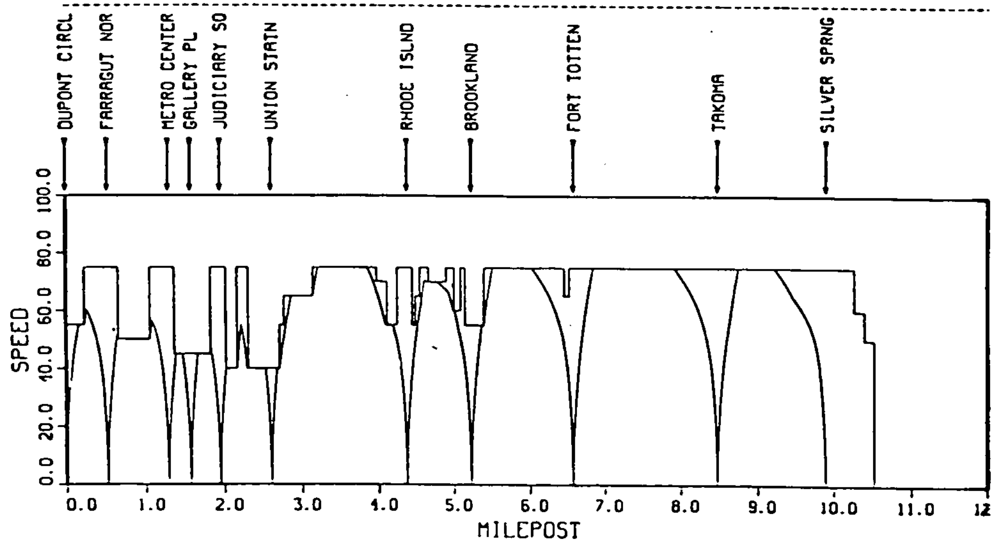


Figure A-18. Speed profile and restrictions.

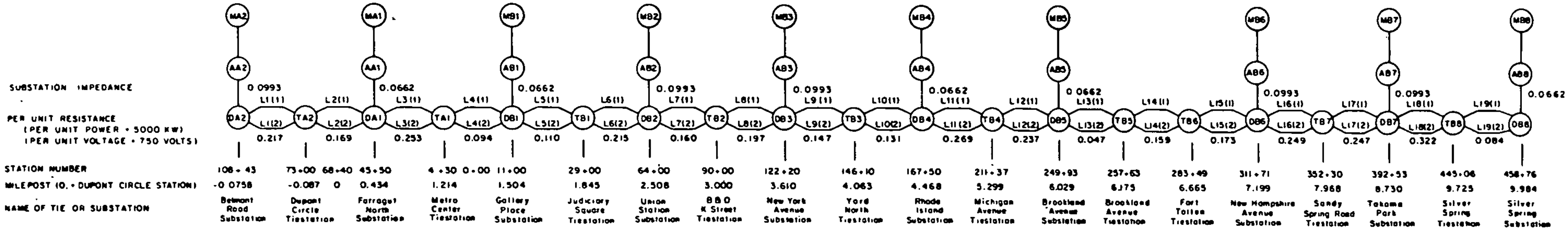


Figure A-19. Red Line electrical distribution network.

Table A-6. Substation characteristics.

SUBSTATION NAME	METER	# OF 2000KW T-R[b]	NO LOAD LOSSES (KW)	IMPED'CE PER UNIT	RAT'G OF AUX. TRANSF.
Belmont Road[c]	MA2	2	16	.0993	450
Farragut North	MA1	3	24	.0662	
Gallery Place	MB1	3	24	.0662	
Union Station	MB2	2	16	.0993	
New York Ave.	MB3	2	16	.0993	150
Rhode Island Ave.	MB4	3	24	.0662	
Brookland Ave.	MB5	3	24	.0662	150
N. Hampshire Av.	MB6	2	16	.0993	
Takoma Park	MB7	2	16	.0993	
Silver Spring	MB8	3	24	.0662[d]	

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[b] Transformer-Rectifiers

[c] 1981 Operation

[d] Obtained from George Care, WMATA

Table A-7. PEPCO power rate structure.

JURISDICTION	DC	MARYLAND	VIRGINIA
Effective	12/81	6/81	4/81
Demand ($/kW)	11.70[e]	9.85[f]	7.85
Energy ($./kWh)	0.52893	0.5796	0.4244
Customer ($/delivery pt.)	150.75	145.0	140.0
Fuel Adjustment[g] ($./kWh)	2.29257	1.8	1.8

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[e] Billing demand is the maximum of three consecutive month monthly demands, including the present month. Monthly demand is the maximum demand for the month.

[f] Billing demand is the maximum of the monthly demands including the present month.

[g] This represents an average for the period.

Table A-8. Summary of simulated running time and energy consumption for 1980 normal operation.

ENERGY CONSUMPTION (KWHPCM)	INBOUND	OUTBOUND
AM Peak		
Six Car Train	5.48	6.60
Eight Car Train	5.48	6.58
Midday		
Six Car Train	5.23	6.76
PM Peak		
Six Car Train	5.16	7.13
Eight Car Train	5.15	7.11
Evening		
Six Car Train	5.10	6.73
Empty Six Car Train (No Dwell)	4.83	6.31
Crush Loaded Six Car Train (No Dwell)	6.37	8.54
RUNNING TIME (MINUTES)		
AM Peak		
Six Car Train	18.66	19.13
Eight Car Train	18.66	19.12
Midday		
Six Car Train	18.63	19.13
PM Peak		
Six Car Train	18.65	19.15
Eight Car Train	18.65	19.14
Evening		
Six Car Train	18.65	19.13
Empty six Car Train (No Dwell)	14.39	14.87
Crush Loaded Six Car Train (No Dwell)	14.52	14.52

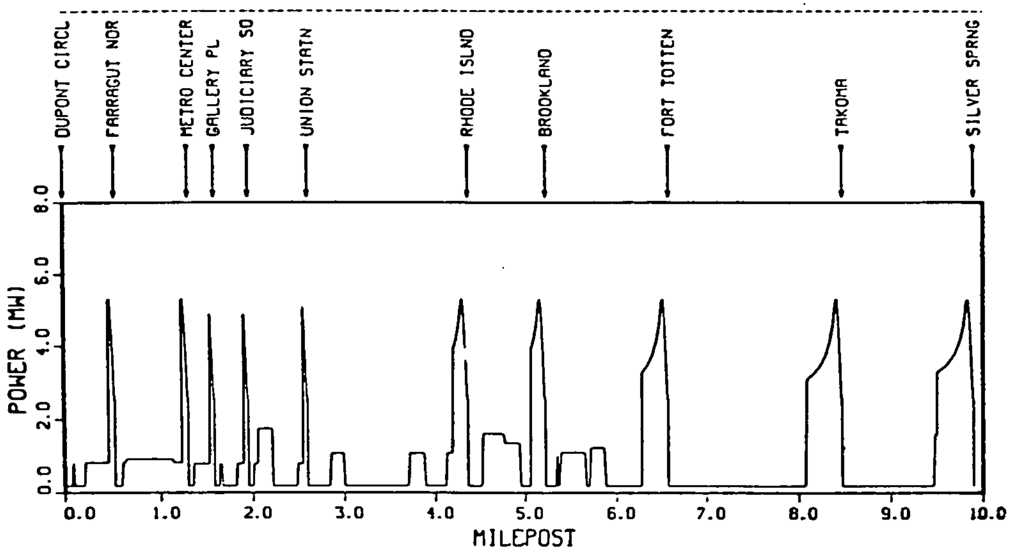

Figure A-20. Power profile—Red Line 6-car empty train inbound, PL2.

Table A-9. Results of the ENS for normal operation during 1980 for the Red Line.

METER NAME	SYMBOL	POWER (KW)[h] AM PEAK	PM PEAK
Farragut North	(MA1)	1070	1046
Gallery Place	(MB1)	1372	1290
Union Station	(MB2)	1264	1261
New York Ave.	(MB3)	632	657
Rhode Island Ave.	(MB4)	1602	1668
Brookland Ave.	(MB5)	1522	1456
New Hampshire Ave.	(MB6)	480	1162
Takoma Park	(MB7)	1428	1472
Silver Spring	(MB8)	474	544
COINCIDENT RED		10540	10556
CAR MILES		1644	1639
KWHPCM		6.41	6.44

Table A-10. Summary of simulated running time and energy consumption for 1980 catch-up operation.

ENERGY CONSUMPTION (KWHPCM)	INBOUND	OUTBOUND
AM Peak		
Six Car Train	7.00	8.20
Eight Car Train	6.92	8.18
PM Peak		
Six Car Train	6.61	8.84
Eight Car Train	6.53	8.81
Empty Six Car Train (No Dwell)	6.25	7.85
Crush Loaded Six Car Train (No Dwell)	8.14	10.31
RUNNING TIME (MINUTES)		
AM Peak'		
Six Car Train	17.16	17.53
Eight Car Train	17.16	17.53
PM Peak		
Six Car Train	17.14	17.61
Eight Car Train	17.14	17.61
Empty Six Car Train (No Dwell)	12.88	13.27
Crush Loaded Six Car Train (No Dwell)	13.14	13.69

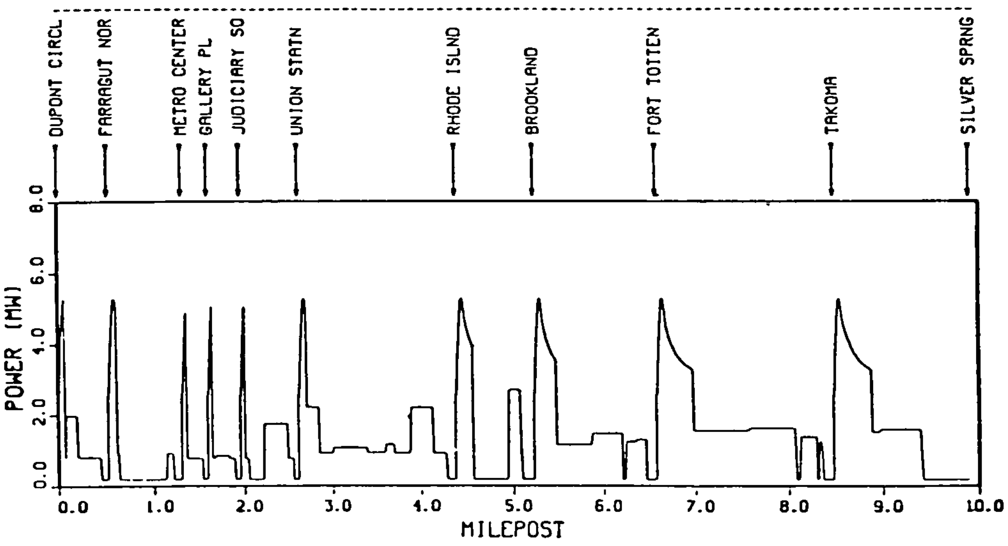

Figure A-21. Power profile—Red Line 6-car empty train outbound, PL2.

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[h] Does not include on-board auxiliary power during turnaround.

Table A-11. Results of the ENS for catch-up operation during 1980 for the Red Line.

		POWER (KW)[1]	
METER NAME	SYMBOL	AM PEAK	PM PEAK
Farragut North	MA1	1668	1577
Gallery Place	MB1	1909	1787
Union Station	MB2	1631	1668
New York Ave.	MB3	848	939
Rhode Island Ave.	MB4	1957	1961
Brookland Ave.	MB5	1796	1813
New Hampshire Ave.	MB6	1349	1387
Takoma Park	MB7	1722	1743
Silver Spring	MB8	614	683
COINCIDENT RED		13493	13557
CAR MILES		1643	1635

---

[1] Does not include on-board auxiliary power during turnaround.

operation can be compared to actual operation are running time and energy consumption.

A.8.1 Running Time

Information on actual running times between stations was obtained by using riders on the trains to clock the interstation time. These samples were taken during the period from June 19, 1981, through July 7, 1981. No significant difference was observed between peak and non-peak operation.

Figure A-22 shows a comparison between simulated and actual running times between stations for the Red Line, for both directions. The small dots indicate the results of observation. Both normal (PL2) and catch-up (PL1) operation simulations are shown in the figures, together with the observations.

There is generally good agreement between the simulation and observed results. The simulated running times for normal operation generally appear at slightly less times than the "clumping" of the observed running times. This indicates schedule slack.

A.8.2 Verification of Energy Consumption

The EMM can only simulate the energy consumption that is due to traction power used to propel the trains and the on-board auxiliaries. Although it is possible to simulate the on-board auxiliary energy consumption during turnaround at the ends of the line using the ENS, it is more economic and convenient to estimate it manually and add it to the appropriate traction meter. Table A-12 gives the results of the estimate expressed in both kilowatt hours per car-mile and kilowatts.

The results of the energy consumption for the Red Line are given in Table A-13. The average power (May 1–October 15, 1980) as metered by PEPCO (the detail of this is given in Appendix E) is shown together with the power as simulated using the ENS to which the background, car layup power, and turnaround powers have been added. Although on an individual meter basis the results do not show good agreement, the energy consumption on a coincident basis is within 3 percent of the observed average power for peak operating periods. The power through the individual meters is very sensitive to the voltage at the individual meter and adjacent meters.

A.8.3 Power Estimation for Present Operation

The PEPCO provided a magnetic tape that contained energy pulses for each 15-min interval for the 26 traction energy meters that were in operation during 1980. A regression analysis was done using the PEPCO traction meter data to determine the dependence of traction energy usage on car-miles and daily temperature. The regression formula was assumed to have the form:

$$P = P_0 + E_1 (CM/H) + P_2 (ADD)$$

where:

P = average power over the revenue operating time as obtained from the meter data;
P_0 = background power in units of kW;
CM/H = average car-miles per hour;
ADD = average degree-day (average temperature −70 F);
E_1 = energy per car-mile, KWHPCM; and
P_2 = average power per degree-day, KWPADD.

The details of this regression analysis are given in Appendix E.

Table A-14 presents a breakdown of background power and the KWHPCM associated with PEPCO traction energy meters

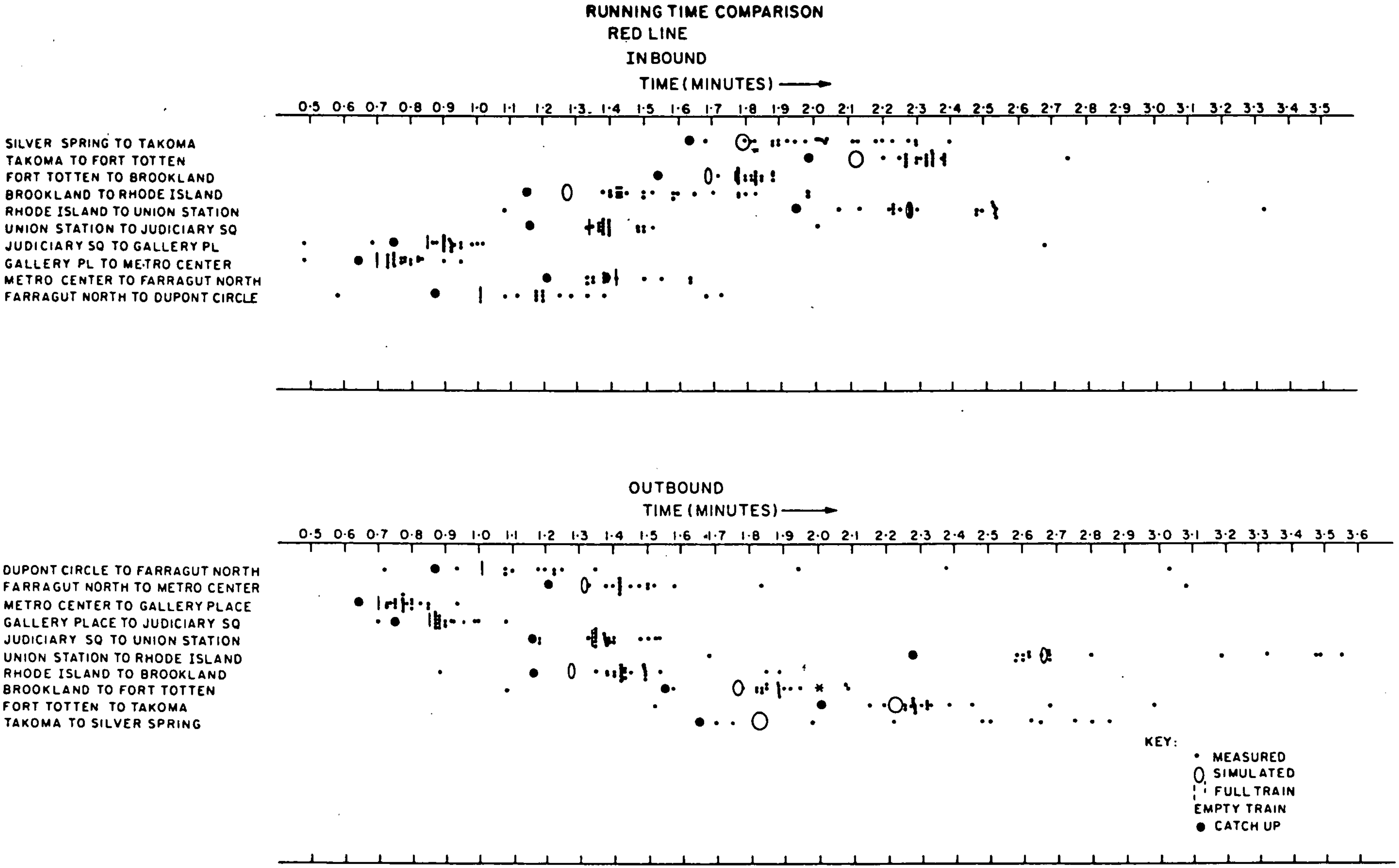

Figure A-22. Running time comparison.

Table A-12. Estimate of auxiliary train power on turnaround.

			PEAK (OFF-PEAK)					
Passenger Station	Substation	Line	Turnaround Time (MIN)	Trains/ HR	Cars/ Train	Car-Miles/ HR	Turnaround KWHPCM	Turnaround Avg. Power (KW)
Dupont Circle	Farragut North	Red	7 (7)	12 (6)	6.9 (6)	1644 (711)	0.17 (0.17)	280 (121)
Silver Spring	Silver Spring	Red	4 (9)	12 (6)	6.9 (6)	1644 (711)	0.10 (0.23)	164 (164)
D/G Junction	Minnesota Ave.	Blue	3 (3)	10 (5)	6 (6)	1470 (735)	0.06 (0.06)	88 (44)
New Carrollton	New Carrollton	Orange	3 (3)	10 (5)	6 (6)	1988 (994)	0.04 (0.04)	80 (40)

Estimate: $\frac{30\ \text{KW} \times (\text{turnaround time})}{60 \times (\text{car-miles/hr})} \times (\text{trains/hr}) \times (\text{cars/train})$

Table A-13. Verification of traction meter power during normal operation on Red Line.

METER	SYMBOL	AM PEAK		PM PEAK	
		PEPCO	SIM	PEPCO	SIM[j]
Farragut North	MA1	1759	1438	1836	1414
Gallery Place	MB1	1585	1470	1663	1388
Union Station	MB2	1116	1397	1283	1394
New York Ave.	MB3	1149	753	1338	778
Rhode Island Avenue	MB4	1160	1686	1259	1752
Brookland Ave.	MB5	1764	1828	1827	1762
New Hampshire Avenue	MB6	970	1425	1086	1412
Takoma Park	MB7	1267	1552	1277	1596
Silver Spring	MB8	1241	846	1278	916
COINCIDENT RED		12011	12395	12847	12412

[j] Includes background, ENS results and turnaround of.

	AM PEAK	PM PEAK
Silver Spring	164	164
Farragut North	280	280

Table A-14. Background power and KWHPCM predicted by EMM for traction energy meter for normal operation.

		BACKGROUND (KW) AT AVERAGE TEMPERATURE[k]		
METER	SYMBOL	PEAK	OFF-PK	NON-REV
Farragut North	MA1	88	88	88
Gallery Place	MB1	98	98	98
Union Station	MB2	133	133	133
New York Ave.	MB3	121	201	321
Rhode Island A.	MB4	84	84	84
Brookland Ave.	MB5	306	306	306
New Hampshire	MB6	250	250	250
Takoma Park	MB7	124	124	124
Silver Spring	MB8	208	328	388

		KWHPCM[l]	
		AM PEAK	PM PEAK
Farragut North	MA1	0.82	0.81
Gallery Place	MB1	0.83	0.78
Union Station	MB2	0.77	0.77
New York Ave.	MB3	0.38	0.40
Rhode Island A.	MB4	0.97	1.01
Brookland A.	MB5	0.93	0.89
New Hampshire A.	MB6	0.71	0.71
Takoma Park	MB7	0.87	0.90
Silver Spring	MB8	0.39	0.43

---

[k] Includes car layup power (KW).

[l] Includes on-board auxiliaries during turnaround.

based on the simulated results. The background was estimated at the average temperature of 67.3F over the period analyzed through a regression study.

Thus, the value of the background and the KWHPCM coefficients for normal operation (PL2) for the Red Line are as follows:

	P_O	P_R
AM Peak	1412	6.67
PM Peak	1412	6.70
Off Peak	1612	6.56
Nonrevenue	1792	

Table A-15 shows a breakdown of the KWHPCM associated with each Red Line traction energy meter based on the simulated results using energy meter based on the simulated results using catch-up operation (PL1) for the peak operating periods.

Catch-up operation (PL1) results in a 10 percent increase in car-miles/hour if the turnaround times are kept the same as normal operation (PL2). The increase in the KWHPCM and the increase in car-miles/hour result in an increase of 34 to 36 percent in power over normal operation. If catchup operation used during a peak operating period coincides with a demand period (a half-hour period beginning each quarter hour), and it occurs over a time period greater than a half-hour, the result could be a 35 percent increase in power demand.

It is clear from the foregoing analysis that a case to be avoided is one-half hour or greater catch-up operations on the Red Line.

A.9 CONSERVATION OPPORTUNITIES

Several traction energy conservation opportunities were identified as potentially beneficial to Metrorail operations. The categories of these strategies are:

1. Performance modification.
2. Regeneration.

Strategies from the first category could be implemented in a relatively short period of time (3 months to 1 year) while regeneration strategy would take substantially longer.

The base operation selected was the 1980 timetable, and for the purpose of the strategy benefit estimates, it was divided into normal peak operation (PL2), and peak catch-up operation (PL1). The latter was used to estimate the upper bound of peak power demand. The KWHPCM coefficients for peak operation were the averages of weekday AM and PM peak. These coefficients, together with the traction power background, are given in Table A-16. Using the 1980 operating timetable, and considering peak operation for 7 hours on weekdays, and off-peak operation for 11 hours on weekdays, 16 hours on Saturdays, and 8 hours on Sundays, the base case peak power demand ranges and annual energy use were computed using the power formula and the coefficients in Table A-15. The results are given in Table A-17. If catch-up operation were used for one-half hour during the peak operating period on the Red Line, a peak demand associated with the catch-up entry would result.

Table A-15. KWHPCM predicted by EMM for each traction meter for catch-up operation.

METER	SYMBOL	AM PEAK	PM PEAK
Farragut North	MA1[m]	1.18	1.13
Gallery Place	MB1	1.16	1.09
Union Station	MB2	0.99	1.02
New York Ave.	MB3	0.52	0.57
Rhode Island Ave.	MB4	1.19	1.20
Brookland Ave.	MB5	1.09	1.11
New Hampshire A.	MB6	0.82	0.85
Takoma Park	MB7	1.05	1.07
Silver Spring	MB8[n]	0.47	0.52
		KWHPCM[o]	
Farragut North		0.17	0.17
Silver Spring		0.10	0.23

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[m] Includes on-board auxiliaries during turnaround.

[n] Includes on-board auxiliaries during turnaround.

[o] During turnaround

A.10 PERFORMANCE MODIFICATION STRATEGIES

Three performance modification strategies were considered in the study:

1. Top speed reduction.
2. Coasting.
3. Optimum performance.

Top-speed reduction means that the maximum speed of the trains is reduced from 75 mph to some lower value that cannot be exceeded under normal circumstances.

A top-speed reduction that results in a 10-percent increase in average schedule time can be implemented immediately by using performance level three (PL3) operation.

Coasting is implemented by allowing no braking except that due to train resistance above some preset speed under normal conditions. Thus, in an approach to a station or speed restriction, power would be cut off, but the brakes would not be applied until the preset speed was attained. The preset speed is referred to as the coasting speed.

This is not the only way that coasting could be accomplished. Another method would be to drop the lower portion of the speed band that controls the power and brake mode, and inhibit the brake from being applied until the lower value of the speed band is reached.

In the sawtooth mode of coasting, the cruising section of the trajectory is replaced by a slightly altered operation. Now, once the train has reached its limiting speed all accelerating or positive tractive effort is removed from the wheels. The train is now free to coast down to a lower speed band, typically of the order of a couple of miles per hour below the upper bound. When this lower bound is reached, full acceleration is applied until the upper bound is reached once again, and the cycle repeats.

The optimum performance modification strategy is discussed in detail in Appendix G.

Table A-16. Values of the coefficient of the average power formula for operation during normal, peak, and off-peak and catch-up periods as base for energy conservation strategies applied to 1980 timetable on coincident Red Line.

	P_O	E_R
Normal Peak (PL2)	1412	6.69
Normal Off-peak (PL2)	1612	6.56
Catch-up Peak (PL1)	1612	8.52
Non Revenue	1792	

The implementation of performance modification strategies that result in running time increases from 0 to 3 percent in schedule time could probably be accommodated.

All performance modification strategies will increase the running time between stations. If the slack is taken up by dwell or turnaround time reduction, there will be no overall effect on the schedule. If the dwell and turnaround time were held constant, a net reduction in car-miles/hour would result.

It should also be noted that application of a performance modification strategy, such as coasting or top-speed reduction, can reduce stress levels on traction equipment and result in less road failures, thus reducing schedule delay. At the present time, this effect is not quantifiable.

Figure A-23 shows plots of percent traction energy decrease as functions of percent schedule time increase on the Red Line for these strategies for peak operating periods. In terms of energy reduction for minimum schedule time increase, coasting is a better strategy than top-speed reduction. At schedule time increases of 2 to 3 percent, which can be achieved by coasting from maximum permitted speed to 50 mph (usually referred as coasting speed = 50 mph), traction energy decreases of 12 to 16 percent are attainable. The best conservation strategy from the point of view of savings is optimum performance (optimization steepest descent) which results in 20 percent reduction in energy with only less than 1 percent increase in schedule time.

Table A-17. Traction power demand and annual energy use for normal operation with 1980 timetable for coincident Red Line.

POWER DEMAND (KW) and ANNUAL ENERGY USE (MWH)

POWER DEMAND			ENERGY USE[p]
Catch-up	Normal	Δ	
15420	12410	3010	50800

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[p] Annual background energy for Coincident Red is 14200 mWh, 1644 CM/H during peak period operation. Annual peak carmiles are 2.467M and off-peak car miles are 3.057M

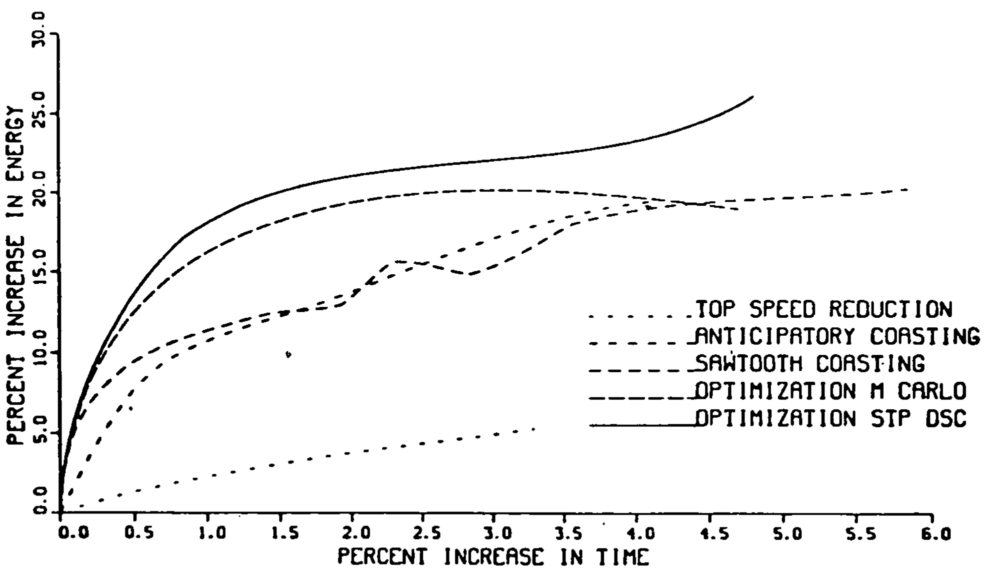

Figure A-23. Performance modification results—WMATA Red Line outbound.

A.10.1 Coasting

A detailed analysis using the ENS was conducted using the coasting strategy with coasting (speed = 50 mph). The results of this analysis are presented in Table A-18. The background power for each of the traction meters would be no different from the base operation.

The actual increase in running times for this coasting strategy is 3 percent on the Red Line.

The power savings by applying coasting (speed = 50 mph), may be determined by using KWHPCM coefficients, which are the differences between those obtained by using the coasting strategy and those of the base operation. These coefficients are given in Table A-19 and may be used directly to determine the peak power demand and energy savings. These savings are shown in energy units and as a percent of traction energy for base operation in Table A-20.

A.10.2 Top-Speed Reduction

A detailed analysis using the ENS was conducted using a top-speed reduction strategy that allowed the running times to be increased by the same amount as for the coasting strategy (coasting speed = 50 mph). This increase in schedule time was 3 percent on the Red Line. To achieve this effect, the top speed on the system was reduced to 55 mph.

The detailed results of this analysis are given in Table A-21. Again, the background power for each of the traction meters would be no different from the base 1980 operation.

The power savings, by reducing the top speed of the system to 55 mph, may be determined by using the KWHPCM coefficients which are the differences between those obtained by using the top-speed reduction strategy and those of the base operation. These coefficients are given in Table A-19 and may be used directly to determine the peak-power demand and energy savings. These savings are shown in both energy units and as a percent of traction energy for base operation in Table A-20.

By comparing the results of energy savings using coasting vs. energy savings using top-speed reduction at the same level of increase in running time, it is clear that under normal operation (PL2) coasting is approximately four times as effective in reducing energy consumption than top-speed reduction. This is also clear from observing Figure A-23.

A.11 REGENERATION STRATEGY

The regeneration strategy investigated in this study was based on 1980 timetable operation using chopper propulsion equipment which BREDA will deliver to Metro. The propulsion system is described in Section A.3.

The strategy was regeneration with natural receptivity in which all of the cars that made up the trains were chopper cars, and the only receptors of the regenerated brake energy were other trains on the line.

Regeneration with natural receptivity was simulated using the EMM. Regeneration would be maintained up to a line voltage of 860 volts DC. At this maximum line voltage, the excess electrical braking power that cannot be accepted by the line is channeled into resistors aboard the car.

Table A-22 gives the results of the simulation for regeneration with the 1980 timetable operation. Although some of the background power that is obtained from the 750-volt DC third rail, such as switchpoint heaters, can be supplied by the regenerating trains, this savings was not considered in the analyses.

As in the case of the coasting simulation, the power savings can be determined by computing the KWHPCM coefficients which are the differences between the regeneration and base operation cases. These coefficients are given in Table A-19.

A summary of the peak power demand and energy savings obtained by a completely regenerating fleet of cars is given in Table A-20. This savings is calculated with respect to the 1980 base operation.

Table A-18. Values of KWHPCM coefficients in the average power formula for coasting with speed above 50 mph.

		NORMAL(PL2)		CATCH-UP (PL1)
METER	SYMBOL	PEAK	OFF-PEAK	PEAK
Farragut North	MA1[a]	0.83	0.81	0.99
Gallery Place	MB1	0.82	0.79	1.07
Union Station	MB2	0.74	0.72	0.87
New York Ave.	MB3	0.34	0.33	0.30
Rhode Island Avenue	MB4	0.86	0.79	0.84
Brookland Avenue	MB5	0.67	0.64	0.66
New Hampshire Avenue	MB6	0.57	0.54	0.54
Takoma Park	MB7	0.60	0.59	0.57
Silver Spring	MB8[r]	0.30	0.43	0.28
COINCIDENT RED		5.72	5.63	6.12
		KWHPCM[s]		
Farragut North	MA1	0.17	0.17	
Silver Spring	MB8	0.10	0.23	

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[a] Includes on-board auxilary during turnaround

[r] Includes on-board auxiliaries during turnaround

[s] During turnaround

Table A-19. Values of the KWHPCM coefficients for the average power savings for different conservation strategies for peak and non-peak PL2 and peak PL1 operation.

STRATEGY	ΔE_R
NORMAL PEAK (PL2)	
Coasting above 50MPH	0.97
Top speed of 55MPH	0.31
Regeneration - Natural Receptivity	2.01
NORMAL OFF-PEAK (PL2)	
Coasting above 50 MPH	0.93
Top speed of 55 MPH	0.31
Regeneration - Natural Receptivity	1.39
CATCH-UP PEAK (PL1)	
Coasting above 50 MPH	2.40
Top speed of 55 MPH	1.83
Regeneration - Natural Receptivity	2.62

Table A-20. Traction power demand and annual energy use savings over 1980 timetable operation by applying different conservation strategies.

TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (MWH)[t]

	PEAK POWER DEMAND		ENERGY USE
STRATEGY	CATCH-UP (PL1)	NORMAL (PL2)	
Coasting above 50MPH	3945	1595	5200
Top speed of 50 MPH	3010	510	1700
Regeneration - Natural Receptivity	4305	3305	9200

TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)

	PEAK POWER DEMAND		ENERGY USE
STRATEGY	CATCH-UP (PL1)	NORMAL (PL2)	
Coasting above 50MPH	26	13	10
Top speed of 50MPH	20	4	3
Regeneration - Natural Receptivity	28	27	18

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[t] Based on 1980 operating timetable of 1644 CM/H. Annual car-miles during peak period is 2.467M, and off-peak period is 3.057M.

Table A-21. Values of the KWHPCM coefficients in the average power formula for top speed reduction to 55 mph.

		NORMAL (PL2)	
METER	SYMBOL	PEAK	OFF-PEAK
Farragut North	MA1[u]	0.83	0.81
Gallery Place	MB1	0.77	0.82
Union Station	MB2	0.79	0.75
New York Ave.	MB3	0.42	0.38
Rhode Island Ave.	MB4	0.90	0.91
Brookland Ave.	MB5	0.80	0.78
New Hampshire Av.	MB6	0.64	0.59
Takoma Park	MB7	0.81	0.71
Silver Spring	MB8[v]	0.42	0.50
COINCIDENT RED		6.38	6.25
		KWHPCM[w]	
Farragut North	MA1	0.17	0.17
Silver Spring	MB8	0.10	0.23

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[u] Includes on-board auxiliaries during turnaround.

[v] Includes on-board auxiliaries during turnaround.

[w] During turnaround.

Table A-22. Values of the KWHPCM coefficients in the average power formula for regeneration with natural receptivity.

		NORMAL (PL2)		CATCH-UP (PL1)
METER	SYMBOL	PEAK	OFF-PEAK	PEAK
Farragut North	MA1[x]	0.63	0.58	0.88
Gallery Place	MB1	0.50	0.66	0.75
Union Station	MB2	0.44	0.54	0.56
New York Ave.	MB3	0.26	0.22	0.27
Rhode Island Avenue	MB4	0.79	0.71	0.76
Brookland Avenue	MB5	0.67	0.61	0.59
New Hampshire Avenue	MB6	0.47	0.54	0.67
Takoma Park	MB7	0.61	0.78	0.96
Silver Spring	MB8[y]	0.31	0.53	0.46
COINCIDENT RED		4.68	5.17	5.90
		KWHPCM[z]		
Farragut North	MA1	0.17	0.17	
Silver Spring	MB8	0.10	0.23	

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[x] Includes on-board auxiliary during turnaround.

[y] Includes on-board auxiliaries during turnaround.

[z] During turnaround.

APPENDIX B

APPLICATION OF EMM TO PATCO

B.1 GENERAL

The PATCO Lindenwold transit line operates from 16th Street Center City, Philadelphia to Lindenwold, New Jersey, a distance of 14.4 miles. Figure B-1 shows a map of the system and station locations imposed on it.

B.2 SYSTEM OPERATING CHARACTERISTICS

The PATCO Lindenwold transit line was the first automated transit system in revenue operation in the United States.

The maximum speed on the system is 75 mph, and a terminal-to-terminal run time of 25 min. Severe speed restrictions occur between 8th Street and Broadway Stations because of the sharp curves in the alignment. The timetable that was in effect during September 1981 was used for analysis. Passenger load factors between stations were developed using information supplied by transit officials (Port Authority Transit Corp.), namely:

1. Passenger statistics reports showing entry-exits for a typical month,
2. Westbound/eastbound traffic check during peak periods for one typical day showing persons per car in each train passing the maximum load point (City Hall Station),
3. Twenty-four hour composite traffic check for a typical weekday.

For the sake of simplicity, it was assumed, while calculating load factors, that all people entering in uptown are exiting in downtown only, and vice versa. A vehicle containing 145 passengers (each weighing 160 lb) was taken as a basis for 100 percent passenger load factor. Graphs of the passenger load factors during the peak periods are also shown in Figure B-2 through Figure B-5. There was no information for the dwell time at each station, and it was taken as 20 sec at each station, for convenience. The milepost location and the dwell times of the various trains at each station are given in Table B-1.

The timetable that was in effect from September 1981 was taken for EMM study purpose. The weekdays are divided into five operating periods given as follows:

12:01 AM to 6:30 AM
6:30 AM to 9:30 AM
9:30 AM to 3:30 PM
3:30 PM to 6:30 PM
6:30 PM to 12:00 AM

In this analysis only peak periods, AM peak (6:30 AM to 9:30 AM), and PM peak (3:30 PM to 6:30 PM), were simulated. The PATCO peak operation consisted of running the following three kinds of six-car trains with the given headway:

TRAIN TYPE	CHARACTERISTICS	HEADWAY
Normal	Stopping at each and every station.	3-7 min
Express	Does not stop at Haddonfield, Westmont, and Collingwood.	7-8 min
Woodcrest Local	Terminates or originates at Woodcrest.	7-8 min

Express trains run only in the westbound direction in the AM peak and the eastbound direction in the PM peak.

B.3 VEHICLE CHARACTERISTICS

B.3.1 Physical Characteristics

Table B-2 summarizes the vehicle characteristics that were used for the simulation. Although the vehicles are of two different types, namely a single car with an empty weight of 39.7 tons and a married pair of A and B cars, each with an empty weight of 37.45 tons, an average weight of 38.4 tons was used for the empty car. The full weight of the car with 145 passengers, each weighing 160 lb, was taken as 50.0 tons.

The average auxiliary power used on each car during revenue operation was given as 40 kW.

B.3.2 Propulsion Characteristics

Table B-3 shows the propulsion characteristics for the PATCO vehicle that is self-propelled with all axles powered. The power conditioning and control subsystem is presently cam control resistor switching. The motor control philosophy using cam control resistor switching is similar to the WMATA car described in Appendix A. Figure B-6 shows the tractive effort speed curve at each of the motor circuit modes. This curve is used for the simulation.

Figure B-7 shows the propulsion system efficiency as a function of speed and tractive effort. These efficiency curves were calculated from the propulsion system model used for a retrogressive cam-control system with transition. The change in slope of the efficiency curve between 10 and 20 mph is caused by the transition from the four series to two series/two parallel motor configuration. The low efficiency obtained at low tractive effort

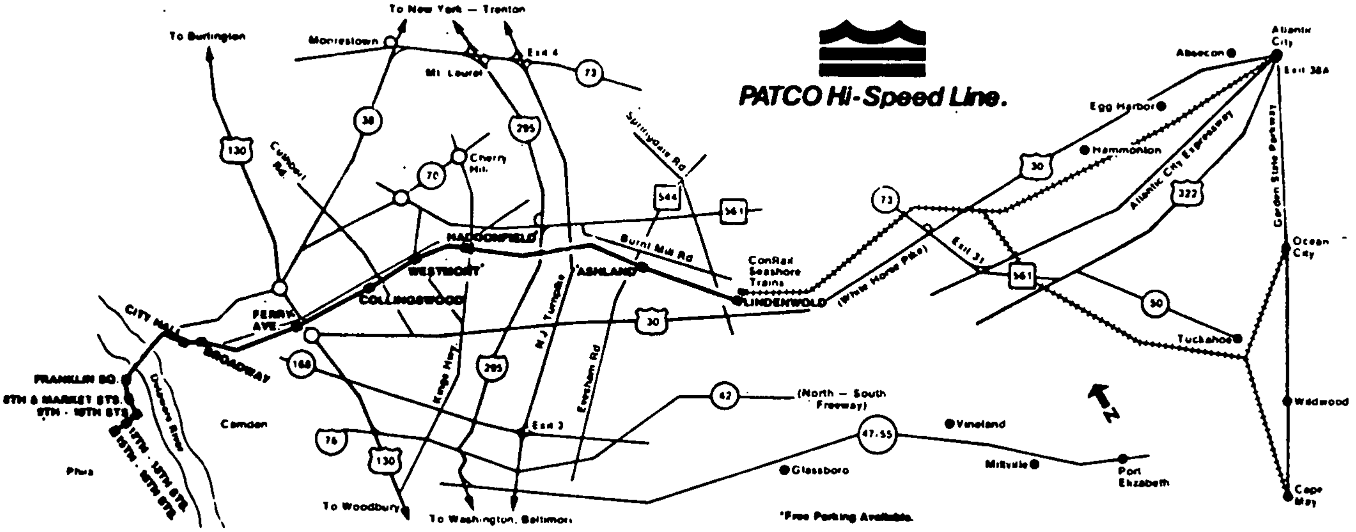


Figure B-1. PATCO Hi-Speed Line.

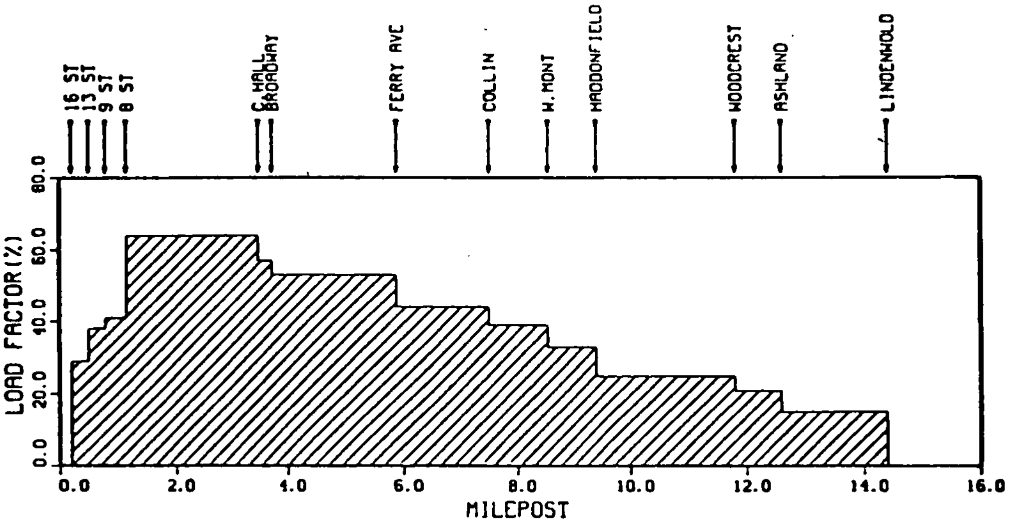


Figure B-2. Passenger load factor—PATCO (AM peak) Lindenwold to Philadelphia.

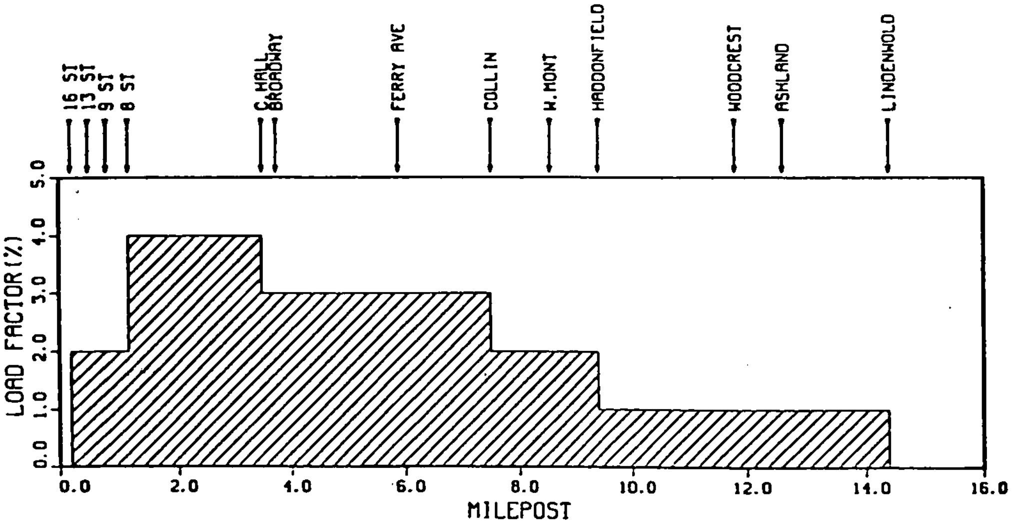


Figure B-3. Passenger load factor—PATCO (AM peak) Philadelphia to Lindenwold.

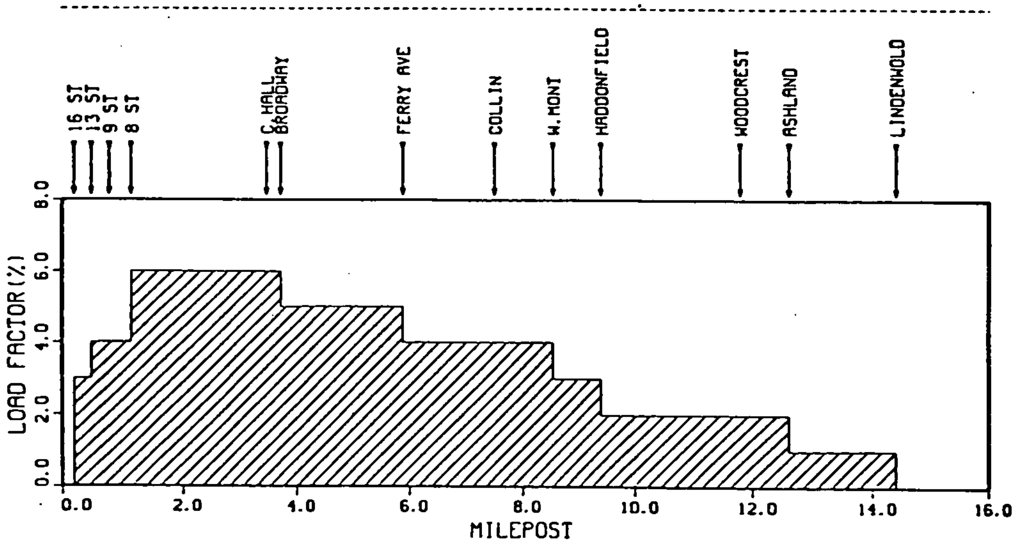


Figure B-4. Passenger load factor—PATCO (PM peak) Lindenwold to Philadelphia.

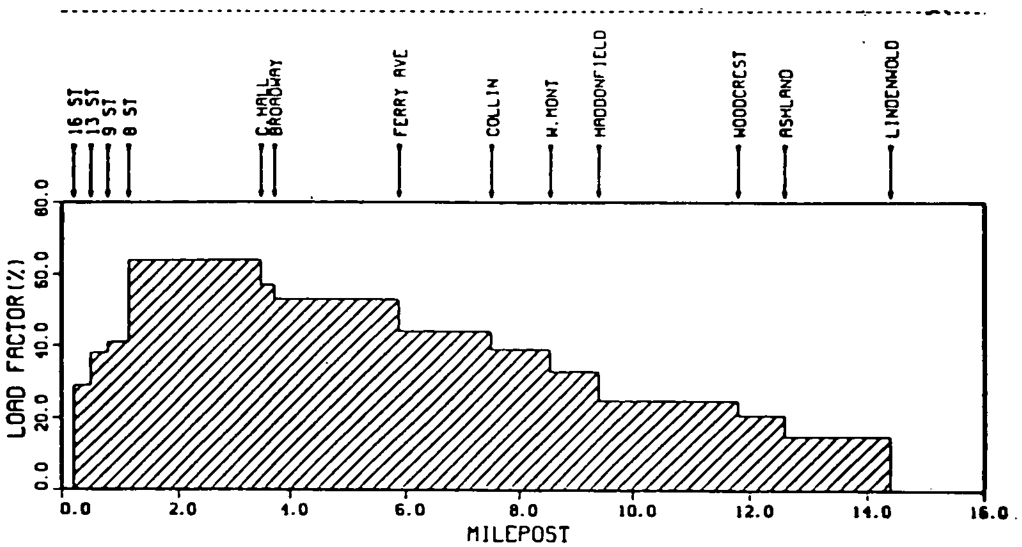


Figure B-5. Passenger load factor—PATCO (PM peak) Philadelphia to Lindenwold.

and high speed arises because of the insertion of resistance into the circuit caused by the retrogressive action of the cam control.

Because of the inefficiency that would be experienced using cam-control resistor switching for regeneration, a hypothetical chopper control (same as that for WMATA) was modeled. Figure B-8 shows the tractive effort speed curve for this model. Efficiency curves using the model were calculated and are shown in Figure B-9.

The motor control philosophy with chopper control is the same as that of cam control. As the speed increased, the chopper increases the voltage applied to the motor circuit. When the voltage to the motor circuit reaches line voltage, the motor field strength is weakened by field shunting steps until 33 percent field strength is obtained. As speed further increases, the tractive effort will follow the 33 percent field strength motor curve.

Figure B-10 shows the electrical braking effort-speed characteristics used for regeneration with chopper control. In regeneration, the motors are permanently connected in a two series/two parallel circuit. Figure B-11 shows the efficiency in regenerative electrical braking as a function of braking effort and speed.

B.3.3 Braking Characteristics

The brake rate has been set at 3.0 mph per sec. The braking is achieved using friction and electric brake.

B.4 RIGHT-OF-WAY CHARACTERISTICS

The PATCO rail line is a two-track system. The east and

Table B-1. Station locations and dwell times for PATCO-Lindenwold Line.

STATION	MILEPOST	DWELL TIMES (In Seconds)
16th Street	0.19	00.
13th Street	0.47	20.
9th Street	0.76	20.
8th & Market	1.12	20.
City Hall	3.47	20.
Broadway	3.72	20.
Ferry Avenue	5.88	20.
Collingwood	7.49	20.
Westmont	8.54	20.
Haddonfield	9.41	20.
Woodcrest	11.8	20.
Ashland	12.60	20.
Lindenwold	14.39	00.

Table B-2. PATCO vehicle characteristics.

Vehicle Empty Weight (tons)	38.4
Vehicle Full Weight (tons)	50.0
Vehicle Length (ft.)	68.0
Cross Sectional Area (sq. ft.)	125.0
Number of Axles (all powered)	4
Auxiliary Power Requirements (kW)	40.

Table B-3. PATCO propulsion characteristics.

Motors per Vehicle	4
Motor Characteristics	(GE) type 1255 A1
Power Conditioner	Cam Control
Maximum Accelerating Rate	3.0 MPHPS
Wheel Diameter	28 in.
Gear Ratio	4.79
Maximum Speed	75 MPH

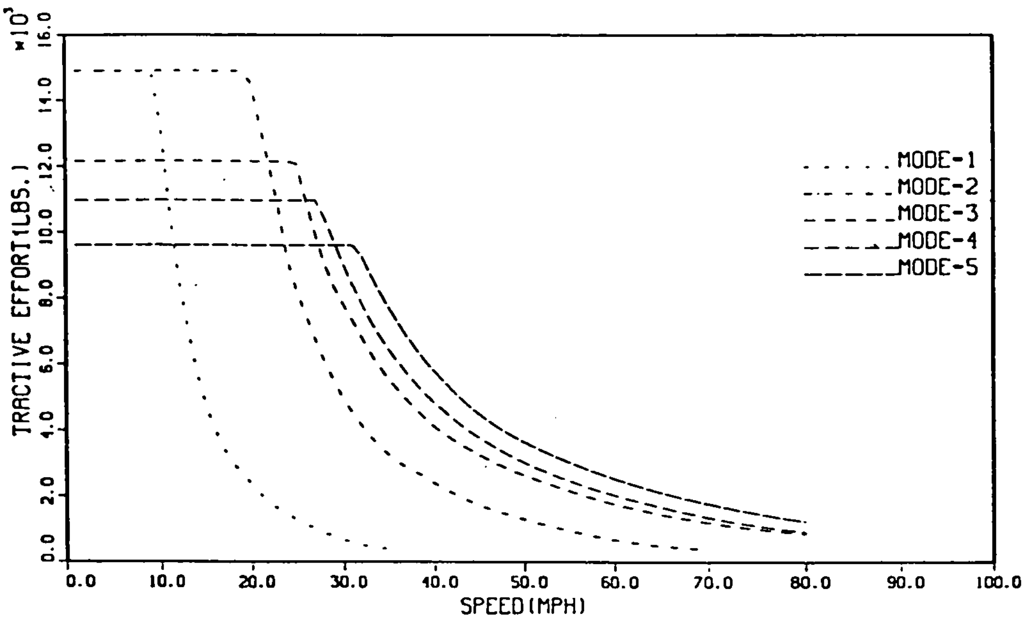


Figure B-6. Tractive effort-speed curve—PATCO car, cam control.

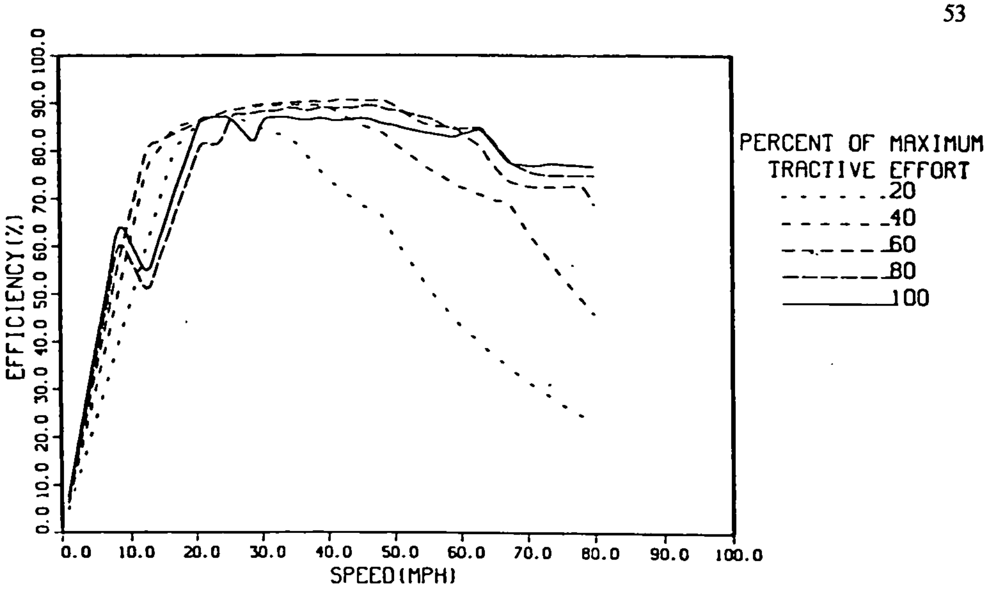


Figure B-7. Propulsion system efficiency—PATCO car, retrogressive cam control.

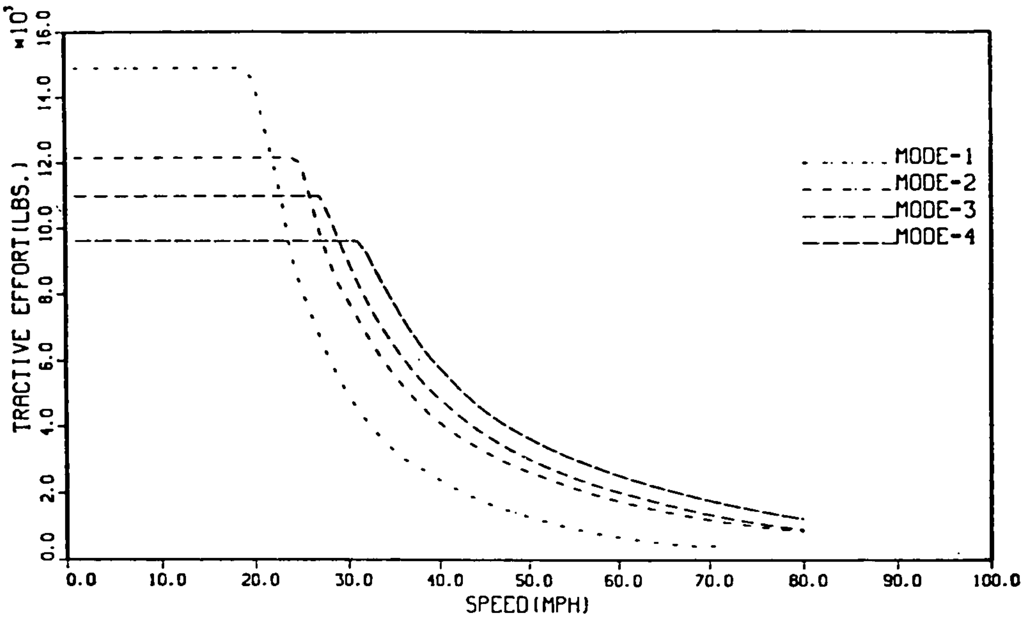


Figure B-8. Tractive effort-speed curve—PATCO car, chopper control.

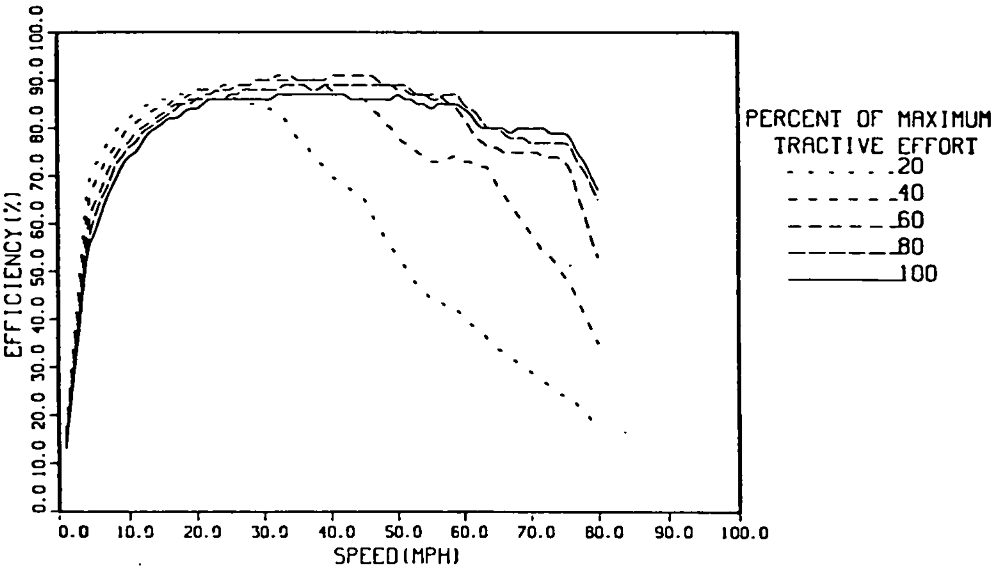


Figure B-9. Propulsion system efficiency—PATCO car, chopper control.

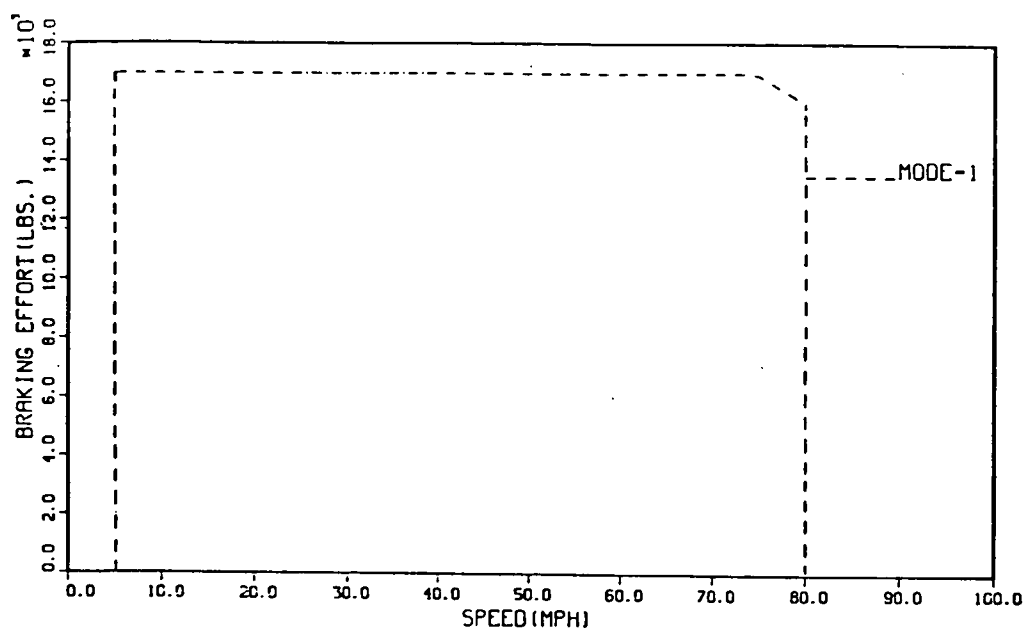


Figure B-10. Braking effort-speed curve—PATCO car, chopper control, regenerative braking.

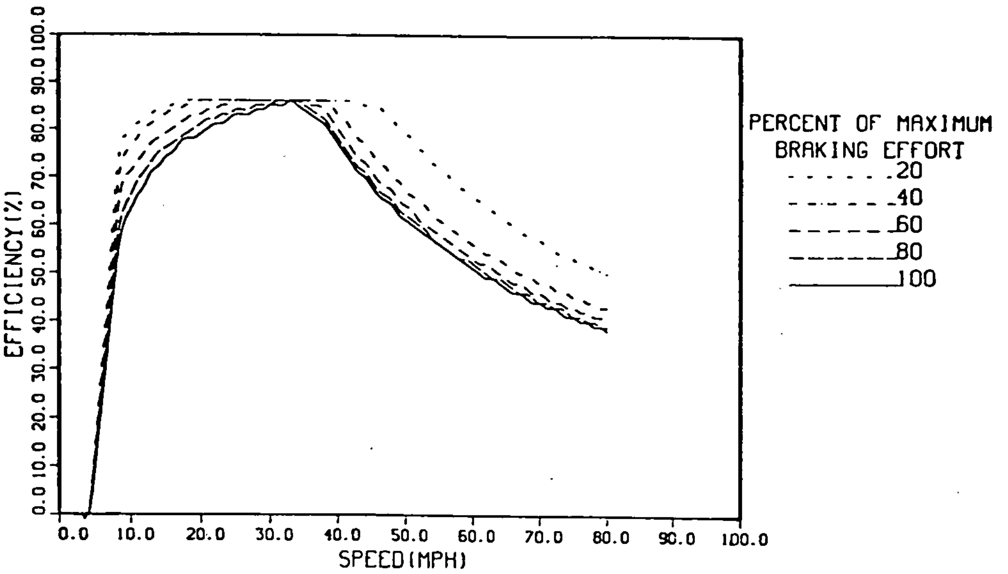


Figure B-11. Propulsion braking efficiency—PATCO car, chopper control, regenerative braking.

west elevation profiles are shown in Figures B-12 and B-13. Maximum grades are 5 percent, and they occur mostly in sections from the underground portion in Philadelphia and Camden, New Jersey, to the approaches of the Benjamin Franklin Bridge over the Delaware River.

Maximum speed on the system is 75 mph. The speed restrictions and profile (as simulated by TPS) for an empty six-car PATCO train are shown in Figures B-14 and B-15 for eastbound and westbound directions.

B.5 POWER DISTRIBUTION SYSTEM

B.5.1 Network Description

A diagram of the PATCO electrical network used in this study is shown in Figure B-16. The nominal DC distribution voltage on the third rail is 700 volts. The high-voltage three-phase AC power is purchased from three utilities at high voltage, three-phase AC. The metering points are:

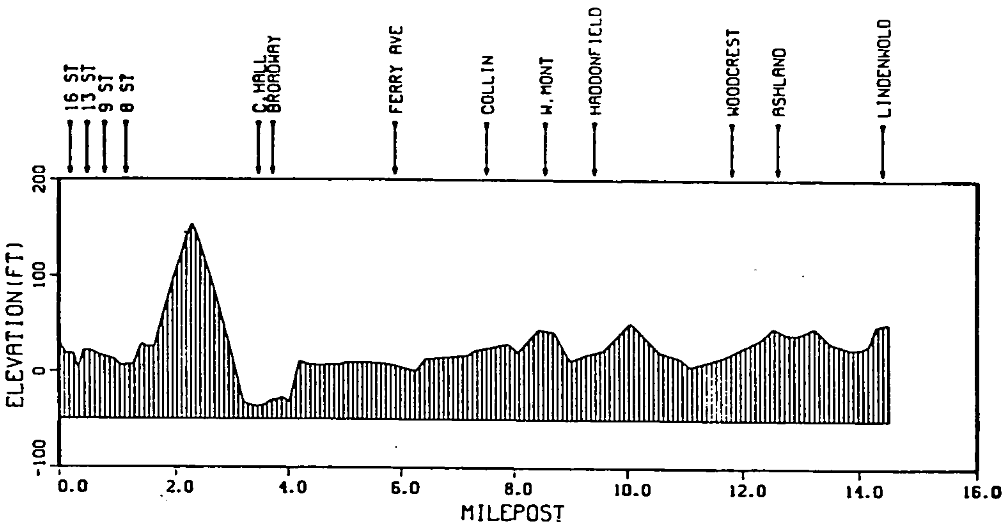


Figure B-12. Elevation profile—PATCO car, eastbound.

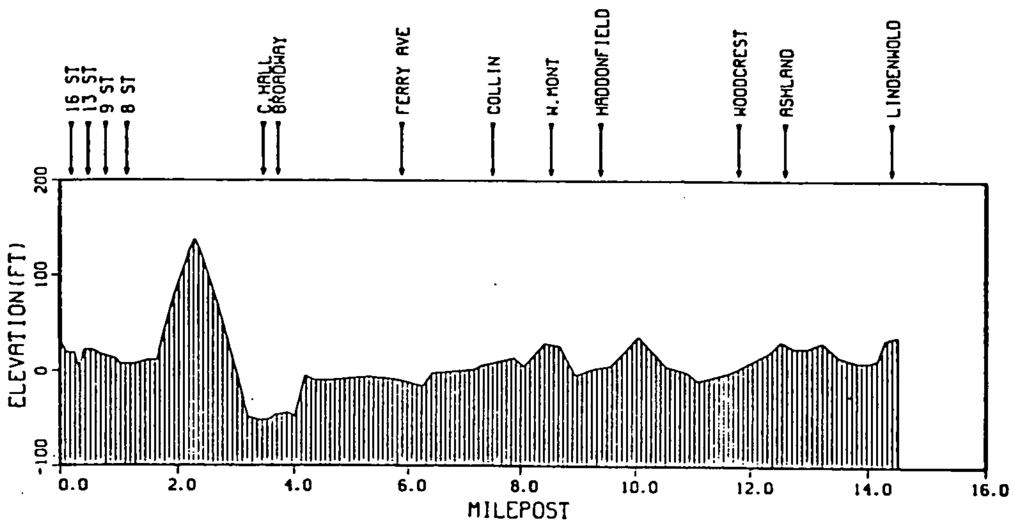


Figure B-13. Elevation profile—PATCO car, westbound.

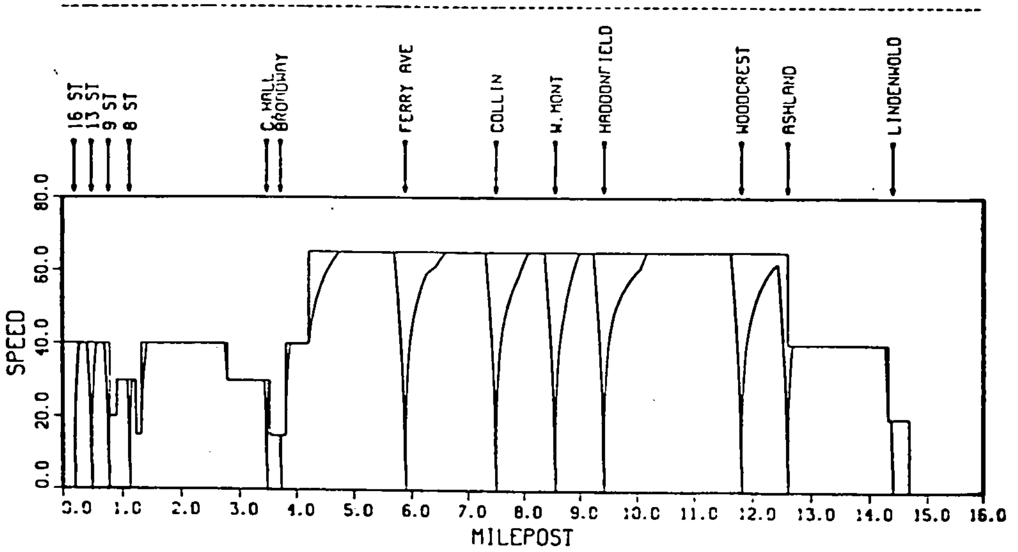


Figure B-14. Speed profile and restrictions—PATCO 6-car empty train, eastbound.

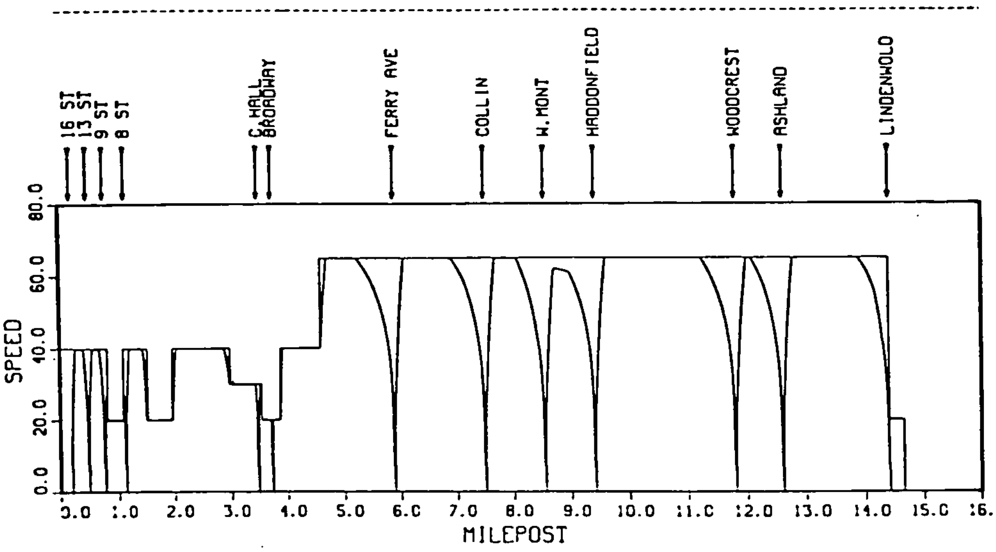
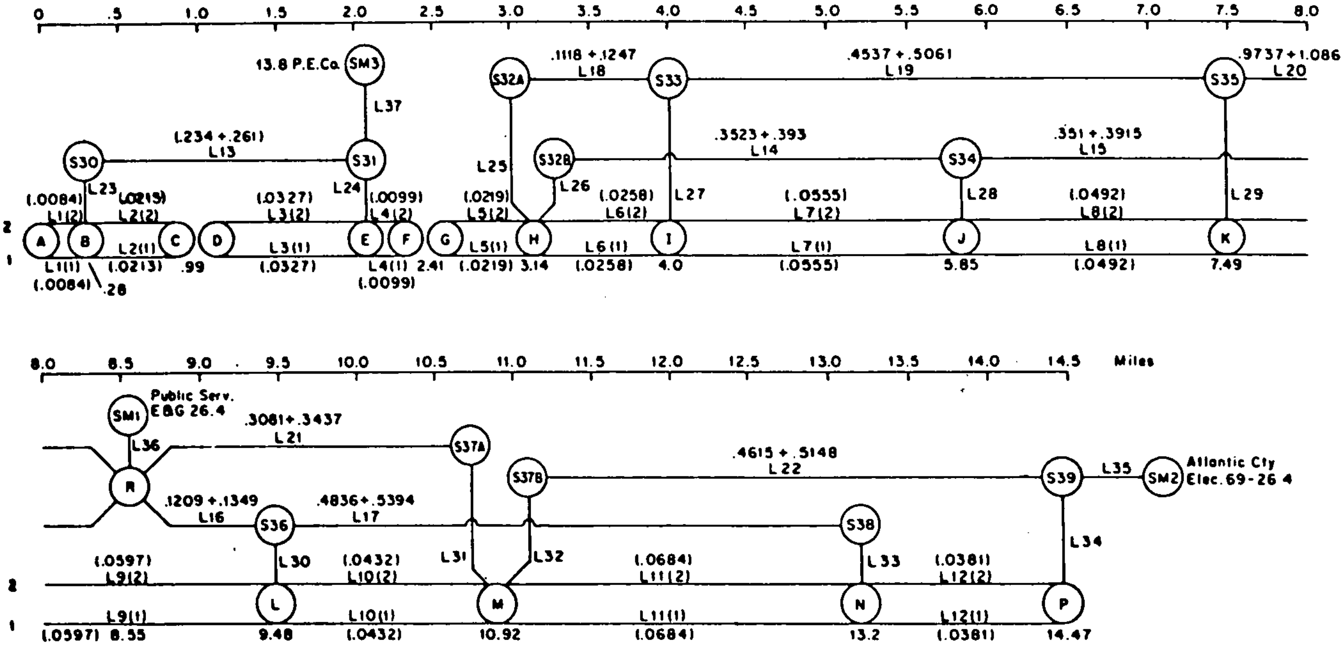


Figure B-15. Speed profile and restrictions—PATCO 6-car empty train, westbound.



( ) = per unit impedances

Figure B-16. Diagram of PATCO electrical network used in simulator.

1. Philadelphia Electric Company (PE) at the Front Street Substation (13.8 kV).
2. Public Service Electric and Gas Company (PSE&G) at Westmont Substation (26.4 kV).
3. Atlantic City Electric Company (ACE) at Lindenwold Substation (26.4 kV).

Public Service Electric and Gas Company supplies approximately 68 percent of total power requirements of PATCO. Atlantic City Electric supplies about 17 percent and Philadelphia Electric supplies about 15 percent.

There is a DC tie to the SEPTA facilities at Locust Street in Philadelphia; however, for the purpose of this study, the tie brakers are assumed to be open. On the nodal diagram of Figure B-16, the metering points described above are shown by SM3, SM1, and SM2 in respective order.

B.5.2 Substation Description

There are ten rectifier substations in the distribution system designated by (S30-S39) in the nodal diagram with two 1500-kW rectifiers in each station which feed the third rail.

B.5.3 Line Impedance

The effective rail/running rail impedance between substaions and the complex impedances used on the AC side in the network are shown in the nodal diagram of Figure B-16. The impedances are on a per unit base of 3 MVA.

B.6 POWER RATE STRUCTURE

PATCO's total electrical power costs are paid monthly on seven separate bills from three separate suppliers. All three suppliers charge their fuel adjustment rates only once per year; Public Service Electric and Gas Company in July and Philadelphia Electric and Atlantic City Electric Company in January. The rate structure of Public Service Electric and Gas Company, serving PATCO, is given in Table B-4. The rate structures are different for traction and nontraction power. PSE&G meters demand at 15 min; however, maximum monthly demand is calculated on 60-min intervals. Consolidation for demand purposes is noncoincident. Billing demand is the average of four greatest maximum demand on separate days, or 75 percent of the maximum demand in the present month, whichever is greatest.

The rate structure for Atlantic City Electric Company is given in Table B-5. All electricity, both traction and nontraction, is billed at the same rate under this late schedule. The demand interval is 15 min, and consolidation for demand purposes is coincident. Billing demand is maximum demand for present month. However, PATCO is allowed 100 kWh of energy for each kW of monthly billing demand so billed.

The rate structure for the Philadelphia Electric Company (SEPTA) is given in Table B-6. The demand interval is 30 min, and consolidation is noncoincident. Billing demand is maximum demand in present month, adjusted for power factor. One portion of this bill is for traction power on the Main Line in Philadelphia, and another portion of this bill is for station operation in Philadelphia. Traction power energy is separate on this bill.

B.7 SIMULATION FOR 1981 OPERATION

B.7.1 TPS Runs for Normal Operation

Train performance simulations were conducted for weekday AM and PM peak periods using 1981 time tables, measured passenger load factors, and estimated average dwell times. The results for schedule time and energy consumption are given in Table B-7. The variation in energy in a fixed direction of travel is due to variation in passenger load factor, but this is relatively a small variation.

Figures B-17 and B-18 show the power profiles for an empty six-car PATCO train running in eastbound and westbound directions.

B.7.2 ENS for Normal Operation

Using the electric network for the PATCO line and the 1981 operational timetable (effective from September 1981), normal operation was simulated using the ENS for the following time periods on a weekday:

SIMULATION TIME	TO REPRESENT
7:45–8:00A	AM peak
5:30–5:45P	PM peak

Table B-8 presents the results of the ENS. These results do not include the background and the effect of turnaround time at the terminals.

B.8 ENERGY SAVINGS BY PERFORMANCE REDUCTION

Two performance reduction strategies were considered in the PATCO system, namely:

1. Top-speed reduction.
2. Coasting.

In this study, the strategies are only tested during the peak hours so that a net increase in schedule time occurs while dwell times are held constant.

Top-speed reduction is one of the easiest strategies to be implemented, and has been extensively studied by the transit industry. The top speed of the train is reduced from maximum allowable speed (75 mph) to some lower value that cannot be exceeded under normal circumstances.

Coasting is applied by modifying the braking effort so that all braking beyond a certain speed results from train resistance only. Under this, to coast beyond this speed means modification of the total braking effort so that there is no applied effort from the brakes beyond the coasting speed and normal applied effort below the coasting speed. As a consequence, the total braking effort depends only on train resistance beyond the coasting speed.

Figure B-19 shows a plot of percent traction energy decrease as a function of percent schedule time increase on the PATCO line for top-speed reduction and coasting strategies.

B.8.1 Top-Speed Reduction

A detailed analysis using ENS was conducted using top-speed reduction strategy by setting top speed to be 55 mph. This allows running time to be increased no more than 2 percent of the normal run time.

The detailed results of this analysis are given in Table B-9. The power savings, by reducing the top speed of the system, can be obtained by calculating KWHPCM coefficients which are the differences between the normal run and those obtained by applying top-speed reduction strategy (ΔE). The coefficient (ΔE) is given in Table B-10.

B.8.2 Coasting

A detailed analysis using ENS was conducted using coasting strategy by setting coasting speed = 55 mph. The result of this analysis is given in Table B-11. The increase in running time, using the strategy, is of the order of 2 percent.

The KWHPCM coefficients, difference between those obtained by using the coasting strategy and those of the base operation (ΔE), are given in Table B-10.

Table B-4. Public Service Electric and Gas Company rate structure.

TRACTION POWER: Effective 4/80 (High Tension Service)
Demand ($/kW): 6.05 (June-Oct.) 5.15 (Nov.-May)
Energy ($./kWh): 3.40 (On-peak) 3.20 (Intermediate peak) 2.76 (Off-peak)
Fuel Adjustment: 1.6579 $./kWh (8/1/81 through 6/30/82)

NON TRACTION POWER: Effective 4/80 (Large Power Lighting Service)

KILOWATT CHARGE IN MONTHS OF JUNE THROUGH OCTOBER:
$475.00 for the first 50 kW or less of monthy demand
$ 7.15 per kW for the next 550 kW of monthly demand
$ 5.85 per kW for the next 1,400 kW of monthly demand
$ 5.15 per kW in excess of 2,000 kW of monthly demand

KILOWATT CHARGE IN MONTHS OF NOVEMBER THROUGH MAY:
$430.00 for the first 50 kW or less of monthly demand
$ 6.25 per kW for the next 550 kW of monthly demand
$ 4.95 per kW for the next 1,400 kW of monthly demand
$ 4.25 per kW in excess of 2,000 kW of monthly demand

KILOWATT CHARGE:
$.04901 per kWh for the first 50,000 kWh used in each month
$.03901 per kWh for the next 450,000 kWh used in each month
$.03351 pe kWh in excess of 500,000 kWh used in each month
Fuel Adjustment: $.017732 per kWh[v]

BILLING DEMAND FORMULA: (HTS Service)

Interval:	15 minutes
Consolidation:	non-coincident
Monthly Demand:	Average of four greatest maximum demands on separate days or 75% of the maximum demand in present month, whichever is greatest.
Ratchet:	None

POWER FACTOR PENALTY: NO
MINIMUM CHARGE: Service charge plus kW charge.
SEASONAL AND TIME OF DAY RATES: Yes

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[v] Effective from 8/1/81 thru 6/30/82

Table B-5. Atlantic City Electric Company rate structure.

Demand ($/kW):	6196.19 for first 1000 kW of monthly demand, 6.14/kW in excess of 1000 kW.
Energy ($./kWh):	In excess of 100 kW hours for each kW of monthly demand billed, $.047/kWh.
Fuel Adjustment:	$.024582/kWh

Table B-6. Philadelphia Electric Company rate structure.

	TRACTION POWER	NON TRACTION POWER
Effective	4/81	
Demand($/kW)	2.82 (capacity)	
Energy($./kWh)	5.86 for the first 150 kWh 4.83 for the next 150, but more than 7.5 million kWh 3.79 for additional use	

Special Facility: HIGH VOLTAGE DISCOUNT. For customer supplied at 33,000 volts, $.05/kW. For customer supplied at 66,000 volts or higher, $.20/kW for first 10,000 volts of measured demand.

Table B-7. Summary of simulated running time and energy consumption for 1981 normal operation.

	ENERGY CONSUMPTION (KWHPCM)	RUNNING TIME (Minutes)
AM PEAK		
Normal-Eastbound	6.13	25.4
Normal-Westbound	6.58	25.1
Express Train-Eastbound	5.16	23.2
Express Train-Westbound	5.56	22.8
Woodcrest Local-Eastbound	6.23	20.9
Woodcrest Local-Westbound	6.61	21.6
PM PEAK		
Special Train-Eastbound	6.08	24.4
Normal-Eastbound	6.49	25.6
Normal-Westbound	6.30	24.9
Express Train-Eastbound	5.42	23.3
Express Special-Eastbound	5.32	22.8
Woodcrest Local-Eastbound	6.61	20.8
Woodcrest Local-Westbound	6.31	21.1

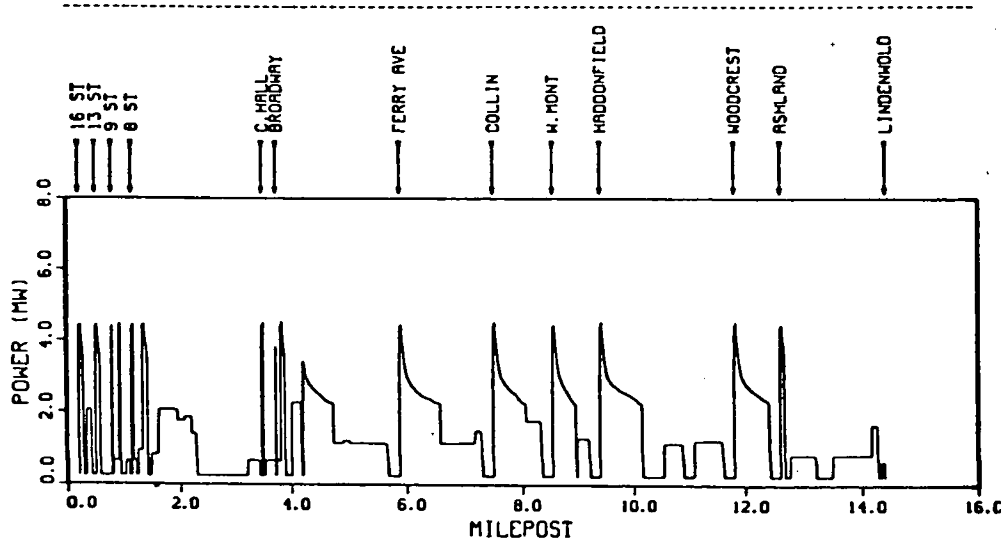

Figure B-17. Power profile—PATCO 6-car empty train, eastbound.

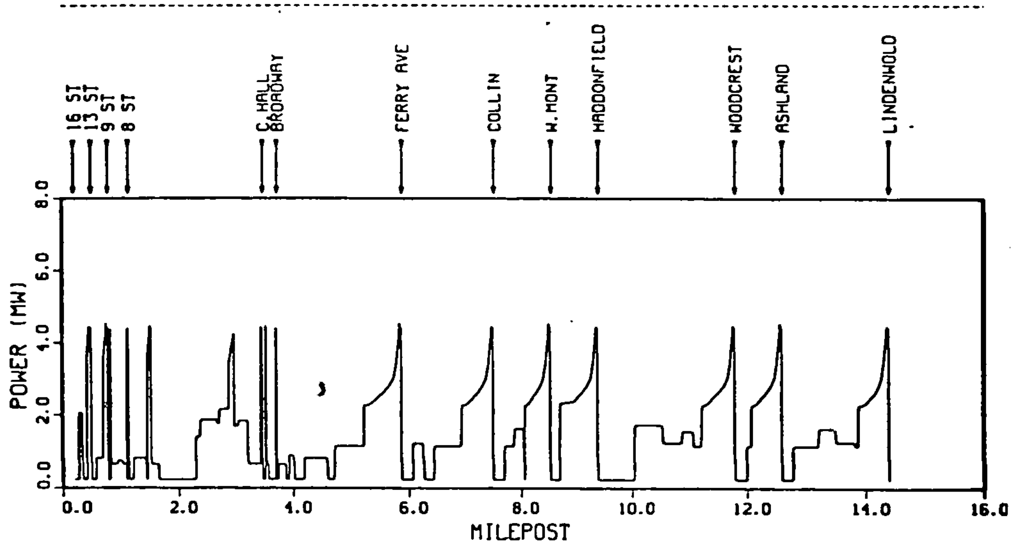

Figure B-18. Power profile—PATCO 6-car empty train, westbound.

Table B-8. Results of ENS for normal operation during 1981.

		POWER (kW)[1]	
METER NAME	SYMBOL	AM PEAK	PM PEAK
Philadelphia Electric Co.	SM3	4030	3992
Public Service Electric & Gas Co.	SM1	10354	10676
Atlantic City Electric Co.	SM2	2351	2488
CAR MILES		2392	2436
KWHPCM		7.00	7.04
KWHPCM (Peak Average)		7.02	

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[1] Does not include on-board auxiliary power during turnaround.

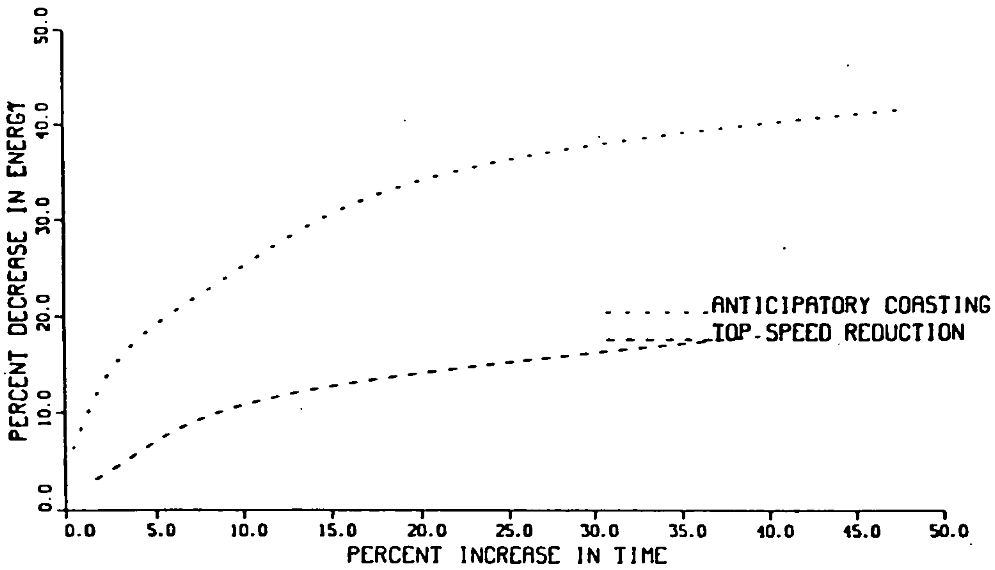


Figure B-19. Performance modification strategy—PATCO Lindenwold Line.

Table B-10. Demand savings using different strategies for peak periods.

STRATEGY	(ΔE) KWHPCM SAVINGS COEFFICIENT	CAR-MILES PER HR*	KW SAVINGS
TOP SPEED REDUCTION	0.58	2415	1401
COASTING	0.87	2415	2101
REGENERATION NATURAL RECEPTIVITY	2.19	2415	5289

*Annual car-miles 4,406,393; information provided by PATCO.

Table B-9. Results of the ENS for top speed of 55 mph during 1981.

		POWER (kW)[aa]	
METER NAME	SYMBOL	AM PEAK	PM PEAK
Philadelphia Electric Co.	SM3	4100	3824
Public Service Electric & Gas Co.	SM1	9385	9351
Atlantic City Electric Co.	SM2	2083	2143
CAR MILES		2396	2400
KWHPCM		6.49	6.38
KWHPCM (Peak Average)		6.44	
Energy Savings (ΔE) KWHPCM		0.58	

[aa] Does not include on-board auxiliary power during turnaround.

Table B-11. Results of the ENS for coasting above 55 mph during 1981.

		POWER (kW)[bb]	
METER NAME	SYMBOL	AM PEAK	PM PEAK
Philadelphia Electric Co.	SM3	4039	3893
Public Service Electric & Gas Co.	SM1	8728	8881
Atlantic City Electric Co.	SM2	1999	2089
CAR MILES		2392	2424
KWHPCM		6.17	6.13
KWHPCM (Peak Average)		6.15	
Energy Savings (ΔE) KWHPCM		0.87	

[bb] Does not include on-board auxiliary power during turnaround.

B.9 ENERGY SAVINGS BY REGENERATION

Regeneration was applied on the PATCO system using hypothetical chopper configuration as described in Section B-3. The strategy was regeneration with natural receptivity in which all of the cars that made up the trains were chopper cars, and the only receptors of the regenerated brake energy were other trains on the line.

Regeneration with natural receptivity was simulated using the EMM. Regeneration would be maintained up to line voltage of 700 volts. At this maximum line voltage, the excess electrical braking power which can not be accepted by the line is channeled into resistors aboard the car. Table B-12 shows the result of the ENS for regeneration with natural receptivity.

The difference between those KWHPCM coefficients obtained by using the regeneration with natural receptivity and those of the base operation is given in Table B-10.

Table B-12. Results of the ENS for regeneration with natural receptivity.

		POWER (kW)	
METER	SYMBOL	AM PEAK	PM PEAK
Philadelphia Electric Co.	SM3	2843	2574
Public Service Electric & Gas Co.	SM1	7259	7010
Atlantic City Electric Co.	SM2	1848	1764
CAR MILES/HOUR		2392	2436
KWHPCM		4.99	4.66
KWHPCM (Peak Average)		4.83	

APPENDIX C

APPLICATION OF EMM TO GCRTA

C.1 GENERAL

The GCRTA Shaker Heights Line is presently a PCC trolley (streetcar) system. It is powered by means of an overhead trolley and uses the running rails as part of the return circuit.

The present operation consists of Blue and Green Lines. The Blue Line extends from Union Terminal to Warrensville, a distance of 9.2 miles. The Green Line extends from Union Terminal to Green, a distance of 9.74 miles. The Blue and Green Lines share a common track from Union Terminal to Shaker Square. All of the streetcars run as a single car train with a schedule speed of 18 mph. Figure C-1 shows a diagram of the system layout.

C.2 SYSTEM OPERATING CHARACTERISTICS

The present trolleys use cam-controlled switching of resistors for traction motor control. The line is presently being upgraded to a light rail vehicle (LRV) system. These highly advanced LRVs are now being introduced into daily service between the hours of 9:00 AM to 4:00 PM. They will soon be added to rush-hour operation. These new cars feature many advancements and improvements to guarantee a more reliable, smoother and comfortable ride. Among these are electronically controlled air-conditioning and heating systems.

The maximum speed on the system is 55 mph, while the PCC car top speed is only 50 mph on level tangent track. The 1981 timetable that was in effect from December of that year was used for analysis. There were no data available on actual passenger flow rate between stations. However, an estimate was made for the passenger load factors on a pattern similar to PATCO. The maximum load point was taken at Shaker Square. Graphs of the passenger load factors during peak periods are shown in Figures C-2 through C-9 for the Blue Line as well as the Green Line. Dwell time information was provided by

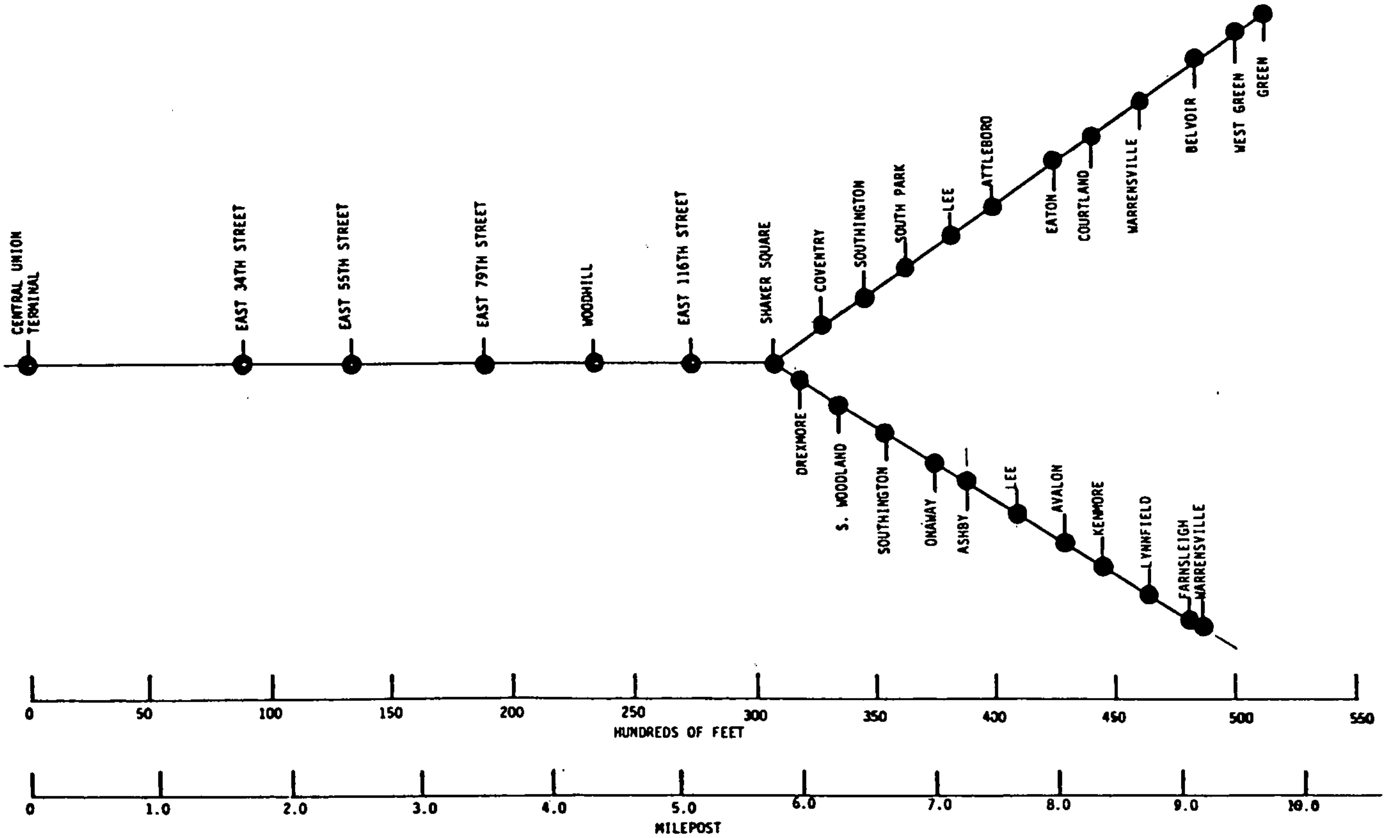


Figure C-1. RTA Blue/Green Line passenger station configurations.

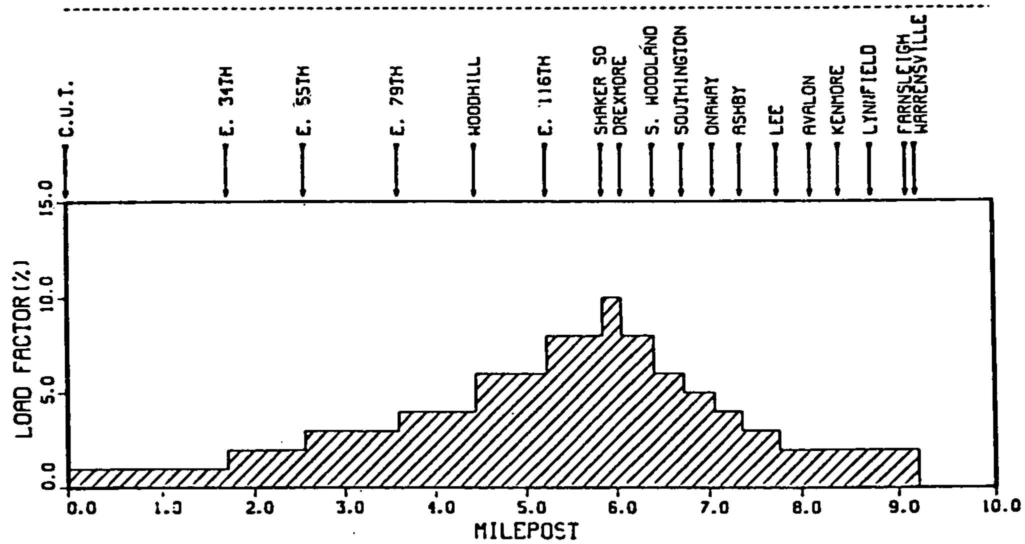


Figure C-2. Passenger load factor—Blue Line (AM peak) Union Terminal to Warrensville.

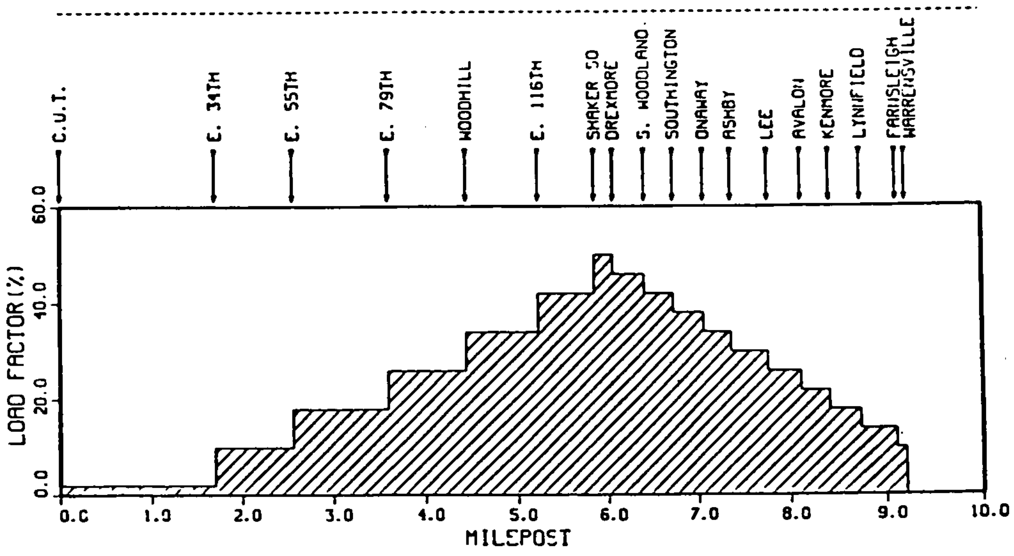


Figure C-3. Passenger load factor—Blue Line (AM peak) Warrensville to Union Terminal.

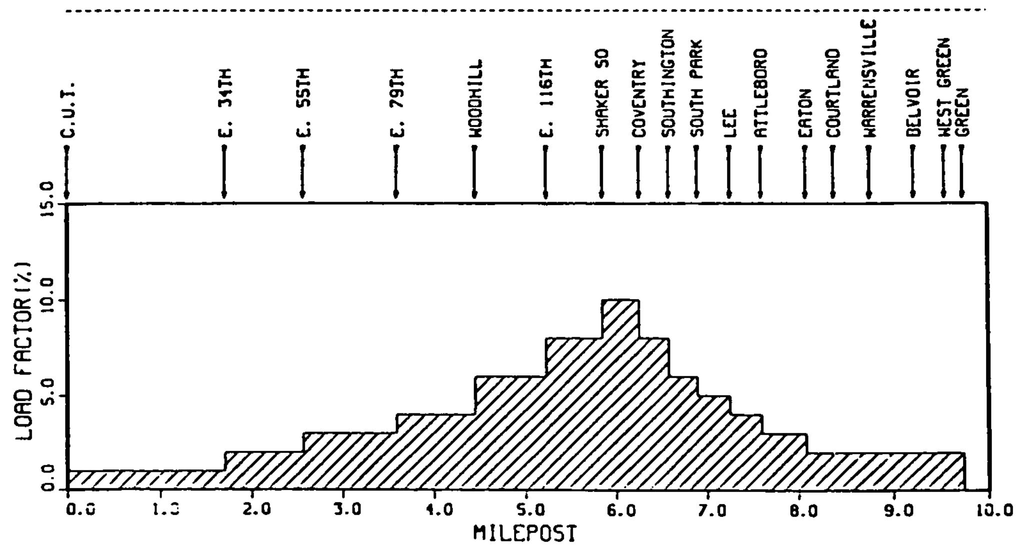


Figure C-4. Passenger load factor—Green Line (AM peak) Union Terminal to Green.

GCRTA. The station location and the dwell times are given in Tables C-1 and C-2 for the Blue and Green Lines, respectively. In peak operations, the PCC car runs with a headway of 8 min.

C.3 VEHICLE CHARACTERISTICS

C.3.1 Physical Characteristics

Table C-3 summarizes the vehicle characteristics that were used for the EMM simulation. The empty weight of the car is 18.5 tons. The full weight of the car, with 100 passengers, each weighing 150 lb, is 28 tons. The average auxiliary power used on the PCC car is 12 kW.

C.3.2 Propulsion Characteristics

Table C-4 shows the propulsion characteristics for the PCC car which uses cam control as the power conditioning unit. The motors used on the PCC car are Westinghouse type 1432. The motor circuit is either four series or two series/two parallel. Transition from one configuration to the other takes place on acceleration at about 4.9 mph at full tractive effort. The motor control proceeds as follows, using the cam control:

1. The motors are initially connected four in series with the cam control set with maximum resistance in circuit at zero speed during acceleration.
2. As the speed increases, resistance is stepped out of the

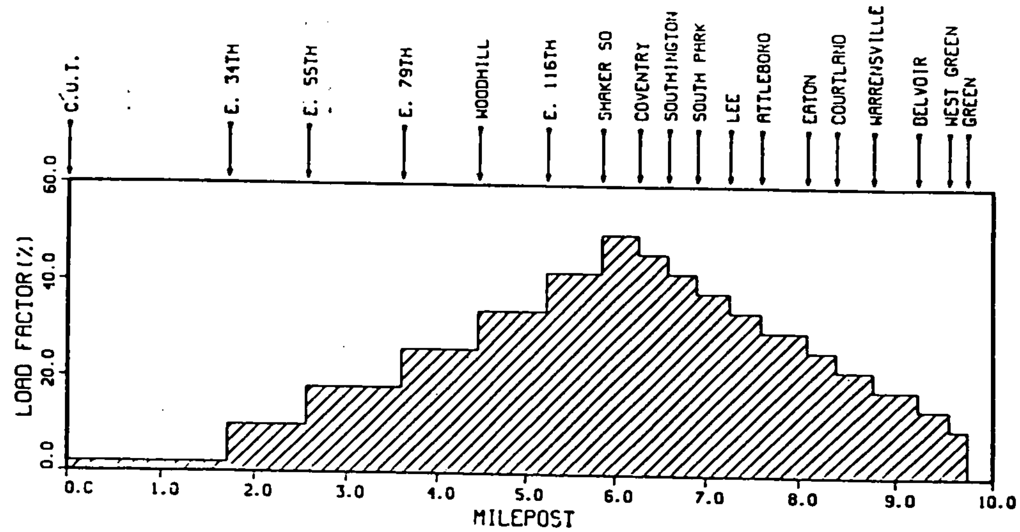


Figure C-5. Passenger load factor—Green Line (AM peak) Green to Union Terminal.

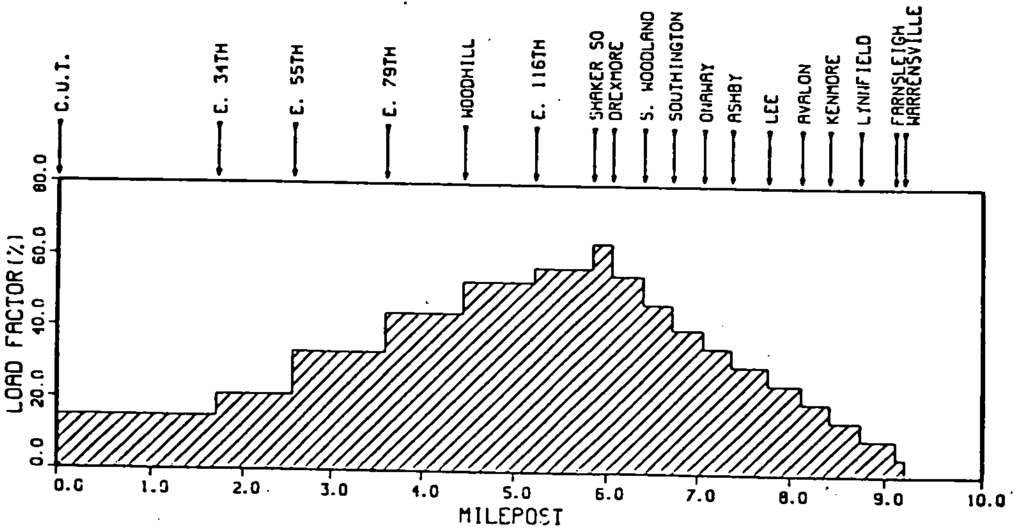


Figure C-6. Passenger load factor—Blue Line (PM peak) Union Terminal to Warrensville.

circuit by the command switches until the speed reaches the point where no resistance is in series with the motor circuit.

3. Transition occurs, and the motor circuit is switched from four-series to two series/two parallel with the cam reset to place some resistance back into the circuit in order to reduce the applied voltage to the motors to the same value it had at the end of step 2.

4. As speed further increases, the resistance is once again stepped out of the circuit until full level voltage appears across the motor circuit.

5. At this point, the motor field is weakened in steps by field shunting until 33 percent field strength is reached. Speed further increases only as the line voltage is applied to the motor circuit.

6. Running at constant speed on the profile is accomplished by working the cam control and the field shunts in such a way that the tractive effort matches the train resistance under the speed and profile conditions. Preference is given to field shunting over series resistance.

Figure C-10 shows the tractive effort speed curve at each of the motor circuit modes. This curve is used in the simulation.

Table C-1. Station locations and dwell times for the Blue Line.

STATION	MILEPOST	DWELL TIME (In Seconds)
Central Union Terminal	0.00	00.
East 34th Street	1.71	15.
East 55th Street	2.56	15.
East 79th Street	3.60	15.
Woodhill	4.45	15.
East 116th Street	5.23	15.
Shaker Square	5.85	15.
Drexmore	6.06	30.
South Woodland	6.40	15.
Southington	6.72	15.
Onaway	7.06	15.
Ashby	7.37	15.
Lee	7.77	15.
Avalon	8.13	15.
Kenmore	8.43	15.
Lynnfield	8.75	15.
Farnsleigh	9.11	15.
Warrensville	9.20	00.

Table C-2. Station locations and dwell times for the Green Line.

STATION	MILEPOST	DWELL TIME (In Seconds)
Central Union Terminal	0.00	00.
East 34th Street	1.71	15.
East 55th Street	2.56	15.
East 79th Street	3.60	15.
Woodhill	4.45	15.
East 116th Street	5.23	15.
Shaker Square	5.85	30.
Coventry	6.25	15.
Southington	6.57	15.
South Park	6.89	15.
Lee	7.25	15.
Attleboro	7.60	15.
Eaton	8.09	15.
Courtland	8.39	15.
Warrensville	8.77	15.
Belvoir	9.22	15.
West Green	9.55	15.
Green	9.73	00.

Table C-3. Vehicle physical characteristics.

Empty Weight (tons)	18.5
Crush Load Weight (tons)	26.0
Vehicle Length (ft.)	46.4
Cross Sectional Area (sq. ft.)	84.0
Measured Flange Coefficient (lbs/ton/mph)	0.045
Number of Axles (all powered)	4.0
Average Auxiliary Power (kW)	12.0
Vehicle Air Drag Coefficient (lbs/ton/mph^2)	0.0024

Table C-4. Vehicle propulsion characteristics.

Motors per Vehicle	4
Motor Characteristics	(W) Type 1432
Control	Cam Resistor Switching
Maximum Accelerating Rate	3.5 MPHPS
Wheel Diameter	25.0 inches
Gear Ratio	7.17
Maximum Speed	50.0 MPH
Nominal Line Voltage	650.0 V
Maximum Line Voltage	800.0 V
Minimum Line Voltage	500.0 V

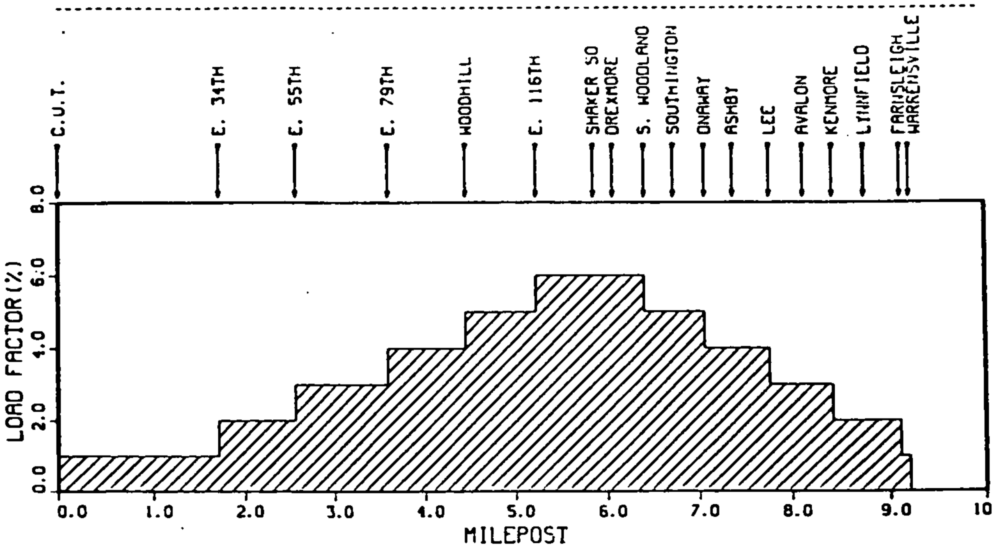


Figure C-7. Passenger load factor—Blue Line (PM peak) Warrensville to Union Terminal.

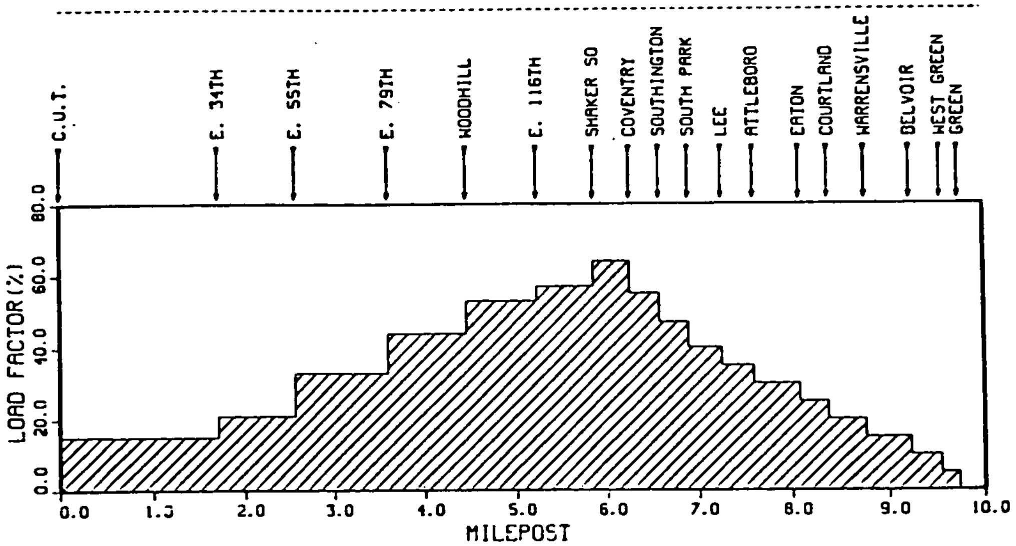


Figure C-8. Passenger load factor—Green Line (PM peak) Union Terminal to Green.

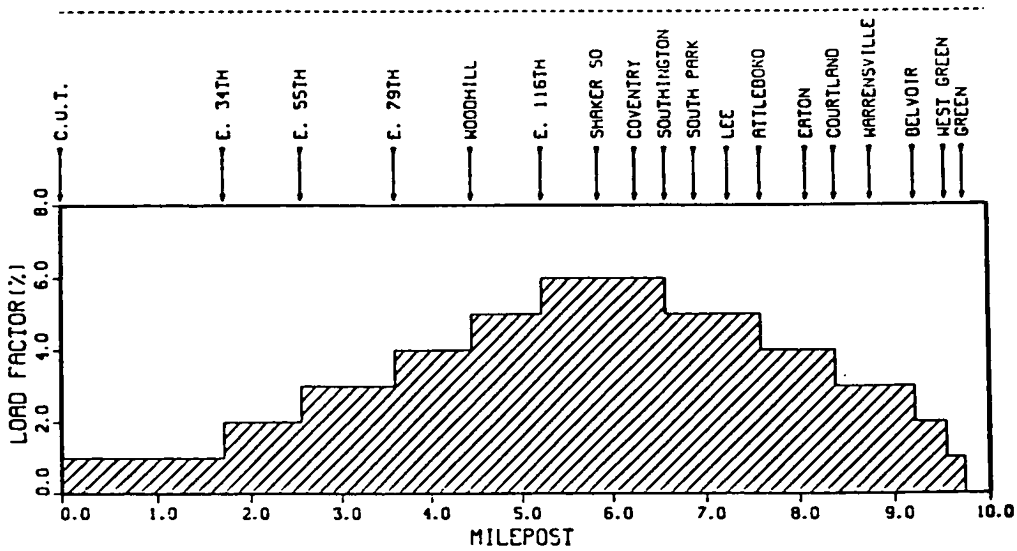


Figure C-9. Passenger load factor—Green Line (PM peak) Green to Union Terminal.

Figure C-11 shows the propulsion system efficiency as a function of speed and maximum tractive effort. Efficiency has been defined as the ratio of the power developed at wheels to input power at trolley.

The motor control philosophy with chopper control is similar to that of WMATA. The efficiency in power as a function of tractive effort and speed are shown in Figure C-12 for the PCC car with chopper control. Figure C-13 shows the tractive effort speed curve for the chopper control PCC car.

Figure C-14 shows the electrical braking effort-speed curve used for regeneration with the chopper control. The efficiency in regenerative electrical braking, plotted as a function of braking effort and speed, is shown in Figure C-15.

C.3.3 Braking Characteristics

The maximum service brake rate was fixed at 3.5 mph per sec, independent of both vehicle speed and load factor. This is accomplished by using electrical and friction brake blending.

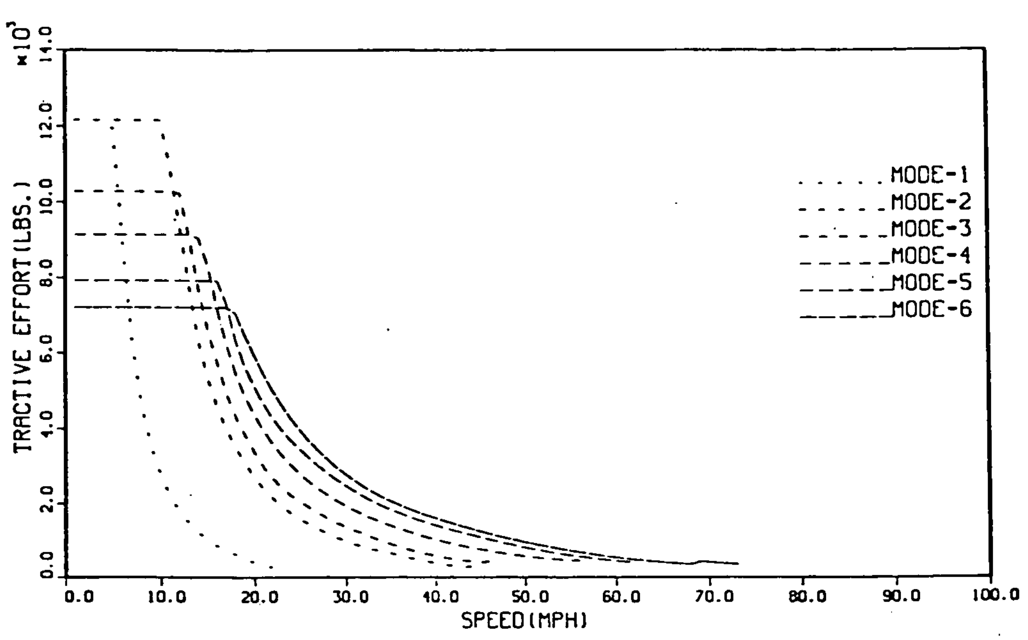


Figure C-10. Tractive effort-speed curve—RTA, PCC car.

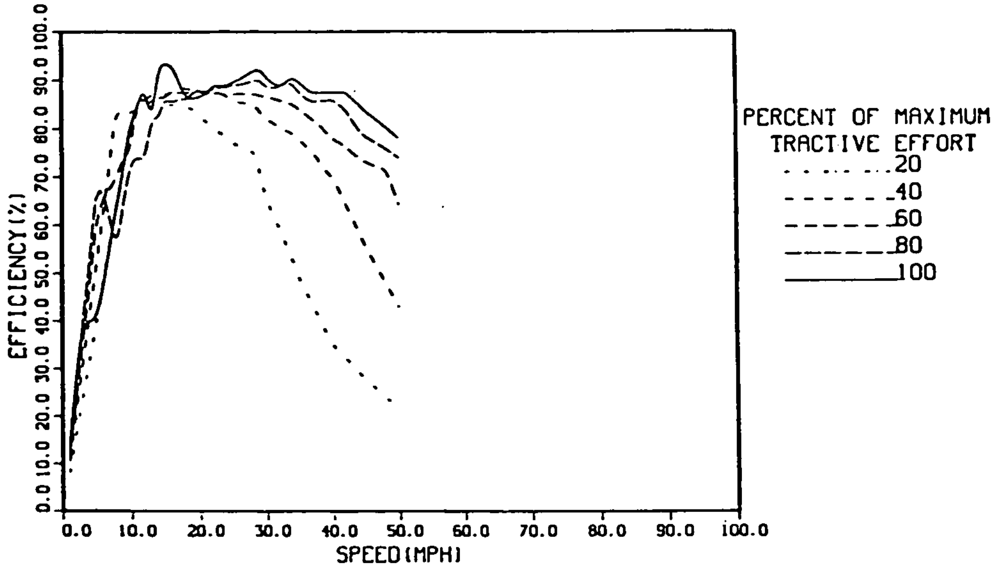


Figure C-11. Propulsion system efficiency—RTA, cam control.

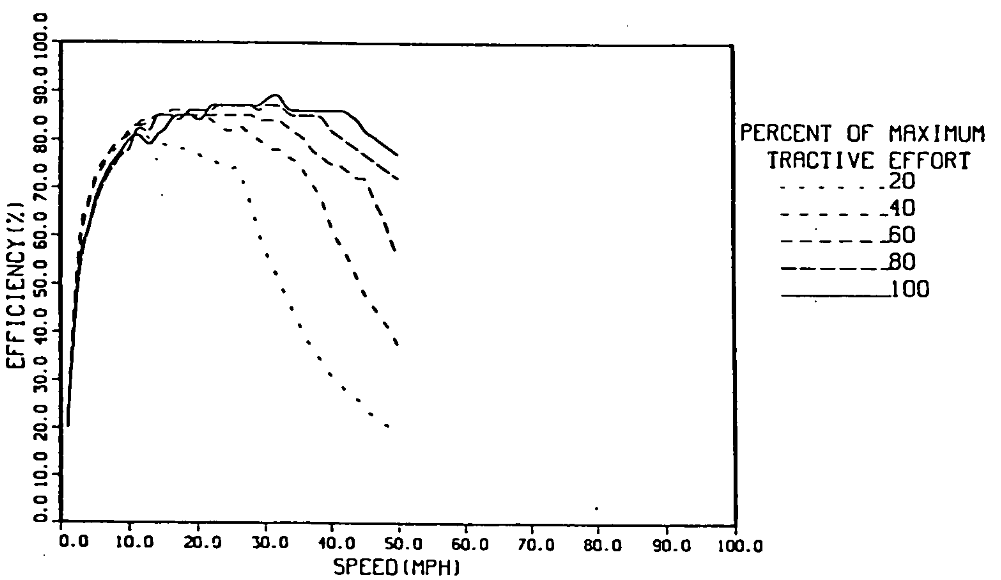


Figure C-12. Propulsion system efficiency—PCC car, chopper control.

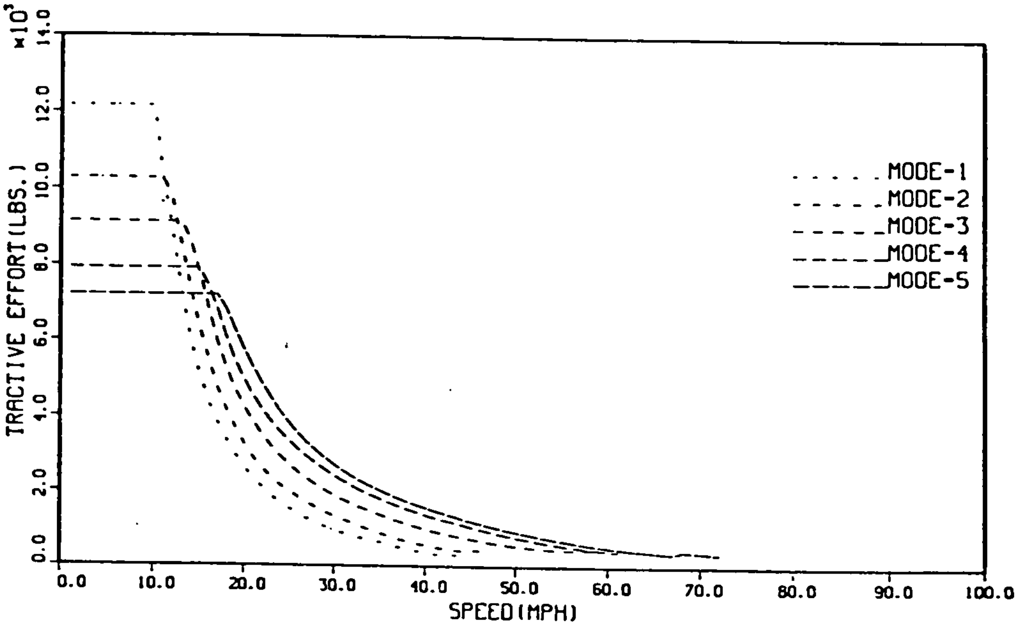


Figure C-13. Tractive effort-speed curve—PCC car, chopper control.

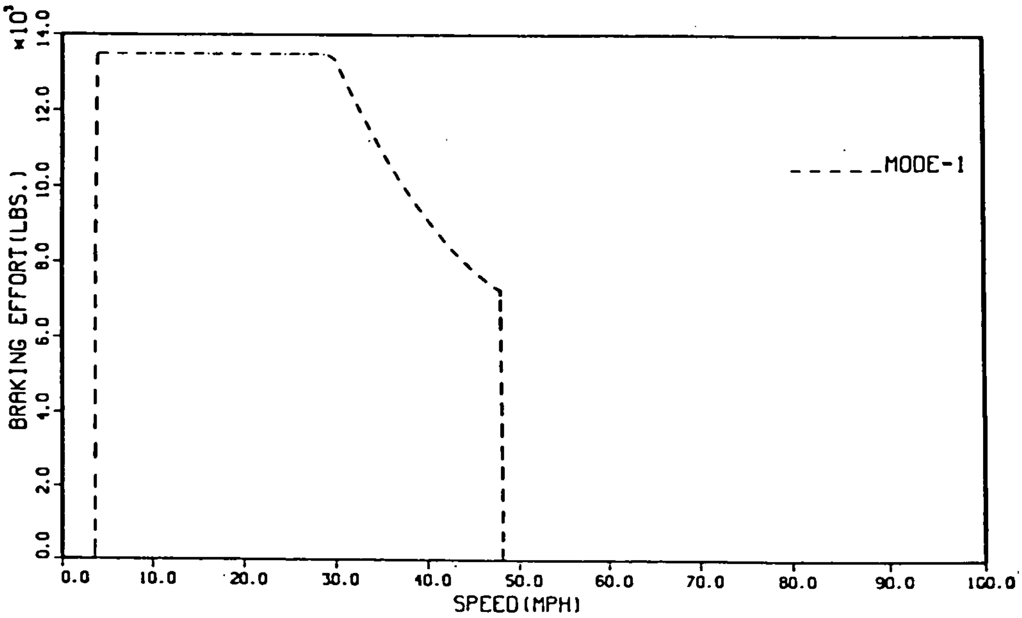


Figure C-14. Braking effort-speed curve—PCC car, chopper control, regenerative braking.

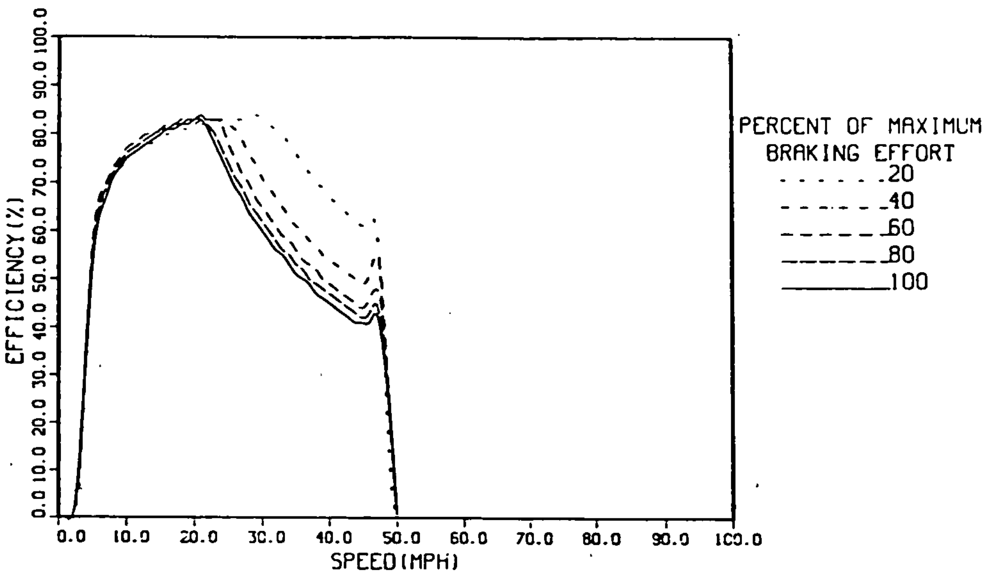


Figure C-15. Propulsion braking efficiency—PCC car, chopper control, regenerative braking.

C.4 RIGHT-OF-WAY CHARACTERISTICS

The GCRTA rail lines are mostly two-track systems. The east and west elevation profiles are shown in Figures C-16 through C-19 for the Blue and Green Lines, respectively. Both Blue and Green Lines have a large elevation change between Union Station and Shaker Square.

Maximum speed on the system is 55 mph. The speed restriction and profiles (as simulated by TPS) for an empty PCC car are shown in Figures C-20 through C-23 for eastbound and westbound directions for both the Blue and Green Lines, respectively.

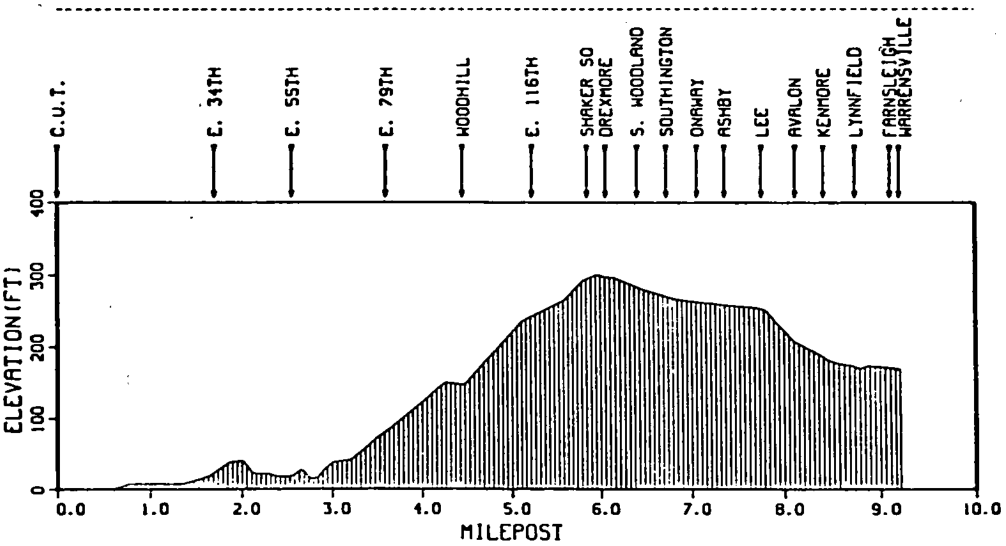


Figure C-16. Elevation profile—RTA, Blue Line, eastbound.

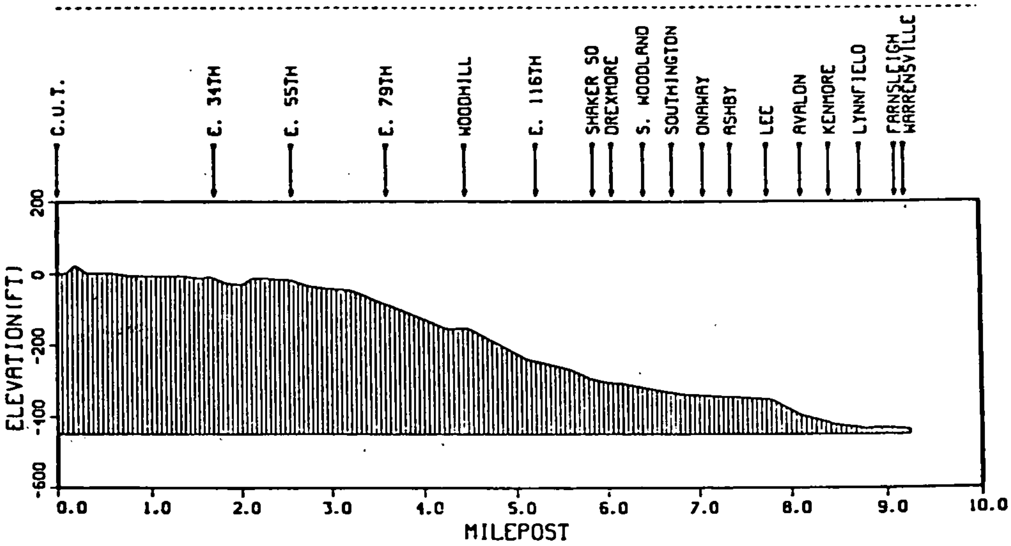


Figure C-17. Elevation profile—RTA, Blue Line, westbound.

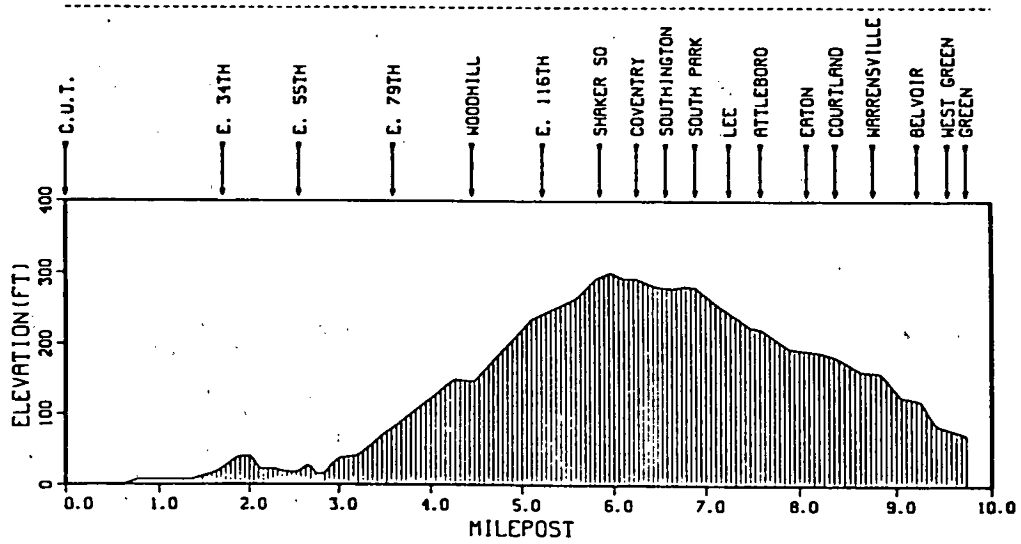


Figure C-18. Elevation profile—RTA, Green Line, eastbound.

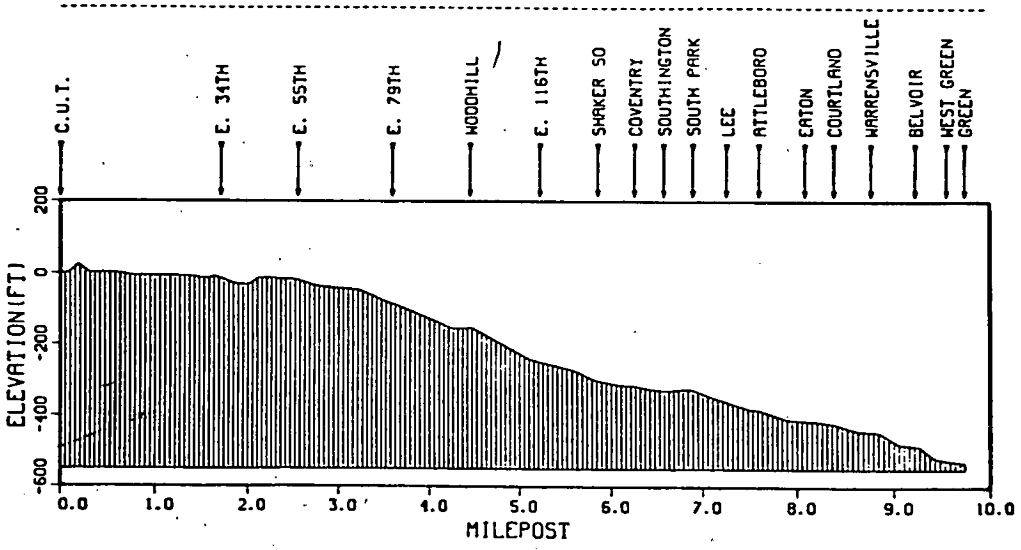


Figure C-19. Elevation profile—RTA, Green Line, westbound.

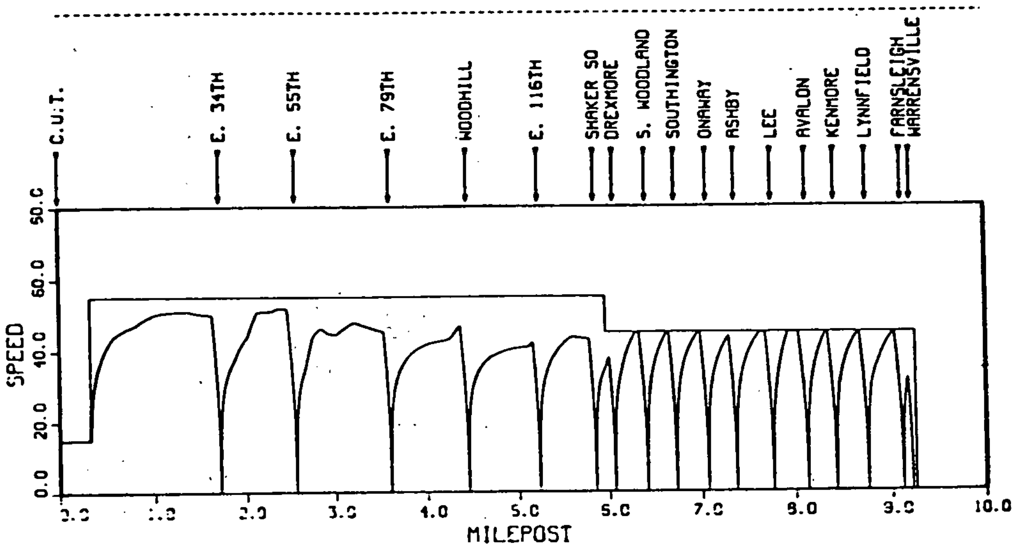


Figure C-20. Speed profile and restrictions—RTA, Blue Line empty car, eastbound.

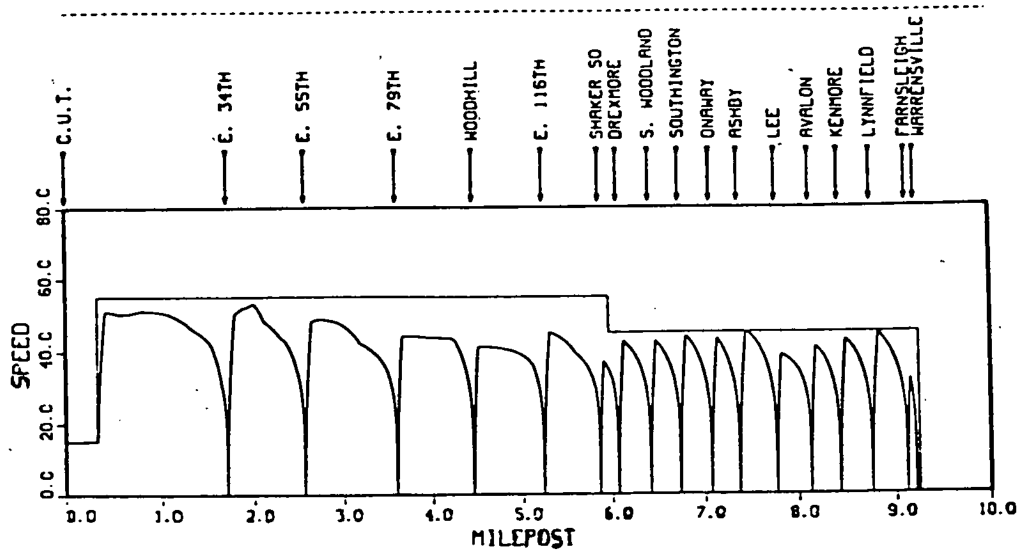


Figure C-21. Speed profile and restrictions—RTA, Blue Line empty car, westbound.

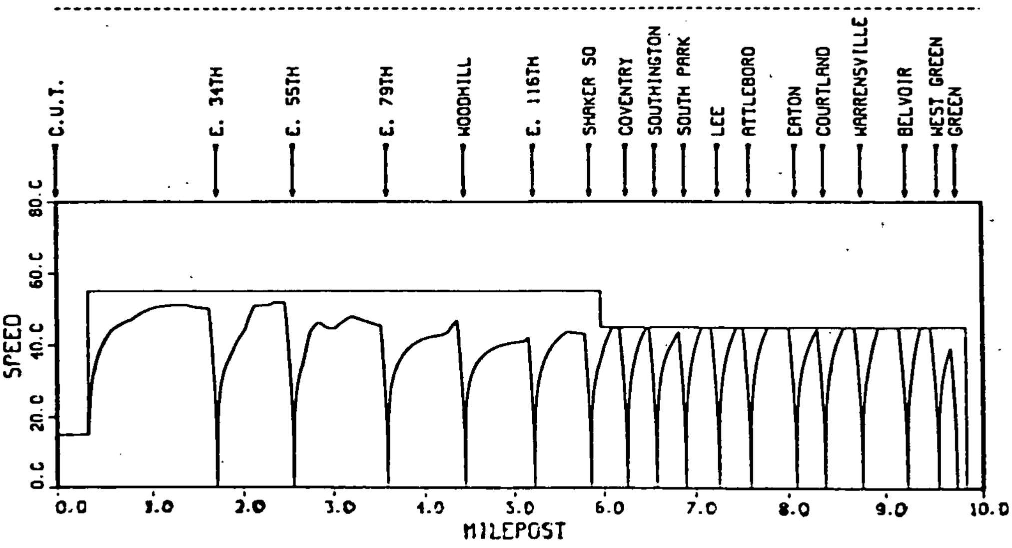


Figure C-22. Speed profile and restrictions—RTA, Green Line empty car, eastbound.

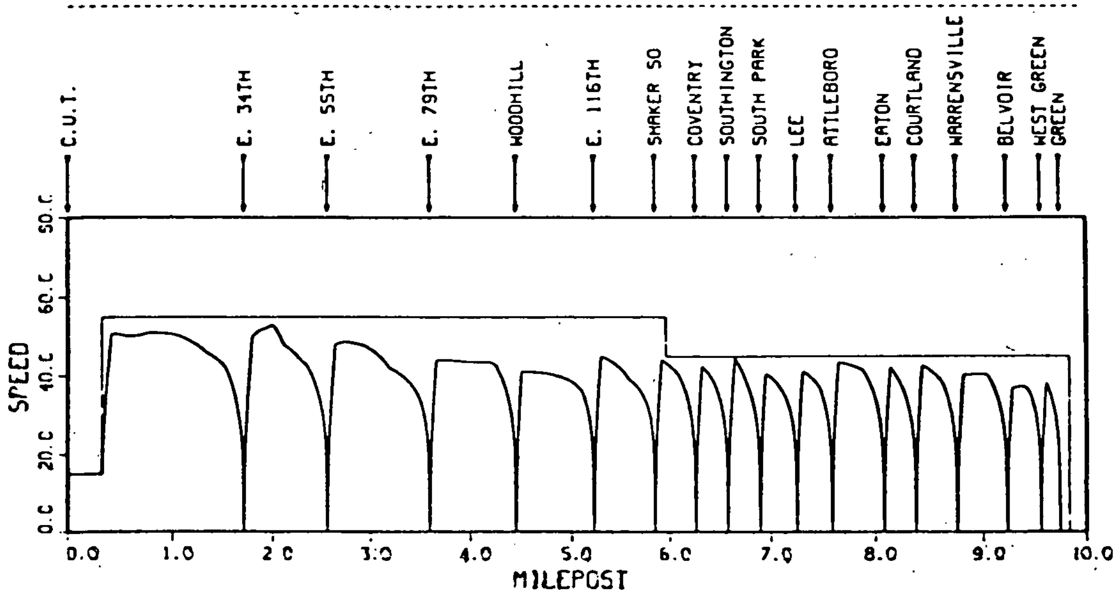


Figure C-23. Speed profile and restrictions—RTA, Green Line empty car, westbound.

C.5 POWER DISTRIBUTION SYSTEM

C.5.1 Network Description

The electrical network of the Blue/Green Line is shown in Figure C-24. The nominal DC distribution voltage is 650 volts. The impedances are per unit values at unit power of 5000 kW, and unit voltage of 650 volts.

The Blue Line, from Union Terminal to Warrensville, and the Green Line, from Union Terminal to Green, are served by six traction substations.

The Blue/Green Line is mostly a two-track system except in the vicinity of Shaker Square. The lines between Shaker Square Substation and Warrensville Substation include four tracks.

C.5.2 Substation Description

Table C-5 gives the substation characteristics appropriate to the Blue/Green Line. The transformer rectifiers provided for each substation are 1500-kW units and they each have a per unit impedance of 0.15.

C.5.3 Line Impedance

The effective rail/running rail impedance between substations and the complex impedance used on the AC side in the network are shown in the nodal diagram of Figure C-24. For the two-track system, the resistance is 0.466/mile in terms of unit ohm, where unit ohm has been calculated by selecting unit power as 5000 kW and unit voltage as 650 volts.

C.6 POWER RATE STRUCTURE

GCRTA has a contract to purchase power from Cleveland Electric Illuminating Company. This power is used for the propulsion of the rail vehicles, the operation of the vehicle's accessories (including overnight heating), heating of some substations, and the operation of the rail switch heaters. Figure C-25 shows kilowatt demand for the year 1981. Costs per kilowatt hour for propulsion electricity averaged $0.059 in 1981. GCRTA also purchases power from the city of Cleveland. Thus, GCRTA directly purchases power from two suppliers: (1) the Cleveland Electric Illuminating Company (CEI), and (2) the City of Cleveland or one of its departments.

The demand interval for traction power for CEI is 60 min and consolidation for demand purposes is noncoincident. Billing demand is the maximum demand in present month.

C.7 SIMULATION FOR 1981 OPERATION

C.7.1 TPS Runs for Normal Operation

Train performance simulations were conducted for weekday AM and PM peak periods using a 1981 timetable, estimated passenger load factors and given dwell times. The results for schedule time and energy consumption are listed in Table C-6.

Figures C-26 through C-29 show the power profile for an empty PCC car running in eastbound and westbound directions for the Blue and Green Lines, respectively.

C.7.2 ENS Runs for Normal Operation

Using the electric network for the RTA Line and the 1981 operational timetable (effective December 1981), normal operation was simulated using the ENS for following time periods on a weekday:

SIMULATION TIME	TO REPRESENT
7:00 - 8:00 A	AM Peak
5:00 - 6:00 P	PM Peak

Table C-7 presents the reuslts of the ENS. These results do not include the background and the effect of turnaround times at the terminal.

C.8 ENERGY SAVINGS BY PERFORMANCE REDUCTION

In this study, the strategies are only tested during the peak hours so that a net increase in schedule time occurs while dwell times are held constant. Two performance reduction strategies were considered on the RTA system, namely:

1. Top-speed reduction.
2. Coasting.

Figure C-30 shows a plot of percent traction energy decrease as a function of percent schedule time increase on the RTA Line for top-speed reduction and coasting.

C.8.1 Top-Speed Reduction

A detailed analysis, using ENS, was conducted using the top-speed reduction strategy by setting the top speed to be increased by 3.5 percent of the schedule time.

The detailed results of this analysis are given in Table C-8. The power savings, by reducing the top speed of the system, can be obtained by calculating KWHPCM coefficients which are the differences between the normal run and those obtained by applying the top-speed reduction strategy. The coefficients are given in Table C-8.

C.8.2 Coasting

A detailed analysis using ENS was conducted using coasting strategy by setting coasting speed = 40 mph. The results of this analysis are given in Table C-9. The increase in running time using this strategy is of the order of 1 percent.

The KWHPCM coefficients (differences between those obtained by using coasting strategy and those of the base operation) are given in Table C-9.

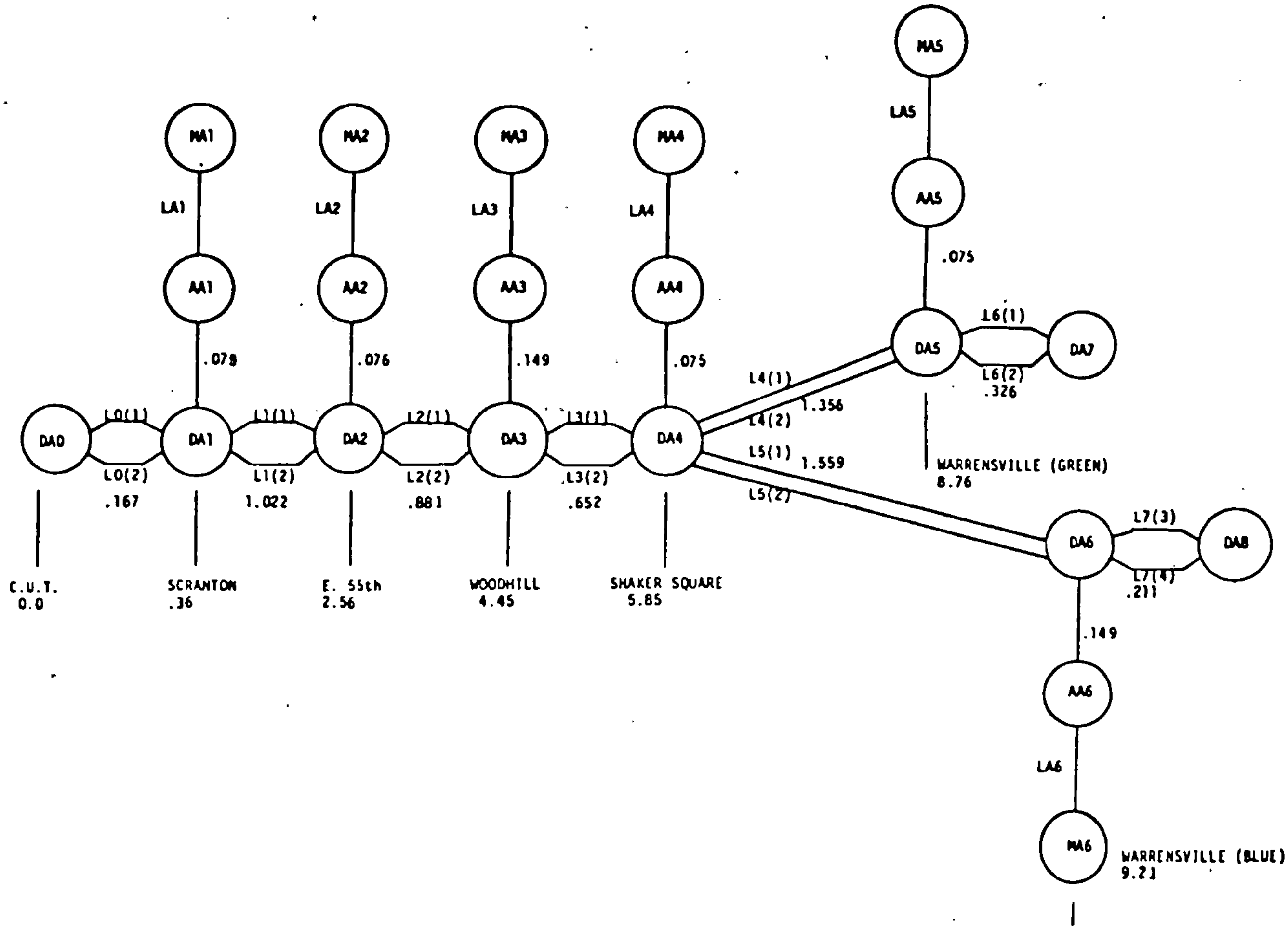


Figure C-24. GCRTA Blue/Green Line electrical network.

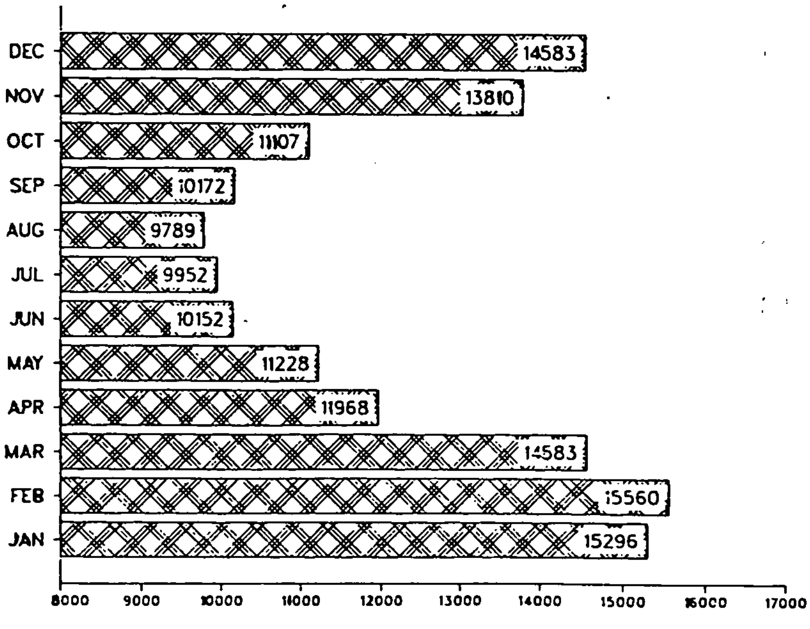


Figure C-25. GCRTA kilowatt demand histogram.

Table C-5. Substation characteristics.

SUBSTATION	METER	NUMBER OF 1500kW TR[cc]	IMPEDANCE (PER UNIT)[dd]
Scranton	MA1	2	.075
East 55th	MA2	2	.075
Woodhill	MA3	1	.150
Shaker Square	MA4	2	.075
Warrensville (Green)	MA5	1	.150
Warrensville (Blue)	MA6	2	.075

[cc] Transformer-Rectifiers

[dd] Obtained from Ray Bleiler, RTA.

Table C-6. Summary of simulated running time and energy consumption for 1981 normal operation.

	ENERGY CONSUMPTION (KWHPCM)	RUNNING TIME (Minutes)
BLUE LINE		
AM Peak		
Eastbound	3.98	21.2
Westbound	4.36	21.6
PM Peak		
Eastbound	4.21	21.6
Westbound	4.18	21.3
GREEN LINE		
AM Peak		
Eastbound	3.81	21.9
Westbound	4.34	22.4
PM Peak		
Eastbound	4.02	22.3
Westbound	4.16	22.1

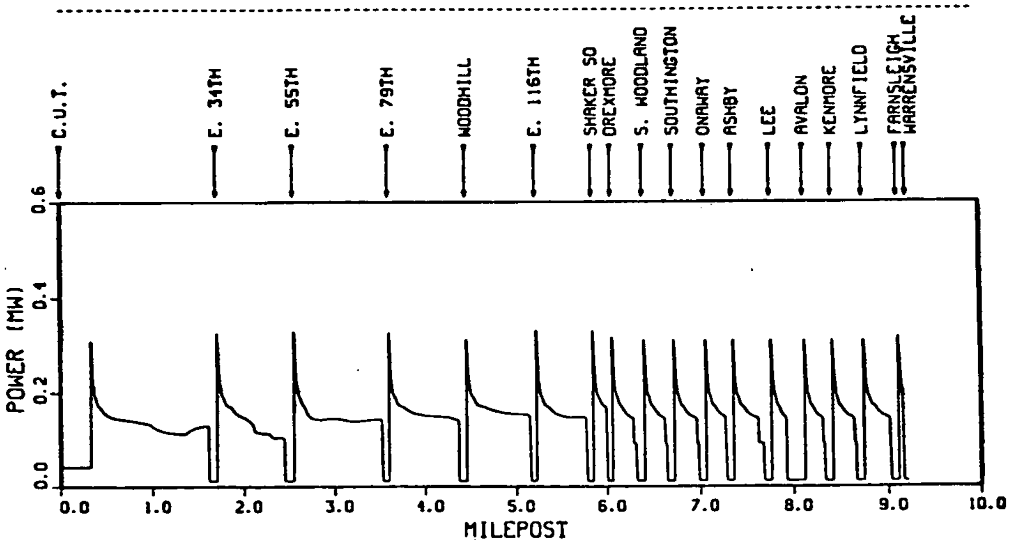


Figure C-26. Power profile—RTA, Blue Line emtpy car, eastbound.

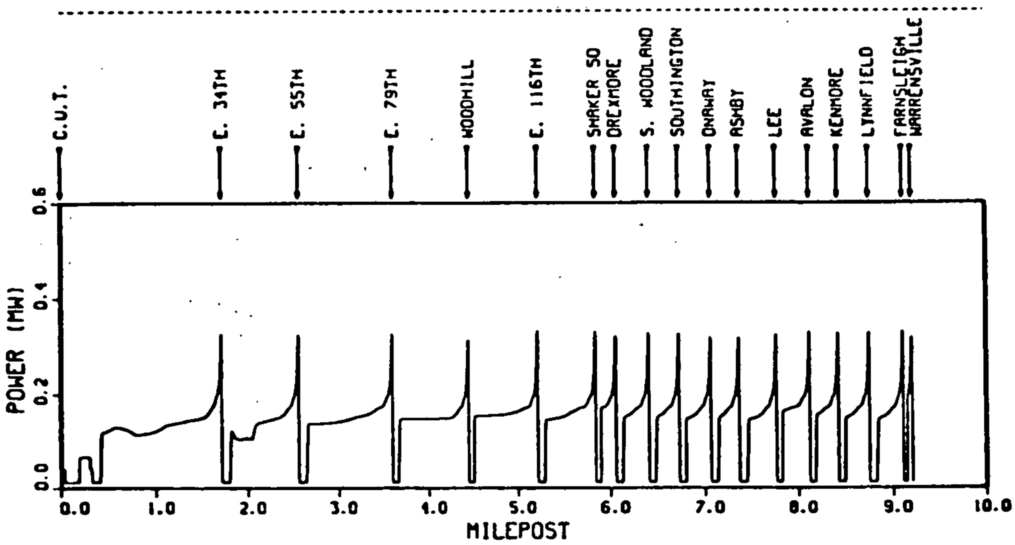


Figure C-27. Power profile—RTA, Blue Line empty car, westbound.

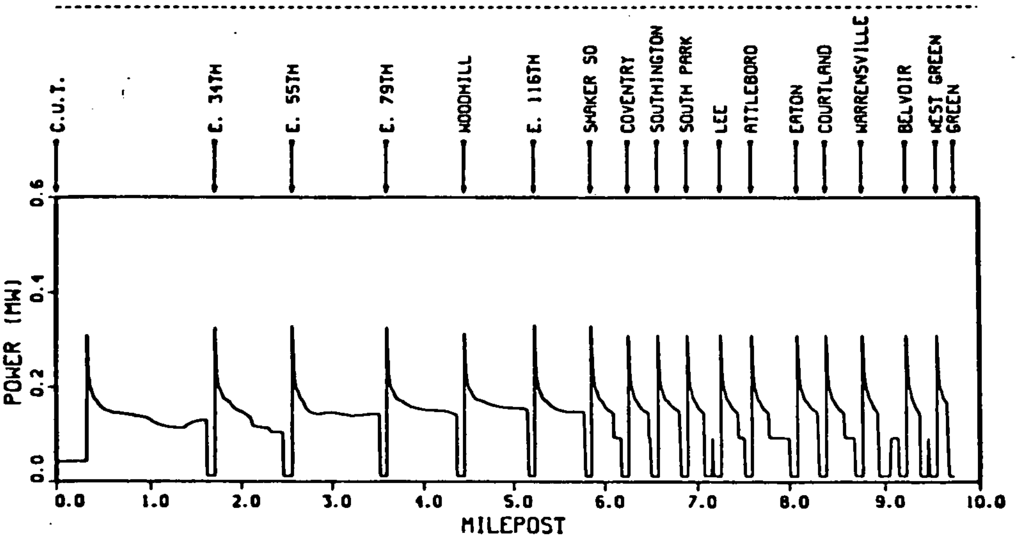


Figure C-28. Power profile—RTA, Green Line empty car, eastbound.

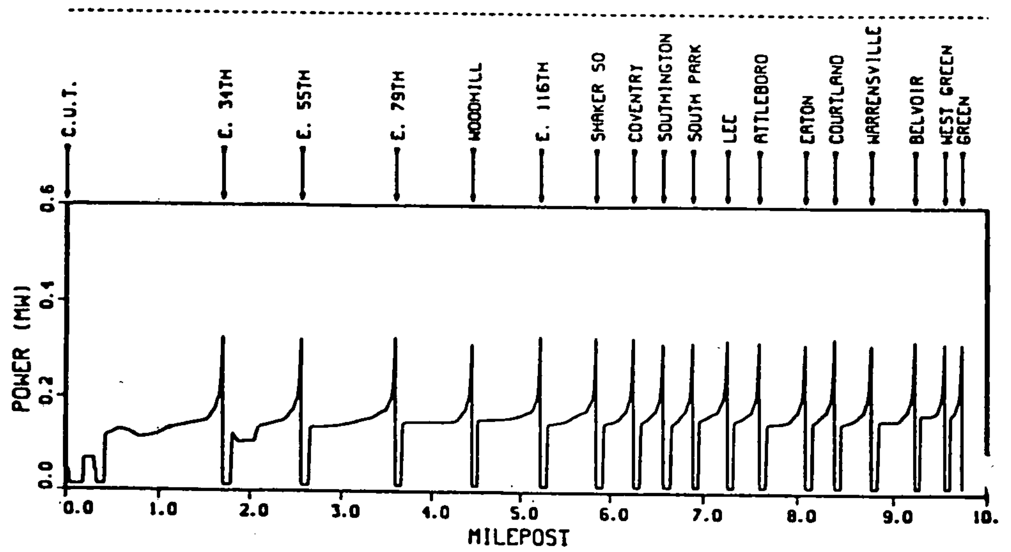


Figure C-29. Power profile—RTA, Green line empty car, westbound.

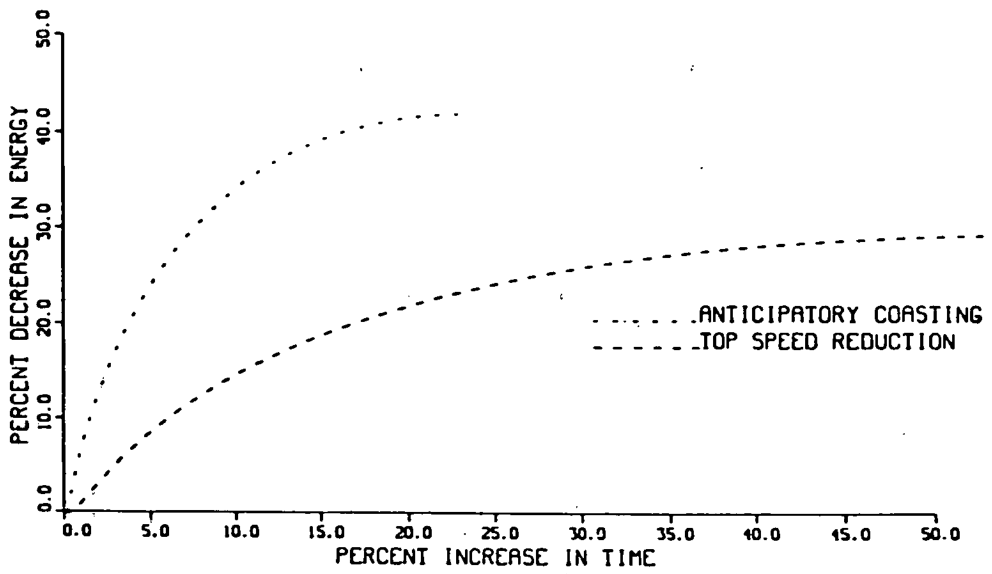


Figure C-30. Performance modification strategy—GCRTA Blue/Green Line.

C.9 ENERGY SAVINGS BY REGENERATION

Regeneration was applied on the GCRTA system using the hypothetical chopper configuration described in Appendix A, Section A-3. The strategy was regeneration with natural receptivity in which all of the PCC cars were chopper cars, and the only receptors of the regenerated brake energy were other PCC cars on the line.

Regeneration with natural receptivity was simulated using the EMM. Regeneration was maintained up to line voltage of 700 volts. At this maximum line voltage, the excess electrical braking power which can not be accepted by the line is channeled into resistors aboard the car. Table C-10 shows the result of the ENS for regeneration with natural receptivity.

The differences between the KWHPCM coefficients obtained by using the regeneration with natural receptivity and those of the base operation are shown in Table C-10.

Table C-7. Results of the ENS for normal operation during 1981.

SUBSTATION	METER	POWER (kW) AM PEAK	 PM PEAK[**]
Scranton	MA1	188	125
East 55th	MA2	317	213
Woodhill	MA3	310	207
Shaker Square	MA4	474	323
Warrensville (Green)	MA5	224	159
Warrensville (Blue)	MA6	174	119
CAR MILES		426	284
KWHPCM		3.97	4.08
KWHPCM (Peak Average)			4.04

[**] Does not include on-board auxiliary power during turnaround.

Table C-8. Results of the ENS for top speed of 40 mph.

SUBSTATION	METER	POWER (kW)[††] AM PEAK	 PM PEAK
Scranton	MA1	170	121
East 55th	MA2	292	204
Woodhill	MA3	297	204
Shaker Square	MA4	435	308
Warrensville (Green)	MA5	202	147
Warrensville (Blue)	MA6	155	108
CAR MILES		426	284
KWHPCM		3.64	3.84
KWHPCM (Peak Average)			3.74
Energy Savings (ΔE) KWHPCM			0.30

[††] Does not include on-board auxiliary power during turnaround.

Table C-9. Results of the ENS for coasting above 40 mph during 1981.

SUBSTATION	METER	POWER (kW)[§§] AM PEAK	 PM PEAK
Scranton	MA1	164	112
East 55th	MA2	270	184
Woodhill	MA3	294	201
Shaker Square	MA4	419	293
Warrensville (Green)	MA5	190	140
Warrensville (Blue)	MA6	139	99
CAR MILES		426	284
KWHPCM		3.49	3.65
KWHPCM (Peak Average)			3.57
Energy Savings (ΔE) KWHPCM			0.47

[§§] Does not include on-board auxiliary power during turnaround.

Table C-10. Results of the ENS for regeneration with natural receptivity.

SUBSTATION	METER	POWER (kW) AM PEAK	 PM PEAK
Scranton	MA1	175	114
East 55th	MA2	268	175
Woodhill	MA3	258	165
Shaker Square	MA4	267	184
Warrensville (Green)	MA5	168	121
Warrensville (Blue)	MA6	119	91
CAR MILES		426	284
KWHPCM		2.95	2.99
KWHPCM (Peak Average)			2.97
Energy Savings (ΔE) KWHPCM			1.07

APPENDIX D

APPLICATION OF EMM TO NYCTA

D.1 GENERAL

The New York Subway was 78 years old on October 27,1982. This is a transit system with 458 stations, 229 miles of routes costing $2.5 billion to construct, and $27 billion to replace. It moves three and one-half million people each day. The New York City Transit Authority was created by the New York State Legislature in 1953 to operate all New York City-owned subway and bus lines. Rapid transit services are identified by division (IRT, IND, or BMT), and by line. In this study, the RR Line of the BMT division was analyzed. The RR Line runs from Ditmars Boulevard Station, Queens, to 95th Street Station, Brooklyn, covering a total distance of 17.67 miles with 37 stations in between. Figure D-1 shows a diagram of the system and its station locations.

D.2 SYSTEM OPERATING CHARACTERISTICS

The RR Line is divided into 244-track sections from 95th Street Station to Ditmars Blvd. Station. The maximum speed on the system is 55 mph, and a terminal-to-terminal run time of approximately 65 min.

Based on NYCTA nonrush-hour timetables for the RR Line, the following station dwell times are assumed:

Dwell Time = 10 sec in Brooklyn from 95th Street Station to Lawrence Street Station.
Dwell Time = 20 sec from Court Street Station, Brooklyn, throughout Manhattan to Queensboro Plaza Station, Queens.
Dwell Time = 10 sec in Queens from 39th Ave.-Beebe Ave. Station to Ditmars Blvd. Station.

There was no information for the passenger load factors developed between different stations, and they were assumed to follow a pattern similar to WMATA Blue/Orange lines. Figures D-2 and D-3 show the graphs of the passenger load factors for northbound and westbound directions of the RR Line. The milepost locations and the dwell times of the RR Line are given in Table D-1. In peak operation, the RR Line runs with a headway between 2 to 5 min.

D.3 VEHICLE CHARACTERISTICS

D.3.1 Physical Characteristics

Table D-2 summarizes the vehicle characteristics that were used for the energy management simulation model. The empty weight of the train is 50 tons. The crush load weight of the

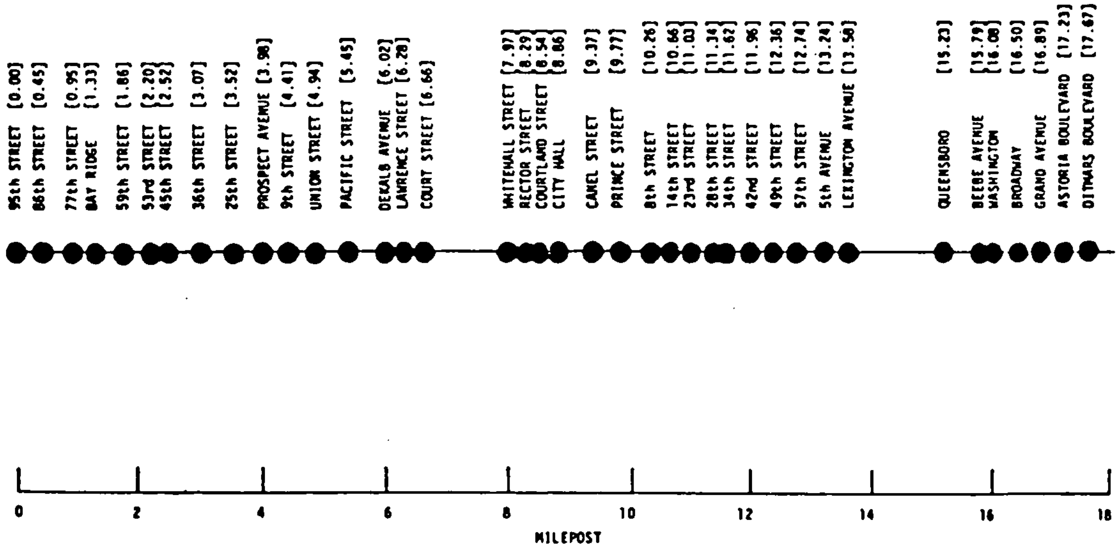


Figure D-1. NYCTA RR Line passenger station configuration.

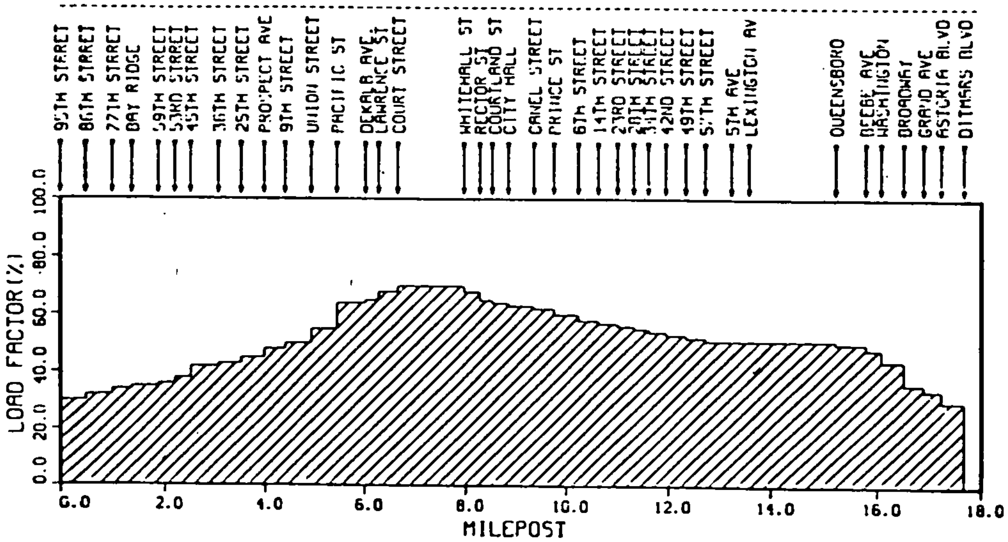


Figure D-2. Passenger load factor—RR Line (AM peak) 95th Street to Ditmars Blvd.

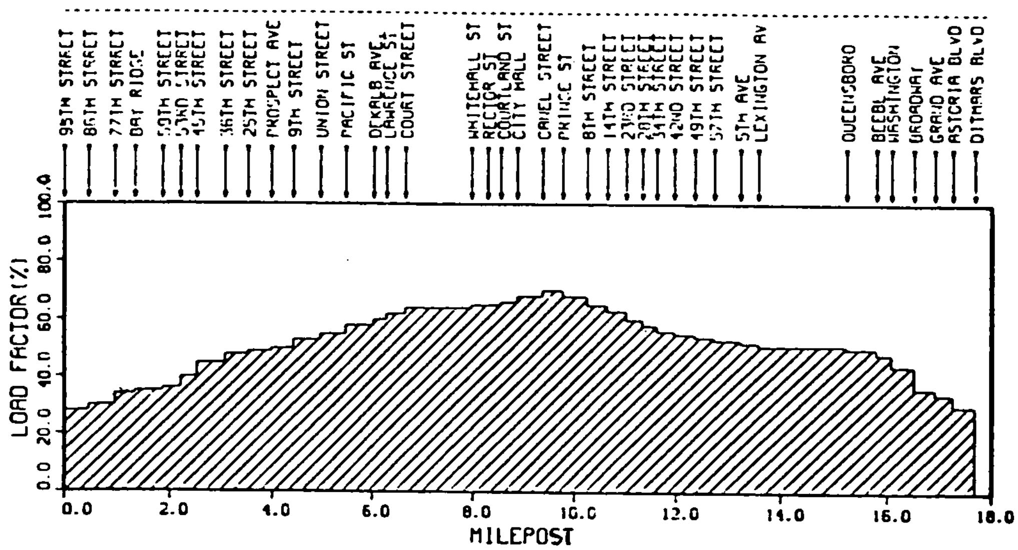


Figure D-3. Passenger load factor—RR Line (AM peak) Ditmars Blvd. to 95th Street.

Table D-1. Station location and dwell times for NYCTA RR Line.

STATION	MILEPOST	DWELL TIMES (In Seconds)
95th Street	0.00	10.0
86th Street	0.45	10.0
77th Street	0.95	10.0
Bay Ridge	1.33	10.0
59th Street	1.86	10.0
53rd Street	2.20	10.0
45th Street	2.52	10.0
36th Street	3.07	10.0
25th Street	3.52	10.0
Prospect Ave.	3.98	10.0
9th Street	4.41	10.0
Union Street	4.94	10.0
Pacific Street	5.45	10.0
Dekalb Ave.	6.02	10.0
Lawrence Street	6.28	10.0
Court Street	6.66	20.0
Whitehall Street	7.97	20.0
Rector Street	8.29	20.0
Courtland Street	8.54	20.0
City Hall	8.86	20.0
Canal Street	9.37	20.0
Prince Street	9.77	20.0
8th Street	10.26	20.0
14th Street	10.66	20.0
23rd Street	11.03	20.0
28th Street	11.34	20.0
34th Street	11.62	20.0
42nd Street	11.96	20.0
49th Street	12.36	20.0
57th Street	12.74	20.0
Fifth Ave.	13.24	20.0
Lexington Ave.	13.58	20.0
Queensboro	15.23	20.0
Beebe Ave.	15.79	10.0
Washington	16.08	10.0
Broadway	16.50	10.0
Grand Ave.	16.89	10.0
Astoria Blvd.	17.23	10.0
Ditmars Blvd	17.67	0.0

train is taken as 65 tons (based on 200 passengers each weighing 150 lb). The average auxiliary power used on the R44 car is 30 kW.

D.3.2 Propulsion Characteristics

Table D-3 summarizes the propulsion characteristics for the R44 car which uses cam control as the main power conditioning unit. The motor used on the R44 car is Westinghouse type 1447. The motor control philosophy using cam control is similar to that for WMATA. Figure D-4 shows the tractive effort speed curve for each of the motor circuit modes. Figure D-5 shows the propulsion system efficiency as a function of speed and maximum tractive effort.

D.3.3 Braking Characteristics

The maximum service brake rate was fixed at 3.0 mph per sec, independent of both vehicle speed and load factor.

Table D-2. Vehicle physical characteristics.

Empty Weight (tons)	50.0
Crush Load Weight (tons)	65.0
Vehicle Length (ft.)	75.0
Cross Sectional Area (sq. ft.)	100.0
Flange Coefficient (lbs/ton/mph)	0.045
Number of Axles (all powered)	4.0
Average Auxiliary Power (kW)	30.0
Lead Vehicle Air Drag Coefficient (lbs/ton/mph^2)	0.0024
Trail Vehicle Air Drag Coefficient (lbs/ton/mph^2)	0.00034

Table D-3. Vehicle propulsion characteristics.

Motors per Car	4
Cars per Train	8
Motor Characteristics	(W) Type 1447
Control	Cam Resistor Switching
Wheel Diameter	32.0 in
Gear Ratio	7.235
Maximum Speed	50.0mph
Nominal Line Voltage	500.0V
Maximum Line Voltage	750.0V
Minimum Line Voltage	450.0V

D.4 RIGHT-OF-WAY CHARACTERISTICS

The RR Line is a two-track system. The northbound elevation profile is shown in Figure D-6.

Maximum speed on the system is 55 mph. The speed restriction and profile (as simulated by TPS) for an empty R44 car are shown in Figures D-7 and D-8 for northbound and southbound directions for the RR Line.

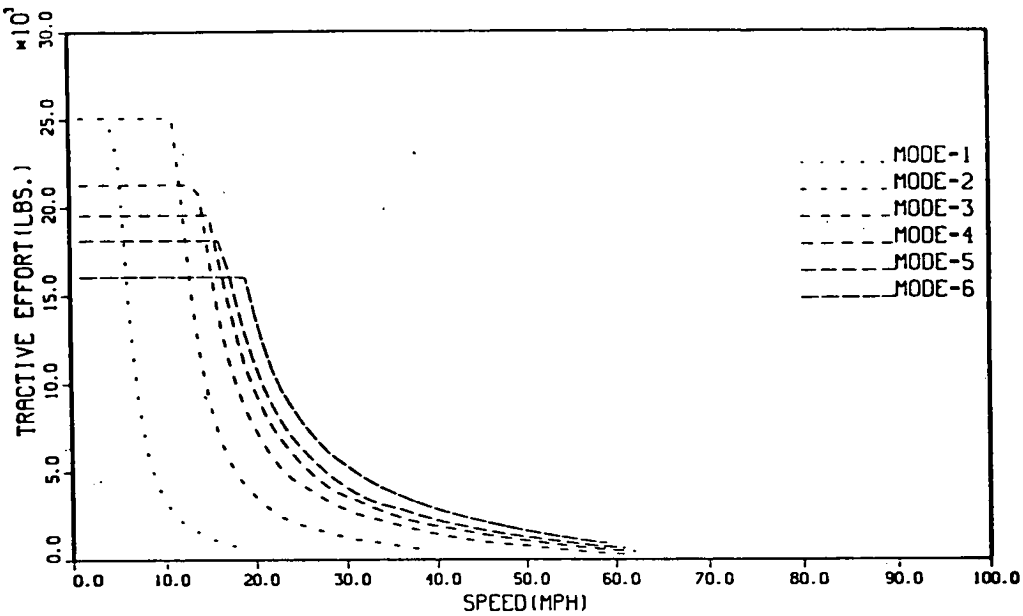


Figure D-4. Tractive effort-speed curve—NYCTA RR Line, cam control.

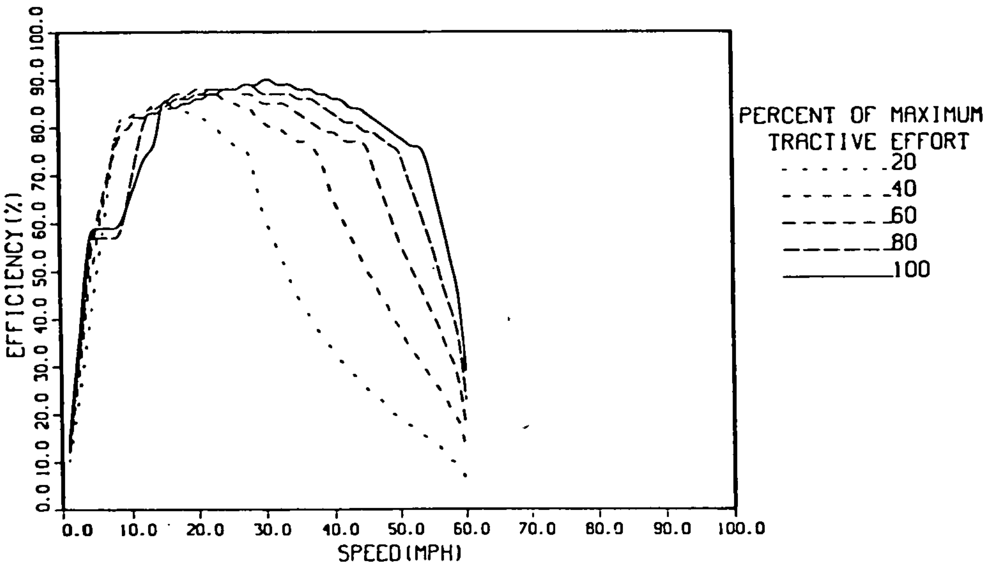


Figure D-5. Propulsion system efficiency—NYCTA RR Line, cam control.

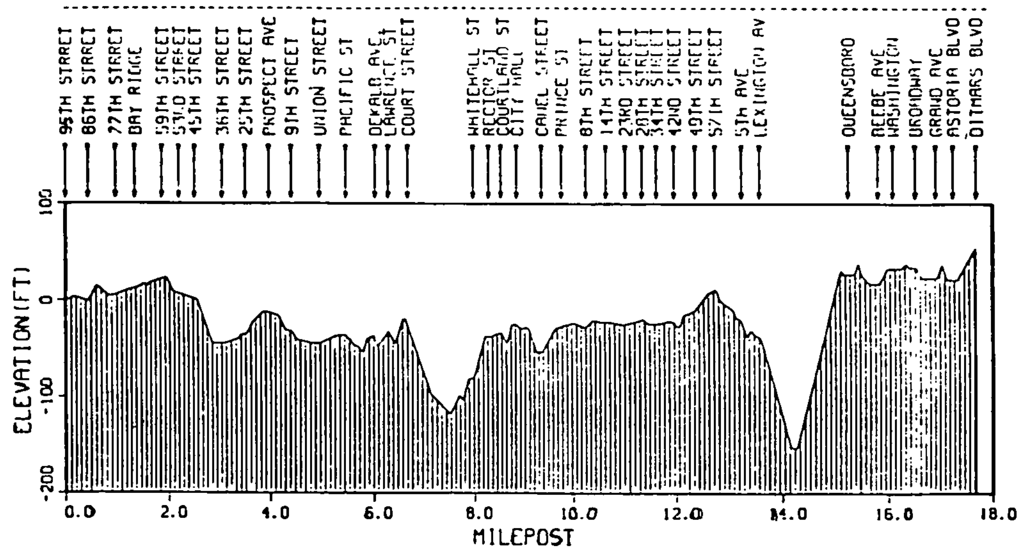


Figure D-6. Elevation profile—NYCTA RR Line, northbound.

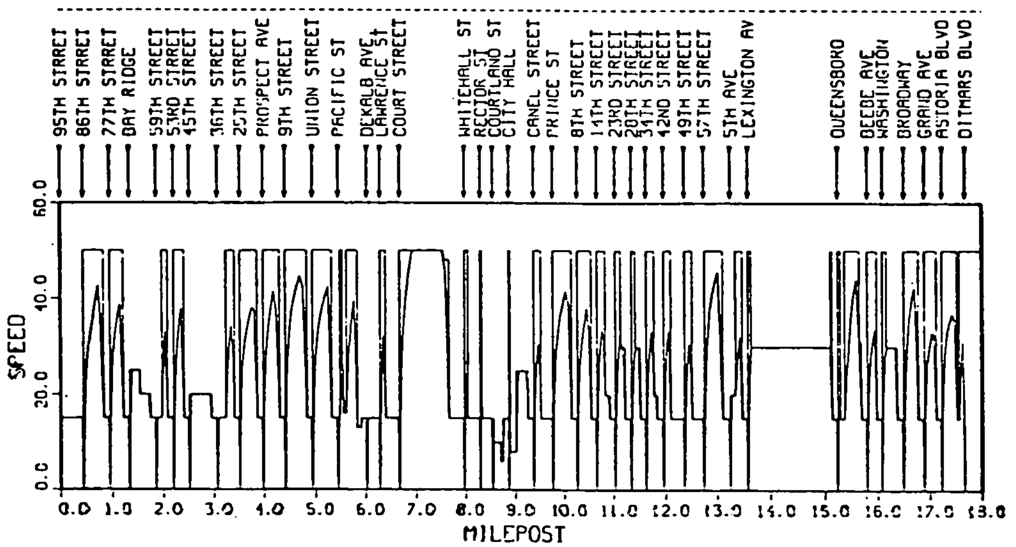


Figure D-7. Speed profile and restrictions—NYCTA RR Line, 6-car empty train, northbound.

D.5 POWER RATE STRUCTURE

NYCTA purchases its power from the Power Authority of State of New York (PASNY). Table D-4 gives the power rate structure. There are different rates for traction and nontraction power. The billing demand is 30 min, and demand consolidation is coincident. Billing demand is the maximum demand in the present month. The ratchet is 75 percent of largest monthly demand in the past 12 months.

D.6 SIMULATION FOR 1981 OPERATION

Train performance simulations were conducted for weekday AM peak periods. The results of schedule time and energy consumption are given in Table D-5.

Figures D-9 and D-10 show the power profile for an empty RR car running in northbound and southbound directions, respectively.

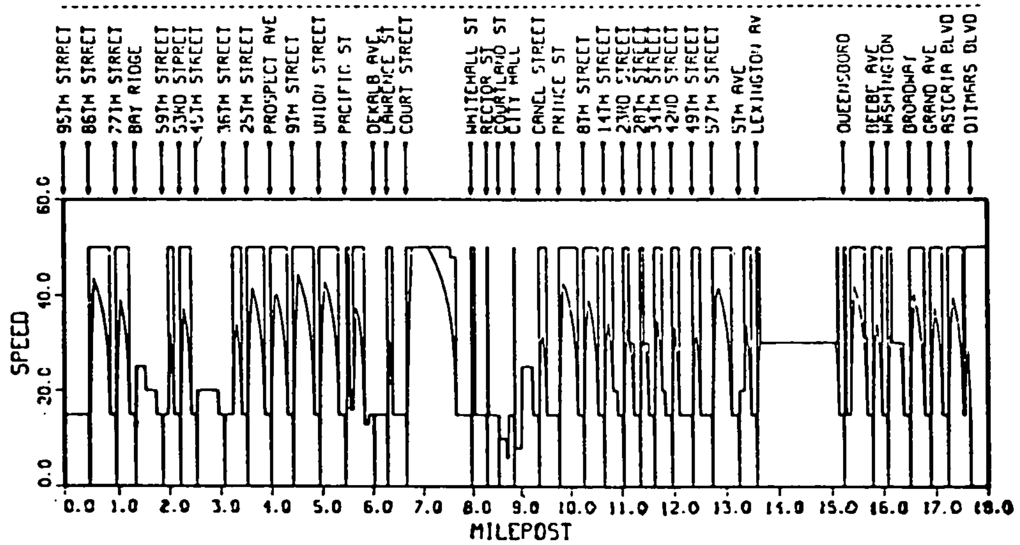


Figure D-8. Speed profile and restrictions—NYCTA RR Line, 6 car empty train, southbound.

Table D-4. Port Authority of State of New York rate structure.

TRACTION POWER

Demand ($/kW):	6.07
Energy ($./kWh):	.0128
Fuel Adjustment:	

NON-TRACTION POWER

SUBSTATION DELIVERY	PLANT DELIVERY
Demand ($/kW): 6.11	Demand ($/kW): 6.08
Energy($./kWh): .0125	Energy ($./kWh): .0123

GENERAL USE LARGE	GENERAL USE SMALL
Demand ($/kW): 8.16	Demand ($/kW):
Energy($./kWh): .0173	Energy ($./kWh): .0491

BILLING DEMAND FORMULA

Interval:	30 minutes
Consolidation:	Coincident
Monthly Demand:	Maximum demand in present month.
Ratchet:	Seventy-five percent of largest monthly demand in past twelve months.

POWER FACTOR PENALTY:

Maintain 85% power factor.

MINIMUM CHARGES:

Charge for 10 kWh per energy meter, plus demand.

SEASONAL AND TIME OF DAY RATES:

Summer/Winter differential only GS small (commercial).

Table D-5. Summary of simulated running time and energy consumption for 1981 normal operation.

	ENERGY CONSUMPTION (KWHPCM)	RUNNING TIME (Minutes)
AM Peak		
Northbound	8.82	65.0
Southbound	8.97	65.0

D.7 ENERGY SAVINGS BY PERFORMANCE REDUCTION

In this study, the strategies were tested in peak periods so that a net increase in schedule time occurs while dwell times are held constant. Two performance reduction strategies were tested on the RR Line, namely:

1. Top-speed reduction.
2. Coasting.

Figure D-11 shows a plot of percent traction energy decrease as a function of percent schedule time increase on the RR Line for the above two strategies.

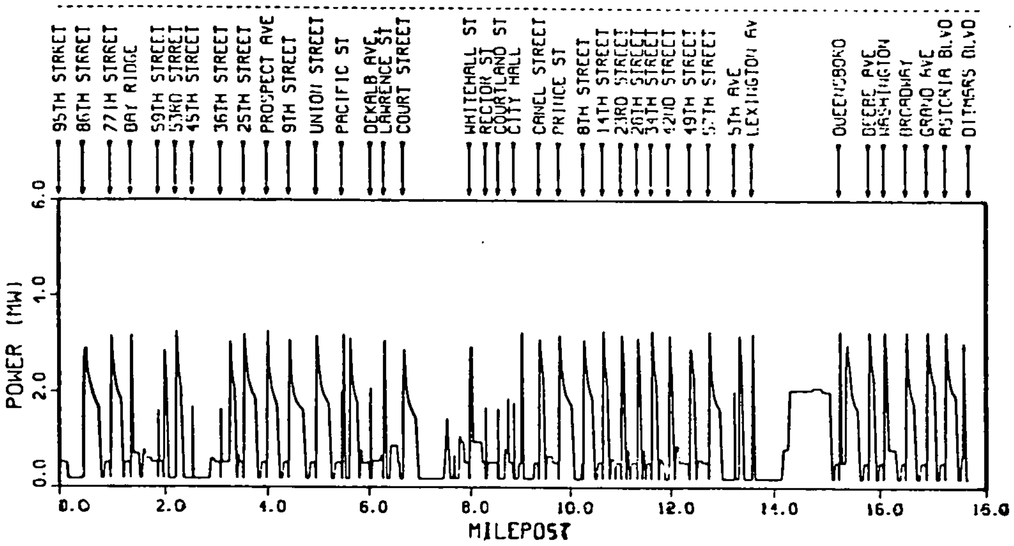


Figure D-9. Power profile—NYCTA RR Line, 6-car empty train, northbound.

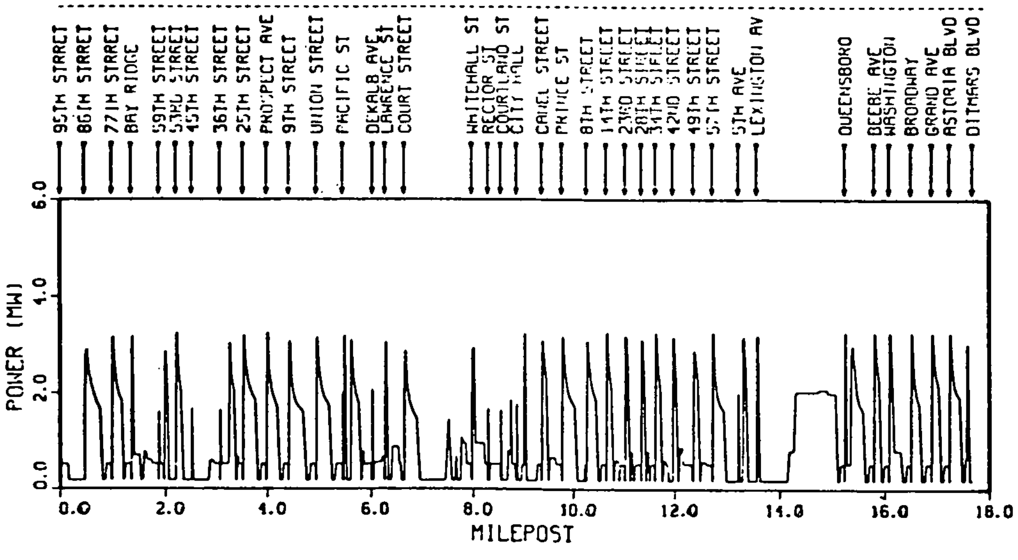


Figure D-10. Power profile—NYCTA RR Line, 6 car empty train, southbound.

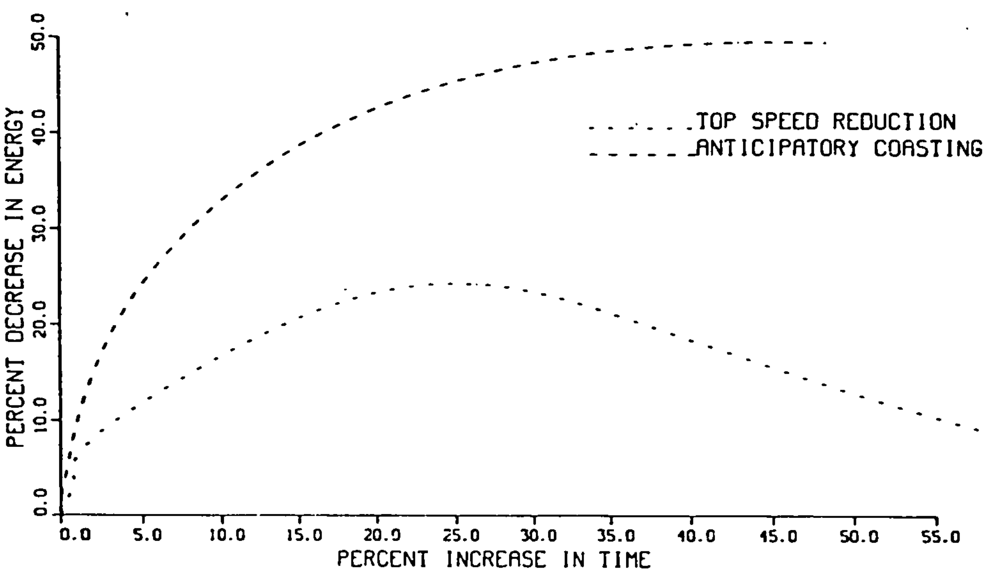


Figure D-11. Energy savings—NYCTA RR Line.

APPENDIX E

REGRESSION ANALYSIS OF WMATA METERING INFORMATION

E.1 DESCRIPTION OF PEPCO METERING DATA

The PEPCO provided a magnetic tape that contained energy usage (pulses) data as given in the PEPCO account. The data had 15-min pulses for 26 traction energy meters which were in operation during 1980. The time span was January 20, 1980, to January 19, 1981. Out of 26 traction metering data provided by PEPCO, 18 meters were in DC, 5 meters were in MD, and 3 meters were in VA jurisdictions. The data were converted into Fortran readable form, using program RU0A09.FOR. The system flow chart is shown in Figure E-1.

Using **A**, plots were created of summary statistics, which provided through bar charts information on mean, standard deviation, and maximum of power demand.

Using **B**, regression analyses of power vs. car-miles/hour and degree-days for revenue operating and nonoperating periods were established.

Using **C**, energy consumption histograms on each time period for various meters were created.

The following describes in detail the regression analysis which was done on PEPCO metering data in order to determine the dependence of traction energy usages on car-miles and daily temperature.

E.2 REGRESSION TECHNIQUES

A package BMDP1R, one of the computer packages of BMDP series, was used that estimates multiple linear regression relating a dependent variable (in this case traction power) to several independent variables (e.g., degree-day and in this case, car-mile/hour).

Let y represent the value of the dependent variable, and x_1, $x_2, \ldots, x_n$ the values of the independent variables, then the proposed relationships is:

$$y = a + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \text{error}$$

The package estimates by least square the coefficient a, β_1, $\beta_2, \ldots, \beta_n$, that is, it finds a, b_1, $b_2, \ldots, b_n$ (estimates of a, β_1, $\beta_2, \ldots, \beta_n$) that minimize:

$$\Sigma(y - a - b_1 x_1 - b_2 x_2 - \ldots - b_n x_n)^2$$

Here the summation is over the cases used in the analysis. The predicted value y for each case is:

$$y = a + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n$$

The residual for each case is $(y - y)$. Thus, a multiple linear regression equation can be written as:

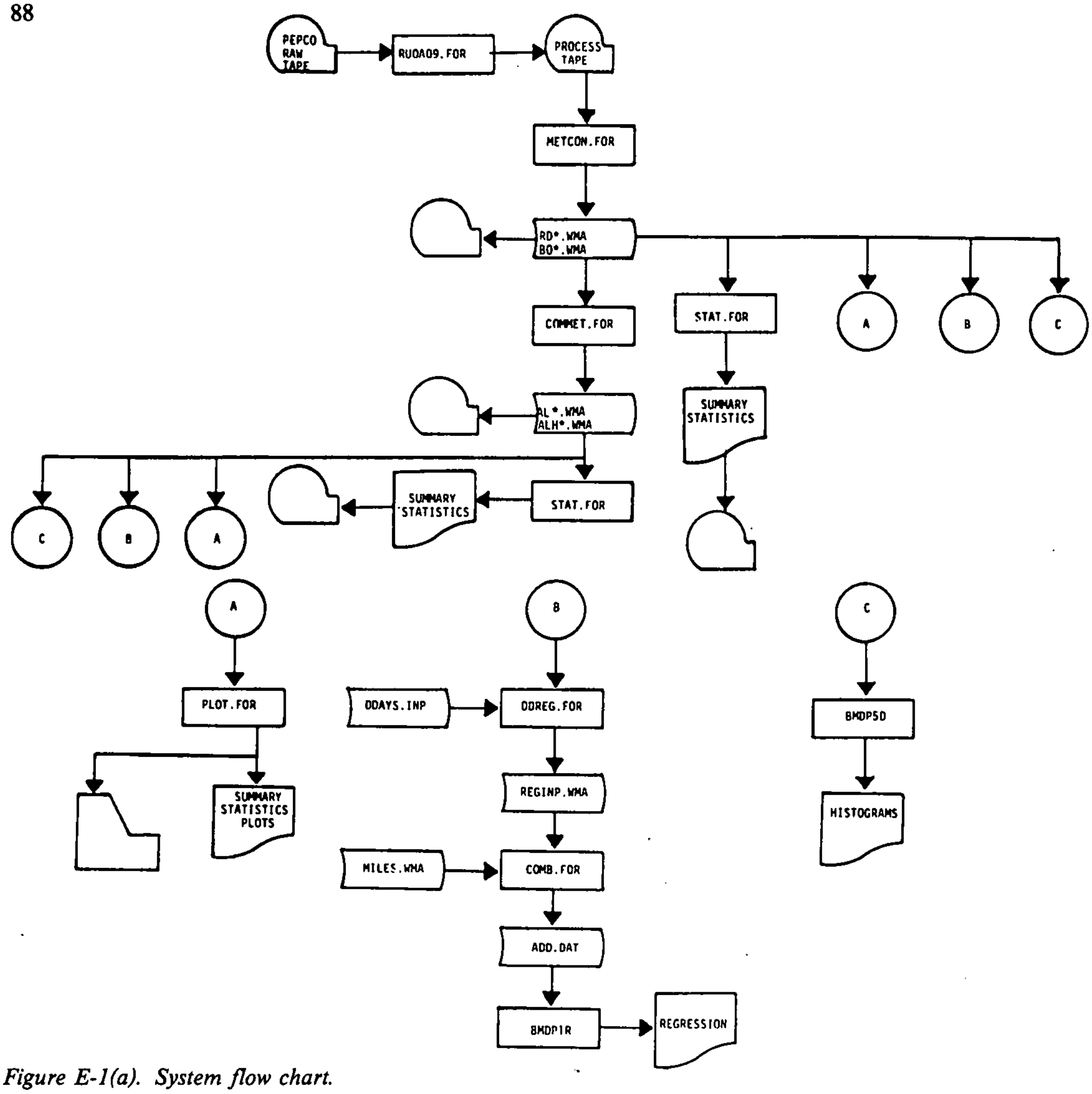


Figure E-1(a). System flow chart.

CONV -	Executive level program which takes the magnetic tapes provided by the electric utilities and converts the information into Fortran readable format.
METCON -	Fortran program which is used to read the process tape and create one file for each meter for future processing.
COMMET -	Fortran program which is used to combine the single meter files into consolidations. The pulses from each meter which occur at the same times are added to obtain the consolidated pulse at that time. This is done for all times.
STAT -	Fortran program which is used to develop summary statistics, which are the mean, standard deviation and maximum for some specified period of time on weekdays, Saturdays, and Sundays.
PLOT -	Fortran program which is used to plot summary statistics.
DDREG -	Fortran program which takes degree-days by date as input and prepares the file for regression analysis.
COMB -	A Fortran program which combines input data of degree days as output from DDREG and car-mile data by date and stores it in a file for regression analysis.
BMDP1R -	A Biomedical Computer Program (BMDP) developed by Health Sciences Computing Facility of the University of California, Los Angeles, for regression analysis.
BMDP5D -	Same as above but for plotting histograms.

Figure E-1(b). Definition of system flow chart.

$$E(y_\gamma - y) = \beta_1(x_{1\gamma} - x_1) + \ldots + \beta_n(x_{n\gamma} - x_n)$$
$$\gamma = 1, 2, \ldots, N \text{ (Number of cases)}$$

In matrix notation:

$$E(Y^1) = X^1B^1$$

The least square estimate b of β is:

$$b^2 = (XX^1)^{-1}\,XY^1$$

E.3 REGRESSION ANALYSIS

The traction energy audit was conducted by analyzing metering information supplied by PEPCO for 9 months of the year 1980. Each day was divided into two periods:

1. Revenue service time.
2. Nonrevenue service time.

Revenue service time was that part of the weekday, Saturday, or Sunday during which trains were scheduled to run according to the operating timetable. Nonrevenue service time was all other time.

E.3.1 Revenue Service Time Regression Description

The regression formula was assumed to have the form:

$$P = P_0 + E_1(CM/H) + P_2(ADD)$$

where:

P = average power over the revenue operating time as obtained from the meter data (kW);
P_0 = background power (kW);
CM/H = average car-miles per hour over revenue service time on a daily basis;
ADD = average degree-day defined as average temperature less 70 F;
E_1 = energy per car-mile (KWHPCM); and
P_2 = average power per average degree day (KWPADD).

In order to conduct the regression, the actual car-miles accumulated each day were obtained from Metrorail (Energy Management Office) over the interval of the audit. A statistical summary of the actual car-miles on the Red, Blue, and Orange Lines of the Metrorail system are shown in Figures E-2 through E-4. The three peaks visible in the figures are attributed to weekday, Saturday, and Sunday operation.

The second independent variable of the revenue service time regression was the average degree day, *ADD*, defined as average daily temperature less 70F. A statistical summary of daily temperature, over the time span considered in the regression study, namely February 1, 1980 through October 15, 1980, is shown in Figure E-5. The average value of *ADD* is −3.7F, which represents an average daily temperature of 66.3F.

E3.2 Nonrevenue Service Time Regression

Because during nonrevenue service time the car-mile effect is small on total traction power, a regression was done on power vs. daily temperature to determine the effect of daily temperature on traction power.

Thus, during nonrevenue service time, the regression formula was assumed to have the form:

$$P = P_0 + P_2(MDD)$$

where, *MDD*, minimum degree-day, is defined as minimum temperature less 70F.

The average value of a minimum degree day is −13F, which represents a temperature of 57F. The minimum temperature was selected as an independent variable because nonrevenue service time generally had the minimum temperature.

E.3.3 Regression Analysis Results

The results of the regression analysis for the traction energy meters are given in Table E-1. In addition to those completed on the individual meters, regressions were also conducted on the Red Line coincident power, and Blue/Orange Line coincident power with the exception of the power metered at Cheverly, Landover, Beaver Dam Creek, and New Carrollton.

During revenue service time, a strong dependence on car-miles is obvious. The confidence limits of this dependence exceeded 99 percent, even for the smallest value of the coefficient E_1 of 0.24 at New Carrollton Yard Substation meter.

Car storage during revenue service time at midday, weekday evenings, and on Saturdays and Sundays has its predominant effect on the meters at New York Avenue (Brentwood Yard), Silver Spring and New Carrollton Yard. The meter at New Carrollton Yard exhibits only a 30 percent dependence on car-miles with the background accounting for nearly the remaining amount. The background is attributed to yard car movement and car storage.

Degree day component of the traction power during revenue service time is quite small. With the exception of the power at Shirley Highway meter, which exhibits an 8 percent temperature component on the average day, the remaining degree-day components are 1 percent or less of the total power during revenue service time.

Since during nonrevenue time the trains are not in operation, the temperature component of power is more during nonrevenue service time than revenue service time. Also, a background of power is registered during nonrevenue service time because of:

1. No load losses of the transformer-rectifier units in the substation,
2. Operation of car auxiliaries during layup,
3. Support services, such as heating and ventilation of substation and other structures, chiller plants metered through the traction meters, tunnel ventilation, lighting and switchpoint heating, and testing of trains.

Nonrevenue service time background was considered the basis for background estimate. Table E-2 contains a summary of the background values for all the traction meters. These backgrounds were derived using the following rules:

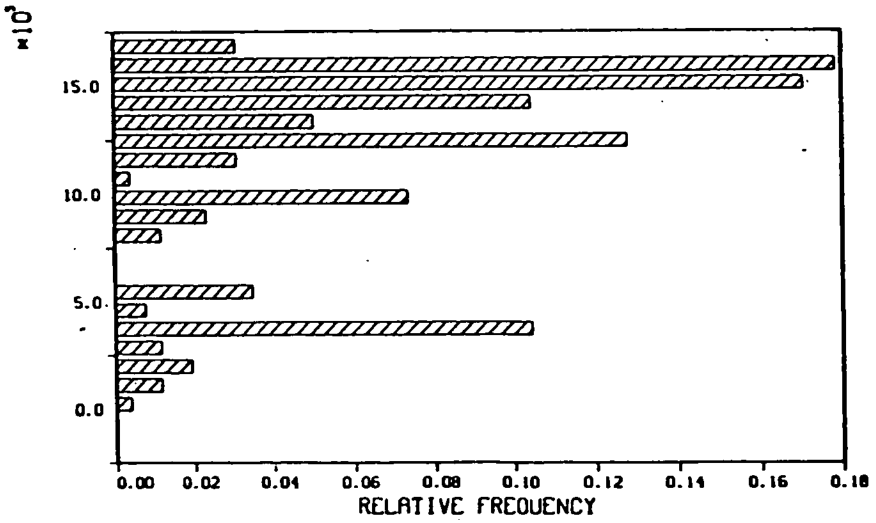


Figure E-2. Histogram—Red Line car-miles (Feb. 1–Oct. 15, 1980).

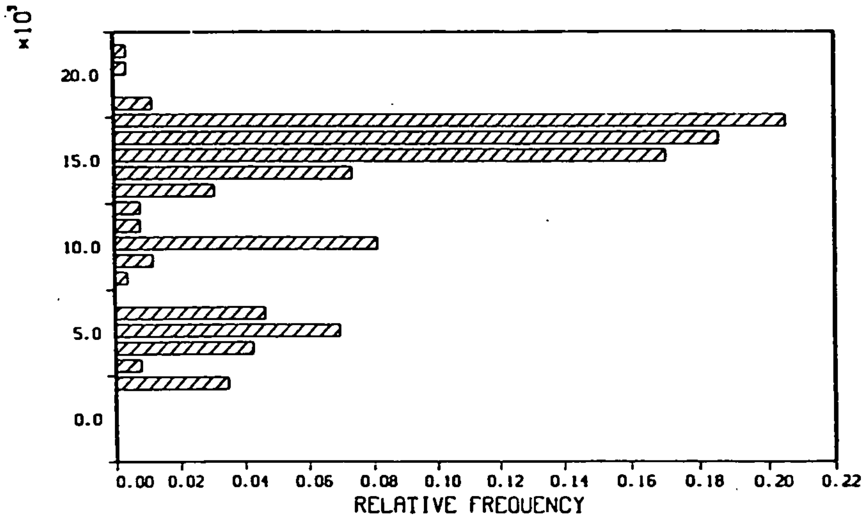


Figure E-3. Histogram—Blue Line car-miles (Feb. 1–Oct. 15, 1980).

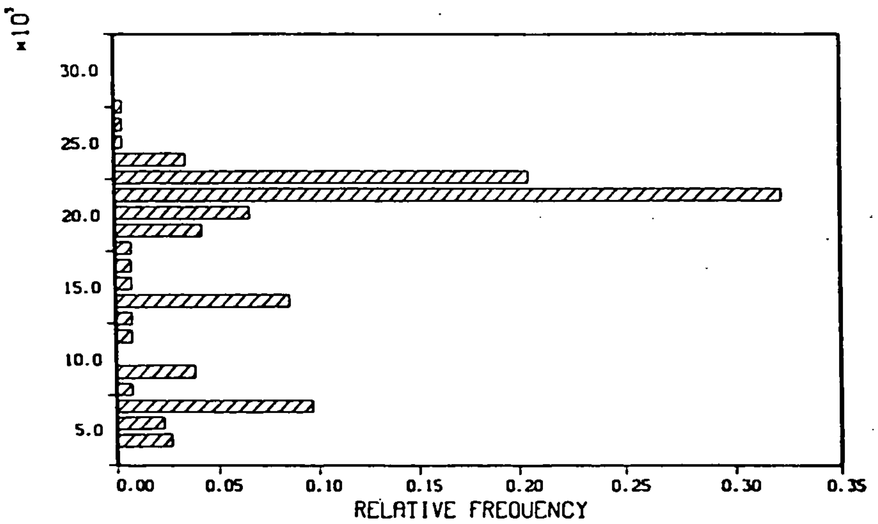


Figure E-4. Histogram—Orange Line car-miles (Feb. 1–Oct. 15, 1980).

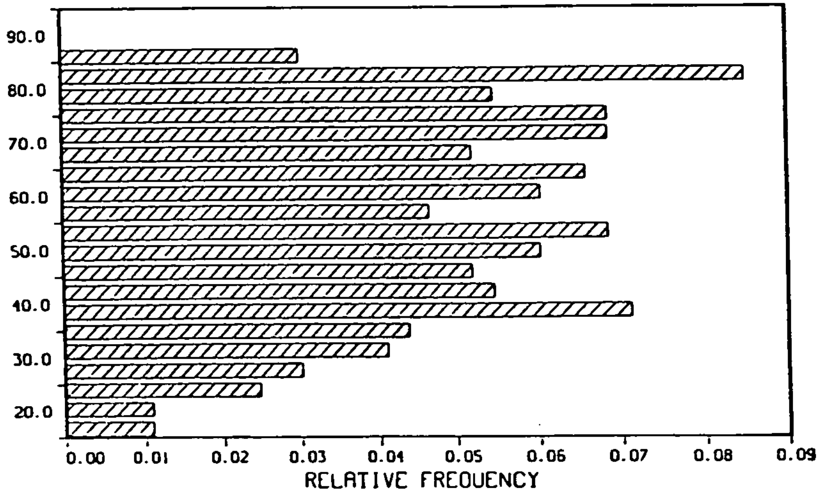


Figure E-5. Histogram—average degree day (Feb. 1–Oct. 15, 1980).

Table E-1. Results of regression analysis for power vs. car-miles and degree-days.

RED LINE METER NAME (SYMBOL)	REVENUE SERVICE TIME*			NON-REVENUE SERVICE TIME**	
	P_0(KW)	E_1(KWHPCM)	P_2(KWPDD)	P_0(KW)	P_2(KWPDD)
Farragut North (MA1)	222	0.90	-1.1	93	0.4
Gallery Place (MB1)	134	0.88	N	98	N
Union Station (MB2)	95	0.69	N	133	N
New York Avenue (MB3)	217	0.75	N	321	N
Rhode Island Avenue (MB4)	44	0.73	-1.6	75	-0.7
Brookland Avenue (MB5)	261	1.00	-3.3	274	-2.6
New Hampshire Avenue (MB6)	170	0.63	N	323	6.3
Takoma Park (MB7)	71	0.82	-2.9	107	-1.4
Silver Spring (MB8)	449	0.62	N	388	N
Coincident Red	1844	6.87	-11.6	1853	N
ORANGE/BLUE LINE METER NAME (SYMBOL)					
Shirley Highway (MC8)	197	.30	7.8	256	6.6
Washington Boulevard (MC6)	106	.60	0.7	81	-0.7
Rosslyn (MC5)	60	.50	3.7	220	2.6
Potomac (MC4)	43	.50	N	91	-0.7
Farragut West (MC3)	-11	.58	1.3	54	N
Metro Center (MC1)	52	.55	2.2	31	N
Smithsonian (MD2)	51	.51	0.9	36	N
Federal Center (MD4)	-57	.40	0.6	22	N
Seward Square (MD6)	64	.62	1.2	41	N
Potomac Avenue (MD7)	-82	.36	N	75	1.7
Stadium Armory (MD8)	197	.55	N	73	-0.3
Minnesota Avenue (MD9)	123	.53	N	79	0.6
Deanwood (MD10)	111	.49	1.7	79	-10.7
Cheverly (MD11)	96	.54	N	132	-1.0
Landover (MD12)	254	.31	2.8	222	-8.4
Beaver Dam Creek (MD13)	176	.39	2.2	266	N
New Carrollton Yard (MDY)	639	.24	7.8	981	6.5
Coincident Blue/Orange (Except MD11, MD12, MD13, MDY)	895	5.52	18.7	1156	N
Coincident Blue/Orange	1526	5.73	37.1	1796	8.2

*Revenue Operating Time

	Red Line	Blue/Orange Line
Weekdays	00:00-00:45; 05:15-24:00	00:00-00:45; 05:30-24:00
Saturdays	00:00-00:45; 07:30-24:00	00:00-00:45; 07:30-24:00
Sundays	09:30-18:45	09:30-18:45

**Non-Revenue Operating Time

	Red Line	Blue/Orange Line
Weekdays	00:45-05:15	00:45-05:30
Saturdays	00:45-07:30	00:45-07:30
Sundays	00:00-09:30; 18:45-24:00	00:00-09:30; 18:45-24:00

N - Not significant with 95% Confidence Limits.

Regression Equations

$P = P_0 + E_1(CM/H) + P_2(DD)$

P : Average Power (KW)
P_0: Background Power (KW)
E_1: KWHPCM (Car-Mile Component Coefficient)
CM/H: Average Car-Miles/Hour
P_2: KWHPDD (Degree-Day Component Coefficient)
DD: Degree-Day

1. The minimum power through any traction meter is the no-load losses of the transformer-rectifier units in the substations. These are estimated at 8 kW/unit. (Data on number of units and no-load losses per unit obtained from George Care, 11/31/81 and 12/18/81.) These no-load losses are also shown in the table.

2. The average layup power used by a car is 5 kW. This number is based on a measured value (Edgar Green, Office of Equipment Design).

The background power for peak and non-peak operation differs because of the layup power of the auxiliaries on board the cars that are stored during non-peak operation.

Table E-3 analyzes the effect of temperature on power. Table E-3, based on Table E-1, shows the degree day coefficient for 5 meter consolidations separated by heating and cooling effect. Load differences between winter (20-30F) and summer (80-90F) are also tabulated. For example, for nonrevenue service time the summer-winter power differential is (235 kW-67 kW) 168 kW.

Several of the meters were found to exhibit increased power with rising temperature (cooling effects dominate P_2 positive), while others exhibit increased power with falling temperature (heating effects dominate P_2 negative). The large cooling effects occur at New Hampshire Avenue, Shirley Highway, Rosslyn, Potomac Avenue and New Carrollton Yard. The effects at Shirley Highway and Rosslyn are the results of chiller plant power being metered through the traction substation and the effect at New Carrollton Yard is due to air conditioning of the yard office building and tower.

An effort was made to quantify the extent of variation of

Table E-2. Derived background of PEPCO traction meters on Red, Orange, and Blue Lines.

METER NAME	LINE	LOCATION (MILEPOST)	SYMBOL	AUXILIARY RATED KW	NUMBER OF 2000 KW TRANSFORMER-RECTIFIER UNITS	NO LOAD LOSSES (KW)	NON-REVENUE SERVICE TIME POWER (KW)	CAR LAYUP POWER (KW)	MINIMUM BACKGROUND (KW) (AM-PM PEAK)	MIDDAY & EVENING BACKGROUND (KW)
Farragut North	Red	0.434	MA1	-	3	24	88		88	88
Gallery Place	Red	1.504	MB1	-	3	24	98		98	98
Union Station	Red	2.508	MB2	-	2	16	133		133	133
New York Avenue	Red	3.610	MB3	150	2	16	321	200	121	241
Rhode Island Avenue	Red	4.468	MB4	-	3	24	84		84	84
Brookland Avenue	Red	6.029	MB5	150	3	24	306		306	306
New Hampshire Avenue	Red	7.199	MB6	150	2	16	250		250	250
Takoma Park	Red	8.730	MB7	-	2	16	124		124	124
Silver Spring	Red	9.904	MB8	-	3	24	388	180	208	328
									1412	1652
Shirley Highway	Blue	1.676	MC8	1500	2	16	163		163	163
Washington Boulevard	Blue	2.796	MC6	500	2	16	90		90	90
Rosslyn	Blue/Orange	4.004	MC5	750	3	24	184		184	184
Potomac	Blue/Orange	5.225	MC4	600	2	16	100		100	100
Farragut West	Blue/Orange	6.171	MC3	-	3	24	54		54	54
Metro Center	Blue/Orange	7.036	MC1	-	3	24	31		31	31
Smithsonian	Blue/Orange	7.770	MD2	-	2	16	36		36	36
Federal Center	Blue/Orange	8.545	MD4	-	2	16	22		22	22
Seward Square	Blue/Orange	9.313	MD6	-	2	16	41		41	41
Potomac Avenue	Blue/Orange	10.748	MD7	500	3	24	52		52	52
Stadium Armory	Blue/Orange	11.387	MD8	225	2	16	77		77	77
Minnesota Avenue	Orange	12.878	MD9	-	2	16	71		71	71
Deanwood	Orange	13.891	MD10	-	2	16	213		213	213
Cheverly	Orange	15.042	MD11	-	2	16	140		140	140
Landover	Orange	16.447	MD12	112.5	2	16	287		287	287
Beaver Dam Creek	Orange	17.395	MD13	75	2	16	266		266	266
New Carrollton Yard	Orange	18.314	MDY	1500	2	16	929	600	329	599
									1134(w/o MD11, 12, 13, Y)	

CAR LAYUP INFORMATION	NUMBER OF CARS	
	NIGHT	MIDDAY
Silver Spring	36	24
Brentwood Yard	40	16
New Carrollton Yard	120	54
Ballston	24	6
National Airport	36	18

Table E-3. Temperature dependent coefficient of regression analysis and load differences for traction meter consolidation.

	P_2(KWPADD)		P_2(KWPMDD)	
	Revenue Service Time		Non-Revenue Service Time	
	Negative	Positive	Negative	Positive
Red Line	8.9	0	4.7	6.7
Blue/Orange Line	0	32.9	21.8	16.3
D.C. Jurisdiction	8.9	7.9	16.4	9.0
MD Jurisdiction	0	12.8	9.4	6.5
VA Jurisdiction	0	12.2	0.7	9.2

LOAD DIFFERENCES (KW)

	P(30°)-P(70°)	P(90°)-P(70°)	P(20°)-P(70°)	P(80°)-P(70°)
Red Line	356	0	235	67
Blue/Orange Line	0	658	1090	163
D.C. Jurisdiction	356	158	820	90
MD Jurisdiction	0	256	470	65
VA Jurisdiction	0	244	35	92

cooling and heating on some of the support meters. This effort is described in the next section.

E.4 EXAMINATION OF THE TUB SHAPE

In this section an effort was made to isolate the effect of heating and cooling on traction energy consumption during nonrevenue service time. It is assumed that the relationship of traction power *P* on temperature *T* should be of the tub form shown in Figure E-6(a and b).

In Figure E-6(a), the change of power with respect to temperature *T* is more abrupt or time based. There are three distinct temperature zones, which are as follows:

1. Predominant heating zone starting at B and extending towards left at low temperatures.
2. Predominant cooling zone starting at C and extending towards right at high temperature which is due to air conditioning at high temperatures.
3. No predominant heating and cooling effects from B to C at moderate temperatures.

In Figure E-6(b) the change of power with respect to temperature is gradual or ambient temperature based.

Certain meters were analyzed and an attempt was made to find the shape of the tub. For some meters tub was found to be smooth, while for others it was abrupt. We also found sta-

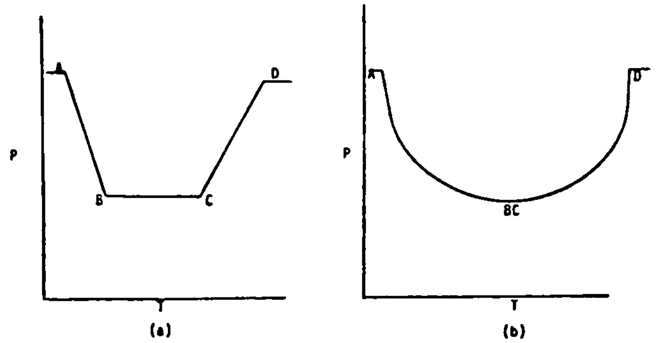


Figure E-6. Relation of traction power P on daily temperature T.

tistically significant cut-off temperature points. The extent of heating and cooling effect was found using regression and test on variance. The following provides the methodology used to examine the tub shape.

E.4.1 Procedure of Analysis

We did series of regression on different meters with changing minimum and maximum cut-off for temperatures in regression analysis. Table E-4 shows the regression for one of the typical meters MOB (office buildings). To examine heating effect, maximum temperature was increased in steps of five starting from 30F. All the points above this maximum temperature were discarded in the regression analysis. The description of each column is as follows:

Column (1) = Cut-off temperature.
Column (2) = Background power not affected by temperature.
Column (3) = Coefficient β in kW/D-Day.
Column (4) = Variance of β.
Column (5) = Variance of *MDD*.
Column (6) = Variance of error $\sigma^2(\epsilon)$ using the following relation: $\sigma^2(\epsilon) = \sigma^2(\beta)^* \sigma^2(MDD)$.
Column (7) = Ratio of successive error variance.

To find the cut-off temperatures in heating zone, the variance of error was analyzed. Let us suppose we are analyzing heating effect shown in Figure E-7.

We have done successive regressions by selecting points up to A_1, A_2, . . ., etc. (with A_1, A_2, . . . as maximum cut-off temperature). The slopes of successive regressions will be quite the same as long as we are on A to B line and variance of error should be small. As soon as we move beyond B (towards C) slopes will differ substantially and the regression line will follow path E_1E_2. At this point variance of error will also increase substantially. This can give an estimate of cut-off temperature point B. Our hypothesis now is to test statistically successive error variances and find the range of temperature where they differ significantly.

Similarly, to determine cooling effect zones, series of regression were done with different minimum cut-off points for temperature. All the points below this minimum temperature were discarded from the analysis. Table E-5 shows the result of regression for one of the typical meter MOB. Description of each column is similar to that for Table E-4. Minimum temperature was increased in steps of five starting from 30F. Test on change in variance was done in the fashion as described for heating effect.

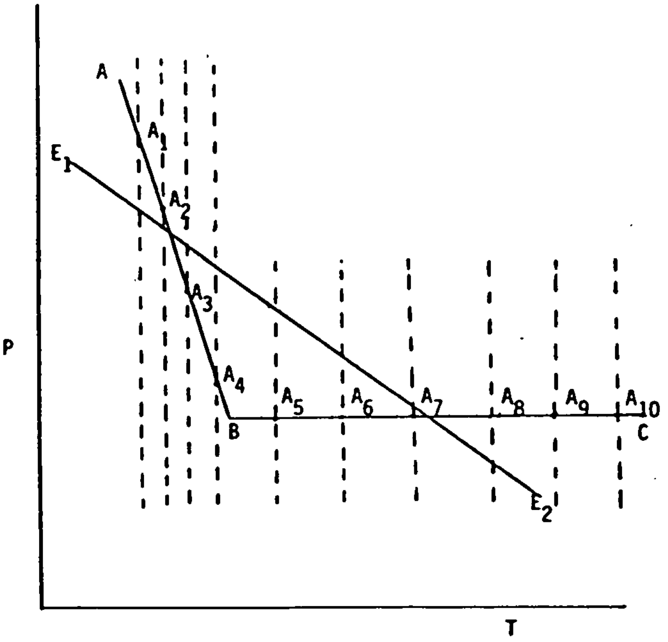


Figure E-7. Demonstration used in the analysis of variance.

As in the heating effect case, our hypothesis now is to test statistically successive error variances and find the range of temperature where they differ significantly, which means we want to test the hypothesis:

$$H_0: \sigma_1^2(\epsilon) = \sigma_2^2(\epsilon)$$

against

$$H_1: \sigma_1^2(\epsilon) \neq \sigma_2^2(\epsilon).$$

This was done statistically using the F test. Successive σ^2 ratios were computed and their significance was tested using the F test at 95 percent confidence level.

E.4.2 Analysis of Tub Shape

Several meters were analyzed using techniques described in the preceding subsection. The meters are: MOB (Office Building), MGCS (Garden City Shop), and MRS (T-St. Repair Shop (Brentwood)). The regression result for each meter is described in the following:

1. *MOB*—As is evident from Tables E-4 and E-5, it has predominant heating and cooling effects at the extreme temperatures, but the change is so gradual that it is statistically insignificant at adjacent temperatures. There is a gradual change in heating effect, and cut-off temperature should lie between 60-65 F. The regression equation at 60 F is $P = 1089.11 - 7.03(T\text{-}70\ F)$, while at 65 F is $P = 1354.74 + 29.16(T\text{-}70\ F)$.

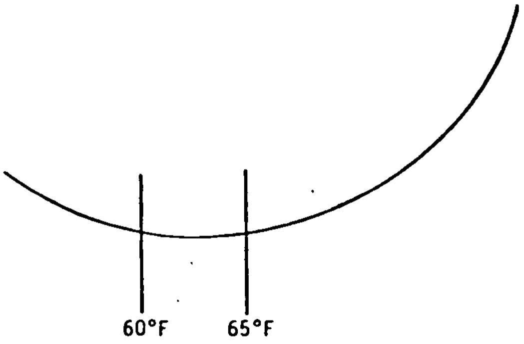
Table E-4. MOB during nonrevenue operation analysis of heating effect.

CUT-OFF TEMP (<) (°F)	INTERCEPT (kW)	β_i (kW/DDay)	$\sigma^2(\beta_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\varepsilon_i)=\sigma^2(\beta_i)*\sigma^2(X_i)$ -	$\frac{\sigma^2(\varepsilon_i)}{\sigma^2(\varepsilon_{i-1})}$ -
92	1499.11	8.64	0.64	335.62	214.80	
85	1463.58	6.92	0.67	304.85	204.25	1.052 > F(286,272)
80	1388.18	3.58	0.69	256.96	177.30	1.152 > F(272,235)
75	1310.64	0.49	0.83	209.67	174.03	1.019 > F(235,201)
70	1238.47	-2.15	0.94	171.35	161.07	1.081 > F(201,174)
65	1196.88	-3.59	1.17	135.96	159.07	1.013 > F(174,148)
60	1089.11	-7.03	1.72	101.00	173.72	1.092 < F(124,148)
55	958.71	-10.95	2.43	72.59	176.39	1.015 < F(103,124)
50	903.77	-12.51	3.57	55.35	197.60	1.120 < F(87,103)
48	808.51	-15.14	4.00	49.00	196.00	1.008 < F(87, 79)
45	693.45	-18.21	5.43	41.60	225.89	1.153 < F(68, 79)
43	711.05	-17.76	6.97	37.70	262.77	1.163 < F(60, 68)
40	726.68	-17.36	12.60	28.62	360.61	1.372 < F(44, 60)
35	477.90	-23.14	26.94	18.32	493.54	1.369 < F(24, 44)
30	245.09	-28.14	63.84	12.60	804.38	1.630 < F(11, 24)

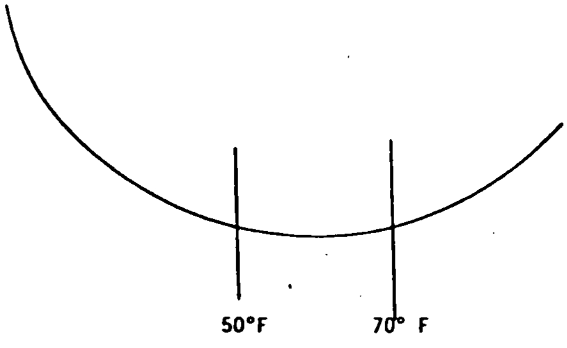
Table E-5. MOB during nonrevenue operation analysis of cooling effect.

CUT-OFF TEMP (>) (°F)	INTERCEPT (kW)	β_i (kW/DDay)	$\sigma^2(\beta_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\varepsilon_i)=\sigma^2(\beta_i)*\sigma^2(X_i)$ -	$\frac{\sigma^2(\varepsilon_i)}{\sigma^2(\varepsilon_{i-1})}$ -
85	1529.56	20.23	859.66	3.28	2819.68	
80	1184.19	40.54	120.12	8.82	1059.46	2.66 > F(33, 70)
75	1306.96	32.72	41.60	16.89	702.62	1.508 = F(70, 96)
70	1334.40	30.80	15.37	31.92	490.61	1.432 > F(96,126)
65	1354.74	29.16	7.18	52.42	376.38	1.303 > F(126,156)
60	1405.40	24.47	4.33	73.62	318.77	1.181 > F(156,177)
58	1410.89	23.91	3.84	79.57	305.55	1.043 > F(177,182)
55	1431.74	21.68	2.86	97.81	279.74	1.092 > F(182,196)
50	1448.06	19.64	2.13	121.44	258.67	1.082 > F(196,210)
45	1467.94	16.85	1.44	161.04	231.90	1.115 > F(210,230)
40	1480.22	14.74	0.98	210.54	206.33	1.124 > F(230,253)
35	1490.58	17.46	0.81	253.13	205.04	1.006 > F(253,271)
30	1496.60	10.55	0.67	295.50	197.99	1.036 > F(271,286)
18	1499.11	8.64	0.64	335.62	214.80	0.922 < F(286,296)

This is a typical office type condition where you have air conditioning as well as heating running simultaneously for some time. There is a predominant cooling effect on an overall basis. The tub shape is smooth and not abrupt. A typical example of an ambient temperature base follows:



2. *MGCS*—As is evident from Tables E-6 and E-7, there is a significant heating effect. There is an abrupt increase in variance between 50 F to 55 F; therefore, cut-off temperature should be around 50 F. The regression equation at 50 F is $P = 235.44 - 18.77(T\text{-}70\ F)$. Similarly, there is a significant cooling effect. Cut-off temperatures in each zone are distinguishable. A typical example of an abrupt or time base tub shape is as follows:



Overall is a predominant heating effect.

3. *MRS*—There is a gradual increase in heating effect and is predominant. As is evident from Tables E-8 and E-9, that cut-off temperature for heating effect should be between 75 to 80 F. There is no cooling effect.

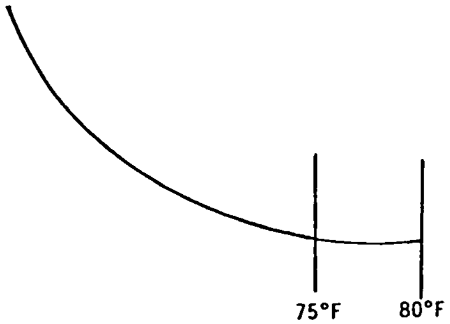


Table E-6. MGCS during nonrevenue operation analysis of heating effect.

CUT-OFF TEMP (<) (°F)	INTERCEPT (kW)	β_i (kW/DDay)	$\sigma^2(\beta_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\epsilon_i)=\sigma^2(\beta_i)*\sigma^2(X_i)$ -	$\frac{\sigma^2(\epsilon_i)}{\sigma^2(\epsilon_{i-1})}$ -
90	332.92	-15.14	2.34	160.78	376.23	
85	324.85	-15.94	2.86	146.17	418.05	1.111 < F(94,100)
80	313.51	-16.92	4.45	122.55	545.35	1.305 < F(82, 94)
75	313.22	-16.93	8.12	97.61	792.59	1.453 < F(67, 82)
70	334.74	-15.73	14.14	79.39	1122.57	1.416 < F(52, 67)
65	371.47	-13.77	23.33	66.10	1542.11	1.374 < F(39, 52)
60	462.51	-9.93	35.40	52.42	1855.67	1.203 < F(26, 39)
55	350.59	-14.23	73.44	32.83	2411.04	1.299 < F(16, 26)
50	235.44	-18.77	45.16	10.05	453.86	5.312 > F(16, 10)
45	65.20	-14.47	53.29	5.66	301.62	1.505 < F(10, 7)

Table E-7. MGCS during nonrevenue operation analysis of cooling effect.

CUT-OFF TEMP (>) (°F)	INTERCEPT (kW)	β_i (kW/DDay)	$\sigma^2(\beta_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\epsilon_i)=\sigma^2(\beta_i)*\sigma^2(X_i)$ -	$\frac{\sigma^2(\epsilon_i)}{\sigma^2(\epsilon_{i-1})}$ -
80	138.46	1.33	0.40	8.01	3.204	
75	194.84	-2.68	7.78	14.90	115.94	36.179 > F(33, 23)
70	236.09	-5.55	9.42	29.05	273.65	2.361 > F(48, 33)
65	301.64	-11.58	8.18	47.06	384.95	1.407 < F(63, 48)
60	321.55	-13.75	6.76	68.72	464.55	1.207 < F(77, 63)
55	344.96	-16.97	5.15	87.61	451.19	1.030 < F(27, 86)
50	333.16	-15.16	4.88	96.24	469.65	1.041 < F(85, 86)
45	333.72	-15.30	3.72	116.64	433.90	1.082 < F(89, 93)
40	332.41	-14.98	2.50	152.52	381.30	1.138 < F(93, 99)
35	332.92	-15.14	2.34	160.78	376.23	1.013 < F(99,100)

Table E-8. MRS during nonrevenue operation analysis of heating effect.

CUT-OFF TEMP (<) (°F)	INTERCEPT (kW)	β_i (kW/DDay)	$\sigma^2(\beta_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\epsilon_i)=\sigma^2(\beta_i)*\sigma^2(X_i)$ -	$\frac{\sigma^2(\epsilon_i)}{\sigma^2(\epsilon_{i-1})}$ -
85	522.98	-0.13	0.028	310.11	8.68	
80	514.18	-0.51	0.033	262.11	8.65	1.003 = F(257,221)
75	503.17	-0.95	0.045	215.80	9.71	1.122 > F(189,221)
70	490.89	-1.39	0.053	177.42	9.40	1.033 = F(189,162)
65	489.37	-1.44	0.068	144.24	9.81	1.044 < F(139,162)
60	500.67	-1.09	0.108	107.95	11.66	1.189 < F(115,139)
55	514.74	-0.68	0.175	78.32	13.71	1.176 < F(95,115)
50	539.18	0.01	0.261	59.75	15.59	1.137 < F(80, 95)
45	578.36	1.07	0.364	42.25	15.38	1.014 < F(80, 61)
40	575.76	1.01	0.642	28.41	18.24	1.186 < F(43, 61)
35	-0.06	-2.73	1.501	36.00	54.04	2.96 > F(32, 43)

Table E-9. MRS during nonrevenue operation analysis of cooling effect.

CUT-OFF TEMP (>) (°F)	INTERCEPT (kW)	B_i (kW/DDay)	$\sigma^2(B_i)$ -	$\sigma^2(X_i)$ -	$\sigma^2(\epsilon_i) = \sigma^2(B_i)\cdot\sigma^2(X_i)$ -	$\frac{\sigma^2(\epsilon_i)}{\sigma^2(\epsilon_{i-1})}$ -
85	715.88	-10.94	34.72	3.334	115.76	
80	556.40	-1.53	5.485	8.94	49.04	2.361 > F(32, 68)
75	546.53	-0.91	1.831	16.89	30.93	1.586 > F(68, 92)
70	522.02	0.85	0.741	32.38	23.99	1.289 < F(92,121)
65	510.87	1.75	0.354	53.58	18.97	1.265 < F(121,149)
60	511.75	1.65	0.213	74.82	15.94	1.190 > F(149,170)
55	512.13	1.61	0.135	99.00	13.37	1.192 > F(170,188)
50	515.58	1.20	0.102	121.88	12.43	1.076 > F(188,201)
45	519.53	0.63	0.072	161.03	11.59	1.072 > F(201,220)
40	522.31	0.17	0.053	203.35	10.78	1.075 > F(220,238)
35	523.30	-0.04	0.04	246.80	9.87	1.092 > F(238,254)
ALL	523.49	-0.11	0.025	340.40	8.51	1.160 > F(254,280)

APPENDIX F

RESULTS OF TRANSIT AGENCY SURVEY

A questionnaire (Exhibit 1) was sent to 12 rail transit agencies outside of the United States. Its purpose was to identify energy conservation programs and load management techniques now being applied on these systems. Nine responses (Exhibits 2–10) were received. These responses are included in this section together with a copy of the questionnaire.

EXHIBIT 1

The objective of this questionnaire is to identify energy conservation programs and electric power load management techniques which are used on rail transit systems outside of the United States. We are only interested in those transit systems which are electrically powered. Any literature which you have to enhance your answers to the questionnaire would be appreciated.

1. What is your annual electric power cost?
2. What portion of your electric power requirements is purchased as opposed to self-generated?
3. What is the ratio of purchased electric power cost to total operating cost?
4. Do you have both a power demand and energy component in your electric power cost?
5. What is the energy component unit cost (cost per kWh)?
6. What is the demand component unit cost (cost per kWh)?
7. What portion of the electric power cost is energy and what portion is power demand?
8. If you have a formal energy conservation program, please describe it. (Please include organization, budget, types of activities, strategies, and expected energy cost reduction goals for energy cost reduction.)
9. If you have a formal power load management system in operation, please describe it. (Include how power demand is monitored, prediction techniques, and strategies which are executed when demand projection is exceeded.)

We greatly appreciate your attention in this matter.

EXHIBIT 2

Hamburger Verkehrsverbund HVV

[illegible]

MELLON INSTITUTE
Rail Systems Center
4617 Winthrop Street

Pittsburgh, Pennsylvania 15213

USA

Ihre Zeichen	Ihre Nachricht vom	Unsere Zeichen	Fernruf (040) 22 60 60	Hamburg
	18. 6. 82	11 vRu-NgZ	Durchwahl 22 606 103	16. 7. 1982

Betrifft
Your questionnaire

Dear Sirs,

we consulted our association members Hamburger Hochbahn AG (HHA) and Deutsche Bundesbahn (DB), Federal Railway Direction Hamburg, who operate the rail transit as subway (U-Bahn) and urban railway (Gleichstrom-S-Bahn). Unfortunately electric power cost of the urban railway is confidential. The electric costs of the subway are in June 1982 prices.

We answer your questions as follows:

1) subway :the annual electric power cost is 10,7 million DM plus added-value-tax
   urban railway:no information

2) both organisations purchase 100 % of the needed electric power

3) subway :8,2 % of the total operating cost is due to electric power
   urban railway:no information

4) subway :only a power demand has to be paid
   urban railway:there is a power demand and an energy component to be paid

5) subway :no energy component
   urban railway:no information

6) subway : the price of the demand component unit is 0,1509 DM/kWh plus added-value-tax

urban railway : no information

7) subway : no energy component

urban railway : no information

8) subway : no energy conservation program. Approaching a station the driver cuts off the energy supply, the train rolls towards the station, reaching the platform at a speed of 40 km/h.

urban railway : If the consumption of energy is too high, unimportant users such as heating systems in the trains are cut off for several minutes. The drivers get the command by radio. The headquarter surveys only the maximum 15 minutes.

9) neither the subway nor the urban railway operate a power load management system.

For your information we enclose a table with all necessary data on the Hamburg Transport Community (HVV).

We hope, the answers are to your satisfaction. We look forward to the summary of the answers of the other transit systems.

Sincerely yours,

Hamburger Verkehrsverbund

Enclosure

EXHIBIT 3

London Transport
55 Broadway
London SW1H 0BD
Telephone 01-222 5600

Extension

Our reference 841/PJA

Your reference

Mr. Richard A. Uher,
Director,
Mellon Institute,
Rail Systems Center,
4617 Winthrop Street,
Pittsburgh,
Pennsylvania 15213,
U.S.A.

29 July 1982

Dear Mr. Uher,

Thank you for your letter of 18 June 1982, with reference to the study you are conducting for the Transportation Research Board of the National Academy of Science, and I am so sorry that I have been unable to reply earlier.

After serious consultation with the department of our Chief Electrical Engineer, the conclusion has been arrived at that the particular information you seek could only be obtained after a great deal of probing and analysis. Therefore, in order to expedite the matter, I feel I can do no better than give you the following facts:

London Transport's 257 mile network over which 30,000,000 train miles are operated annually requires a combined daily peak demand of 180,000 kw, and an annual consumption of 908,600,000 units for both traction and non traction purposes at a total cost of £30,000,000 (excluding HV distribution depreciation etc.).

Furthermore, London Transport generates approximately 75% of its total energy requirements and purchases 25% from the National Grid supply, Electric power costs generated in our own stations vary according to the type of fuel used. Both stations are equipped for dual oil or gas burn. The total cost of operating our two generating stations during 1981 (excluding depreciation rates etc.) was £24,000,000.

Purchased supplies from the grid network are charged according to maximum power demand and total energy used and totalled £6,000,000 in 1981.

Our own generated supplies are operated to run totally independently of the National Grid inputs but the HV distribution system permits

certain open sections of the railway to be fed from either London Transport Generating stations or from Grid sources. This gives a facility for power load management, which is exercised on a day to day basis according to the operational needs of the system.

I do hope that this information will be of assistance to you.

Yours sincerely,

G. K. B. Benson.
GEOFFREY BENSON
Senior Public Relations Assistant

EXHIBIT 4

Commission de transport
de la Communauté urbaine
de Montréal

July 5th 1982

Mr. Richard A. Uher
Mellon Institute
Rail Systems Center
4617 Winthrop Street
Pittsburgh, Pennsylvania
15213 U.S.A.

Subject: Energy Management of Electric Rail Transit Systems.

Dear Sir:

In reply to your request, I am pleased to send you herewith duly filled, the questionnaire you sent us on the above mentioned subject.

Should you require additional information do not hesitate to contact me.

Yours very truly,

George Donato
Director
Engineering Department

GD/rr

QUESTIONNAIRE

1. What is your annuel electric power cost?

   $7 350 000.00 in 1981 for an average cost of $0.028/kwh.

2. What portion of your electric power requirements is purchased as opposed to self-generated?

   Totally purchased.

3. What is the ratio of purchased electric power cost to total operating cost?

   7%.

4. Do you have both a power demand and energy component in your electric power cost?

   Yes. See Appendix A which describes the tariff structure applicable for large industry in 1982.

5. What is the energy component unit cost (cost per kwh)?

   $0.015/kwh based on 1981 unit cost.

6. What is the demand component unit cost (cost per kwh)?

   $0,013/kwh (1981)

7. What portions of the electric power cost is energy and what portion is power demand?

   55% energy and 45% demand.

8. If you have a formal energy conservation program, please describe it.

   Energy conservation:

   - curtailment of fans operation during peak hours and floor heater (winter).
   - train regenerative braking (chopper traction equipment)
   - we have one converter to change DC current in AC to increase the receptivity of the traction network. We are considering the installation of others.
   - dish pan profile: As much as possible we design the tunnel profile to accelerate the trains going down-hill and brake going up-hill.

... 2

9. If you have a formal power load management system in operation, please describe it.

The demand meter sends pulses to a relay that integrates the projected variation for a 15 minutes period. If this projection exceeds a preset value, a signal is sent to our Central Control and an automatic signal shuts off all tunnel fans and floor heaters (in winter) of our passenger stations.

After peak hour (maximum number of trains in service) when this preset value is reached, again an alarm informs Central Control operator to restore fans and heaters operations.

EXHIBIT 5

Stadtwerke München · Verkehrsbetriebe

Stadtwerke München - Verkehrsbetriebe
Postfach 80 18 60 8000 München 80

Einsteinstraße 28
Zimmer
Sachbearbeiter
Durchwahl (089) 2191-/.21 04
Fernschreiber 05 22 063

Werkreferat · Zentrale und Kaufmännische Verwaltung · Elektrizitätswerke · Gas- und Wasserwerke, Badebetriebe · Verkehrsbetriebe

Mit Luftpost

MELLON INSTITUTE
Herrn Direktor
Richard A. Uher
Rail Systems Center
4617 Winthrop Street

Pittsburgh, Pennsylvania 15213

USA

Ihr Zeichen
Ihre Nachricht vom 18.06.82
Unser Zeichen Dpl1/Bey/Wk
München, 15. Juli 1982

Ihre Anfrage zur U-Bahn-Stromversorgung (R. A. Uher) vom 18.06.82

Sehr geehrte Damen und Herren!

Ihren Fragebogen beantworten wir wie folgt:

Zu 1: Die Gesamtkosten für die U-Bahn betrugen 1981 DM 17.934.618

Zu 2: Der Strom wird bezogen von den Stadtwerken München - Elektrizitätswerke. Notstromaggregate sind im U-Bahnbereich vorhanden (für sicherheitsrelevante Komponenten des Systems).

Zu 3: Im Jahre 1981

Gesamtstromkosten	DM 17.934.618
Betriebsaufwand (ohne Abschreibungen)	DM 104.570.298

Zu 4: Stromverbrauch der U-Bahn wird getrennt ausgewiesen nach:

Gesamtverbrauch
Fahrstromanteil
Licht und Kraftanteil (Bahnhöfe)
U-Bahn-Werkstätten (Betriebshof)

<u>Zu 5, 6 und 7:</u>	Fahrstromanteil	86.122.680 KWh = 74.92 %
	Licht- und Kraftanteil	26.390.635 KWh = 22.96 %
	U-Bahn-Betriebshof	2.433.140 KWh = 2.12 %

Der Strombezugspreis für die U-Bahn betrug 1981 DM 0,15 pro KWh.

<u>Zu 8 und 9:</u>

Zur Einsparung der Stromkosten wird u. a. auch der neue U-Bahn-Wagentyp beitragen. Dieser hat Drehstromantrieb und kann beim Bremsen Strom in den Einspeisungsabschnitt des Netzes rückspeisen.

Bei der Bahnhofsbeleuchtung kann zeitweise eingespart werden.

Kurz beschrieben <u>zu 9:</u>

- Elektrizitätswerk liefert 10 KV Spannung an Unterwerke der U-Bahn.
- Unterwerke transformieren und richten gleich auf 750 V (dc); ohne Bedienungspersonal
- Zentrale Schaltwarte der U-Bahnstromversorgung mit rechnerunterstützter Fernwirkanlage sowie mit doppelt ausgestalteten Überwachungsarbeitsplätzen.
- Anzeigen über Datensichtgeräte.
  Analogaufzeichnung des Stromverbrauches.
  Konzeption bleibt.

Mit freundlichen Grüßen

I. A.

Beyer

Beyer
Ang.i.geh.techn.Dienst

Dear Ladies and Gentlemen,

Your questionnaire is answered as follows:

1-- The total costs for the subway in 1981 amounts to 17,934,618 DM.

2-- The current is supplied from the city works of Munich-Electricity works. There are emergency generators in the subway systems for components that are important for the security of the system.

3-- In year 1981, total cost: DM 17934618 Expenses-- (without depreciation) DM 104570298

4-- The current consumption of the subway is split up as follows: Total consumption, current for rail ways(what actually drives the engines), Light and energy used for train stations, and subway work-shops(like garages).

5,6,7--Current for rail ways: 74.92%, Light and energy used for train stations: 22.96%, Subway work-shops: 2.12%.

8,9--One of the factors that will contribute to energy conservation is a new type of subway. This system is driven by 3-phase current, and so by slowing down it is able to put the current back into a certain part of the current system. The lighting of the stations can be reduced.

Short description of 9(Key points are:)

-- The local current supply provides voltage of 10KV to the secondary plants of the subway. Secondary plants transform this current, and at the same time change it to 750V (dc) without help from personnel.

-- Important parts are: a central switchboard of the subway supply, with remote control monitoring by computers, supplemented by two supervisor stations.

-- Announcements on terminals (CRT's)

-- Analog recordings of the current consumption.

-- No change.. everything stays as planned.

EXHIBIT 6

REGIE AUTONOME DES TRANSPORTS PARISIENS RATP

53 TER QUAI DES GRANDS AUGUSTINS 75271 PARIS CEDEX 06 TEL 346 33 33

DIRECTION DES SERVICES TECHNIQUES
2 BOULEVARD DIDEROT
75012 PARIS

TÉLEX : 680 407 TECMET-PARIS

Pour la présente affaire
tél : 346.33.68

24 AOUT 1982

TT 1755
P.J. : 1

MELLON INSTITUTE
Rail Systems Center
4617 Winthrop Street
Pittsburgh, Pennsylvania 15213
(U.S.A.)

Monsieur le Directeur,

Par lettre du 18 juin 1982, vous avez transmis à la RATP un questionnaire relatif à l'étude "Energy Management of Electric Rail Transit Systems", que vous menez actuellement.

J'ai le plaisir de vous adresser ci-jointe la réponse, que nous avons préparée, aux différentes questions posées.

En espérant que ces éléments répondront à votre attente, je vous prie d'agréer, Monsieur le Directeur, l'assurance de ma considération distinguée.

Le Directeur des Services Techniques

Questionnaire du MELLON INSTITUTE

Etude "Energy Management of Electric Rail Transit Systems"

Question n° 1

Pour l'année 1981, la consommation d'énergie a été approximativement de 950 000 MWh, pour un coût de l'ordre de 220 MF.

Question n° 2

En situation normale, l'énergie est entièrement fournie par Electricité de France, compagnie nationale productrice et distributrice.

Les divers modes de fonctionnement des générateurs de secours, à puissance limitée, représentent une production très faible, de l'ordre de 0,03 % de la consommation totale.

Question n° 3

Pour le réseau ferré (Métro et RER) le coût de l'énergie consommée est environ 4 % des charges d'exploitation.

Questions n° 4, 5 et 6

La tarification en vigueur impose une prime fixe fonction de la puissance demandée, et une facturation fonction de l'énergie consommée, selon une grille complexe tenant compte d'un régime d'été et d'un régime d'hiver, de périodes d'heures creuses et d'heures de pointe.

Question n° 7

La part de la facturation fonction de l'énergie consommée est comprise entre 75 et 80 % de la facturation totale.

Question n° 8

Depuis plusieurs années, la RATP a conduit un programme d'actions et d'études portant sur les économies d'énergie.

Les actions ont été menées dans tous les secteurs : réseau ferré, réseau routier, bâtiments et ateliers.

En 3 ans, ces actions ont permis une économie globale, toutes installations et réseaux confondus, de plus de 10 %.

La participation la plus importante est celle du réseau ferré, où la modernisation progressive du matériel roulant a permis de constituer un parc où actuellement près de 50 % des trains sont dotés d'équipements de récupération d'énergie (l'équipement à hacheurs à thyristors autorise une récupération allant jusqu'à 35 %). Des actions ont été aussi menées dans les domaines de l'éclairage, de la ventilation, des escaliers mécaniques. D'autre part, des études plus globales sur le fonctionnement des lignes montrent l'intérêt de cette voie de recherche.

Les actions menées dans le domaine des bâtiments et ateliers (politique de chauffage, de modernisation et d'entretien) et au réseau routier, par la meilleure maîtrise des consommations des autobus, ont eu également une part significative dans les économies réalisées.

Question n° 9

L'ensemble des installations de transformation et de distribution d'énergie est actuellement télécommandé et télécontrôlé depuis un poste central d'énergie (PCE), proche des postes de commande centralisée d'exploitation de ligne.

Outre les moyens d'action directe par télécommande, le PCE dispose de moyens informatiques de surveillance, d'enregistrement, et de traitement.

Mr. Director,

In your letter of June 18, 1982, you transmitted to RATP a questionnaire in regards to the study "Energy Management of Electric Rail Transit Systems" that you are actually directing.

I have the pleasure to address to you here the answers which we prepared to the different questions you posed.

I hope that the responses to which I've given my uttmost attention will answer your questions.

1— For the year 1981 the energy consumption was approximately 950000 MWh, for a cost in the order of 220 MF.

2— In normal situations, the energy is entirely supplied by "Electricite de France", a national company, that is both a producer and a distributor. The different modes of operation of the secondary generators, represent a very weak production, in the order of 0.03% of the total consumption.

3— For the rail way, the cost of energy consummed is approximately 4% of the charges of "exploitation".

4, 5, 6—There is a fixed cost of power demand and a price list for energy consumption, according to a scheme for summer and a scheme for winter, during periods of peak and non-peak hours.

7— The price list of the consummed energy is around 75-80% of the total.

8— For several years, RATP has conducted a program and study on the economies of energy. These actions were carried out along all sectors: rail-way, street - car systems, buildings and apartments. In 3 years these actions allowed for a system-wide economization of more than 10% over all installations and networks. The most important contribution is that of the rail way, where the modernization of the rolling stock allowed to form a yard, where actually close to 50% of the trains are equipped with machinery to recycle (re-acquire) energy. The actions were also carried out along the light domains, that of ventillation and mechanical staircases. Studies on a greater scale on the functionning of power lines show the interest of this research. The actions carried out in the domain of buildings and apartments (heating, modernization and maintenance), and in the street-car systems also played an equally significant part in the economies considered.

9— Both the transformer installations and the energy distribution are remotely controlled and monitored by PCE which is situated close to the central power consumption controller. The PCE has information means for supervision, registration and transactions.

EXHIBIT 7

COMPANHIA DO METROPOLITANO DE SÃO PAULO – Metrô
CEP 01304 Rua Augusta, 1626 TEL 289-4133
CEP 01000 Caixa Postal 30813
Telex 011 22013 MSPO BR
SÃO PAULO - SP

Ct.P/ 312/82 São Paulo, July 22 , 1982.

Dr. RICHARD A. UTHER
Mellon Institute
Rail Systems Center
4617 Wenthrop Street
Pittsburgh, Pennsylvania 15213

Dear Dr. Richard

In answer to your letter of June 18, 1982, we wish to tell you that :

The São Paulo Metro has now in operation 17 km in the North-South Line and 7,2 km in the East-West Line. Those lines have 20 stations and 7 stations respectively (the Praça da Sé Station, which belongs to the two lines has been included in both of them).

Both lines are electrically fed wholly by the Eletropaulo concessionary.

We do not have our own energy generators, except for a system of generation comprising groups of low potency Diesel generators, which are used only in situations of emergency, to keep some vital equipment working, as well as 50% of ilumination at the stations, computers, fire detection and extinction, some water pumps, battery chargers of the communication systems.

On the North-South Line we now have three(3) primary substations and on the East-West line two(2), which are electrically fed by the concessionary, they receive 88 kV, transform them into 22 kV and feed the rectifier substatios and the low tension substations of the stations.

We will now proceed to answer the questionaire which you have sent us.

1. The annual cost of electric energy, at July 82 prices is Cr$ 370.000.000,00 (three hundred and seventy million cruzeiros). To help you figure out what that sum means we tell you that US$ 1.00 = Cr$ 176,26.

2. All energy used by the São Paulo Metrô is bought, as we have no generation of energy.

3. The electric energy which is used up by the operation of the São Paulo Metrô corresponds presently to 5% of the total operational cost.

Note : Maintenance costs have not been included in the total operational cost.

4. Both power demand and energy component have been included in our cost of electric energy.

5. Unit cost energy component (cost per kWh) is Cr$ 0,8467/kWh.

6. Unit cost of demand component (cost per kW) is Cr$ 288,90/kW.

7. The cost of electric energy is comprised by : 50% of the cost in electric energy;
50% of the cost in energy demand.

8. We do not have a program of energy conservation, as any restriction in energy consumption normally implies a degradation of the operational conditions of the system. We have, never the less, considered the application of strategiers which minimize demand peaks, especially at peak hours, such as for instance the phase displacement of train departures at certain stretches of the lines. In case of electric system failures, a strategy is adopted

which implies a reduction of the acceleration level of the trains and consequently a decrease of the demand; that strategy interferes with revenue operation.

The São Paulo Metrô trains have a system of regenerating brakes, which have a 20% performance (twenty per cent).

9. In our experience, energy demand has been proportional to the number of trains in operation. Considering that the energy consumption of stations is practically constant, supervision of demand is refered to the number of trains in operation.

We thank you for the invitation to participate in your research and will be glad to answer any further questions.

Sincerely,

CÁSSIO FLORIVALDO DE CASTRO
President

EXHIBIT 8

AB STORSTOCKHOLMS LOKALTRAFIK
Utredningsavdelningen
Teknisk utveckling
Vår handläggare, tel ankn
Sture Sahlén, 786 19 45

Datum
1982-07-02
Er datum

Vår beteckning
Unr 013
Er beteckning

Mr Richard A. Uher
Mellon Institute
Rail Systems Center
4617 Winthrop Street
Pittsburgh, Pennsylvania 15213
USA

Dear Mr Uher,

Refering to your letter of June 18, 1982 we have the following answers to your questions.

1. 60 million SEK (excl stations and depots)

2. We purchase 100 %

3. Of the budget cost of 1,73 SEK/carkm , which includes capital, maintenance and salary, the power cost is 0,45 SEK/carkm

4. Our contract for power delivery contains three different parts:

   - cost for power system (substations for transformers and rectifiers)

   - power cost (kW)

   - energy cost (kWh)

   The total price is 0,30 SEK/kWh

5. 0,10 SEK/kWh

6. 0,05 SEK/kWh

7. See point 4-6

8. This year a program for energy conservation will be approved. The goal is to reduce power consumption in the rail system with 15 GWh in the period 1982-1987 and another 15 GWh 1987-1992.

   Total consumption (1981) approx 200 GWh.

The means to achieve this are mainly:

- increase the number of cars equipped with regenerative braking

- more energysaving drivning during off peak hours.

Within our organization we have one man handling energy matters concerning traffic (rail and buses)

9. We have no power load management system

Mr Elmberg, who at the moment is very busy preparing his going back to Gothenburg, has asked me to answer your letter and he sends his best regards.

Yours sincerely

Sture Sahlén

Sture Sahlén

EXHIBIT 9

TORONTO TRANSIT COMMISSION
1900 YONGE STREET, TORONTO, CANADA, M4S 1Z2
TELEPHONE (416) 481-4252, TELEX: 06524670

JULIAN PORTER, Q.C.
CHAIRMAN

KARL L. MALLETTE
VICE-CHAIRMAN

PAUL GODFREY
JEFFERY S. LYONS, Q.C.
JUNE ROWLANDS
COMMISSIONERS

ALFRED H. SAVAGE
CHIEF GENERAL MANAGER

LLOYD G. BERNEY
GENERAL MANAGER – OPERATIONS

STANLEY T. LAWRENCE
GENERAL MANAGER – ENGINEERING AND CONSTRUCTION

DAVID C. PHILLIPS
GENERAL SECRETARY

July 7, 1982

Mellon Institute
Rail Systems Centre
4617 Winthrop Street
PITTSBURGH, Pennsylvania 15213

Attention: Mr.R.A.Uhler

Dear Sirs:

Energy Management -
Traction Power Systems
File Ref: 136.2

Further to your letter of June 18th requesting information on our traction power system, the following and attached comments are provided for your consideration.

The T.T.C. operates streetcars, trolley coaches and a subway system powered by electricity. The traction power systems for the three modes are integrated. In many cases, a substation will feed two or more of the modes.

The T.T.C. also operates a large fleet of diesel buses.

Our specific comments, attached, are based on the number scheme in your questionnaire.

If you have any further questions on our electric traction power system, please contact Mr.R.I.Kingston, Manager of Plant Department, at (416) 534-9511, extension 764.

Yours very truly,

A.H. SAVAGE
Chief General Manager

7-100-10
Attachment

ANSWER TO QUESTIONNAIRE

1. 1981 Annual Traction Electric Power cost is $12,220,953.12.

2. 100% of T.T.C.'s electric power requirements is purchased from Hydro utilities. The five utilities that T.T.C. purchased power from are:

   a) Toronto Hydro
   b) Etobicoke Hydro
   c) Scarborough Public Utilities
   d) North York Hydro
   e) York Hydro

3. Total operating cost for 1981 is $284,000,000.00. The purchased traction electric power is 4.3% of the total operating cost. This operating cost includes all modes of transit, subway, deisel bus, streetcar and trolley coach.

4. Yes, demand and consumption are charged separately by each utility.

5. The average energy component unit cost in 1981 is 2.92¢/KWH.

6. The demand component unit cost in 1981 is 0.92¢/KWH.

7. The energy component is 76% of the electric power cost. The demand component is 24% of the electric power cost.

8. The T.T.C. has a semi-formal energy conservation programme for the traction power system. Conversion of existing mercury arc rectifiers for traction power system to solid state rectifiers will increase the overall system efficiency

8. Cont'd

by 2% from 92% to 94%. The programme was executed in 1975 and should be completed in 1982. The authorized budget was $2,405,900.00. The energy cost reduction goal in 1981 dollars is approximately $245,000. New vehicles are equipped with regenerative braking.

9. No formal power load management system is used as yet. Load sharing is adjustable between traction power substations using transformer taps. Loading conditions are studied and by using tap setting on each rectifier transformer, the load at the substation can be regulated. Load management has been identified in our energy conservation programme and will be studied in detail in the future.

Plant Department
July 5, 1982
7-100-67:10

EXHIBIT 10

Wiener Stadtwerke
Verkehrsbetriebe
Direktion

4, Favoritenstraße 9—11 Postfach 40
A-1041 Wien
Telefon 65 9 30
Vorwahl Wien 0222

Wien, 1982-09-03

D-Zahl: 3600/82/27 Ma
Bei Rückschreiben bitte unbedingt anführen.

Fragebogen Mellon Institute

Sehr geehrter Herr Direktor!

Wir erlauben uns, Ihren Fragebogen wie folgt zu beantworten:

zu Frage 1:

Im Jahre 1981 betrugen die Kosten für den Traktionsstromverbrauch 156,3 Mio S.
Davon entfallen auf den

Straßenbahnbetrieb	59,1 Mio S
Stadtbahnbetrieb	4,4 Mio S
U-Bahnbetrieb	66,0 Mio S.

Nach Fertigstellung des erweiterten U-Bahn-Grundnetzes im heurigen Jahr kann im Jahr 1983 mit Kosten für den Traktionsstromverbrauch der Schienenbetriebe von ca. 182,0 Mio S gerechnet werden.

zu Frage 2:

Der gesamte Traktionsstrom wird bei den Wiener Stadtwerken - Elektrizitätswerke gekauft.

zu Frage 3:

Der Anteil der Stromkosten an den Gesamtbetriebskosten beträgt beim

Straßenbahnbetrieb	2'3 %
Stadtbahnbetrieb	1'6 %
U-Bahnbetrieb	14'3 %.

zu Frage 4:

Eine Aufgliederung in eine Strombedarfs- und Energiekomponente erfolgt nicht.

zu Frage 5 und 6:

Der Arbeitspreis beträgt für den Straßenbahn- und Stadtbahnbetrieb derzeit S 0'574 pro kWh.

Für den Arbeitspreis im U-Bahnbetrieb werden S 1'1095 pro kWh verrechnet.

zu Frage 7:

Siehe Antwort zu Frage 4.

zu den Fragen 8 und 9:

Bei den Wiener Stadtwerken - Verkehrsbetriebe liegt kein offizielles Energiesparprogramm und kein offizieller Stromversorgungs- bzw. Stromverteilungsplan vor.

Wir hoffen, Ihnen damit gedient zu haben und ersuchen Sie, die verspätete Beantwortung entschuldigen zu wollen.

Mit vorzüglicher Hochachtung

Wiener Stadtwerke
Verkehrsbetriebe
Der Direktor:

Dkfm. Mag. KEIBL
Obermagistratsrat

MELLON INSTITUTE
Rail Systems Center
Director
Richard A. Uher

4617 Winthrop Street
Pittsburgh, Pennsylvania 15213
U. S. A.

Dear Director,

We take the liberty to answer your questionnaire as follows:

1-- In year 1981 the cost for the use of ?(Traktion) was 156,3 Million Schillings. The distribution was as follows: trams: 59,1 Million Shillings, street cars: 4,4 Million sch., subway: 66,0 Million Sch. After having completed the extended subway system this year, the costs for 1983 for the use of ? (Traktion) can be calculated to 182,0 Million Sch.

2-- The total ? is purchased by the Viennese city works and electricity works.

3-- The share of expenses for energy amounts to the following: Trams: 2'3%, street cars: 1'6%, subway: 14'3%.

4-- The structure (organization) does not result in a power demand(current) and energy component.

5,6--The labor cost for the street cars and the city trams or subways, for the time being accounts to 50' 574/KWh.

7-- Look at answer #4.

8,9--In the Viennese city works and traffic plants, there exists no official energy conservation program and no official power maintenance plan, or power distribution plan.

APPENDIX G

OPTIMIZATION OF TRAJECTORIES

G.1 INTRODUCTION

Low energy consumption and minimum running time are conflicting objectives in a transit system. Transit cars are generally used to their maximum capability, so that over given running profiles the minimum running time is achieved. Use of full capability does not result in minimum energy consumption.

Figure G-1 shows a two dimensional objective space for the two conflicting objectives, running time and energy. The accessible region is the area in the running time vs. energy consumption plane which can be realized by a train with a fixed passenger load factor between two stations. Any point in this plane is accessible to the train as it moves between the stations.

The border of the accessible region is the noninferior curve. It represents the extremum of energy consumption for a fixed running time which is greater than the minimum running time.

The problem of finding the optimum performance modification strategy is to find those strategies which lie near the lower portion of the noninferior curve, so that for a given small increase in running time a maximum energy saving is possible.

Here the optimization of the trajectory of an individual train is considered. The physical and performance characteristics of the train and its tracks are specified. The principal concern is that total energy E and total running time T be as small as possible.

G.2 PROBLEM DESCRIPTION

The problem is to minimize:

$$J = E$$

where E is the total energy, subject to the constraints on the speed and propulsion system.

The train must meet the speed limits along the route,

$$o \leq v(x) \leq v_{\max}(x)$$

where x is the position along the route.

$$x_0 \leq x \leq x_f$$

and where x_0, x_f are the positions of the beginning and end of the route. The quantity $v_{\max}(x)$ is the speed limit at position x.

Propulsion system models can relate the electric power, P_e, at the third rail shoe of the vehicle to the applied force, u, of the propulsion system at the wheels and the speed of the train, v. This relation has the form,

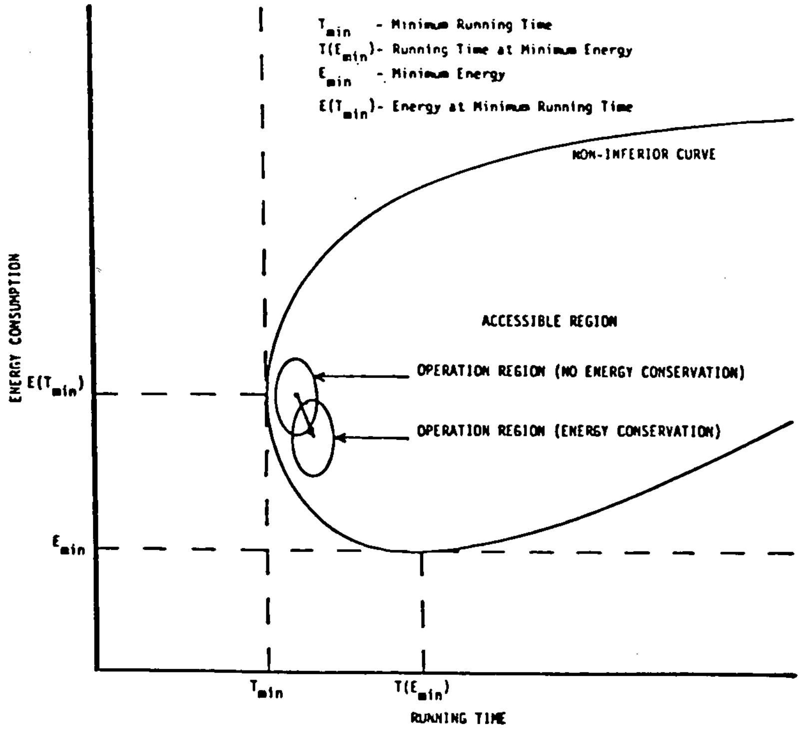


Figure G-1. Energy running time plane.

$$P_e = g(u, v).$$

The applied force at the wheel, u, has a maximum and minimum value depending on the speed of the train, which is expressed in the form,

$$u_{\min}(v) \leq u \leq u_{\max}(v)$$

Figure G-2 shows the equation of motion and describes its components. The position of the train along the route is related to its speed by the equation:

$$v = dx/dt$$

The curve resistance, C, and the grade resistance, G, are functions of the position of the train and the train resistance terms T_{RR} and T_{RA} are functions of the speed, v, of the train.

The total running time, T, can be expressed as the quantity

$$T = \int_{x_0}^{x_f} \frac{dx}{v(x)}$$

while the total energy consumed is

$$E = \int [P_a(t) + P_e(t)]dt$$

where, $P_a(t)$, is the power drawn by the auxiliaries (such as heating and air conditioning units), which is generally assumed to be constant in time.

It is desired to make T and E as small as possible. This problem was solved using two approaches. In the first approach, Monte Carlo techniques are used to generate all feasible trajectories in the E-T plane and only those are selected which have minimum E for fixed T. The second approach is a multiobjective optimization technique which minimizes the quantity, $J = E$.

G.3 MONTE CARLO ALGORITHM

A Monte Carlo simulation was done for the problem of the form described in the previous section, namely,

$$\begin{aligned} & \text{Min } E(v, t) \\ \text{subject to:}\quad & T < T\,a \text{ (prespecified)} \\ & \propto \leq v \leq \beta \text{ (prespecified)} \\ & o \leq v \leq v_{\max}(x) \end{aligned}$$

Here $\propto$ and β are the minimum and maximum speeds generated by the propulsion system, i.e., speeds corresponding to minimum and maximum applied force that can be delivered through the propulsion system at the wheels.

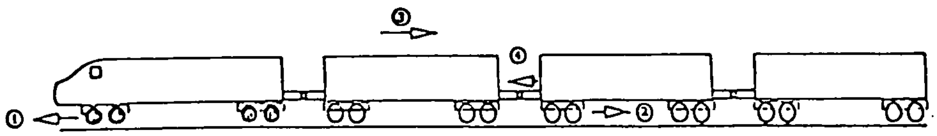
The Monte Carlo procedure generates random vectors v distributed on two-way negative exponential distribution with mean $R_1 \propto + R_2\beta$ $(R_1 + R_2 = 1)$ and variance R_3.

The quantities R_1, R_2, and R_3 are randomly generated using a random number generator, and these are the same for a set of speeds.

Each v_i randomly generated was checked for the three constraints, and v_i was set to the constraint each time it violated a constraint. Energy was calculated for the vector v and T. Energy was retained if it did not violate the time constraint, and energy was less than the previously stored values. In this way, the lower most bottom portion of the accessible region was traced.

Appropriate choice of R_1, R_2, and R_3 ranges has provided fairly efficient runs of Monte Carlo. Overall, as long as $R_1 \propto + R_2\beta$ is tilted towards β, and R_3 is around 20, it provides good results.

The random number generator used for the purpose was system routine RAN(IDUM) which generates random number



EQUATION OF MOTION: $U - T_{RR} - T_{RA} - G - C = M_E \frac{dv}{dt}$

FORCES (INDICATED BY NUMERALS AND ARROWS)

1 APPLIED FORCE AT WHEELS BY PROPULSION SYSTEM

2 ROLLING PORTION OF TRAIN RESISTANCE, CURVE RESISTANCE, GRADE RESISTANCE AND BRAKING EFFORT (FRICTION BRAKES)

3 AERODYNAMIC PORTION OF TRAIN RESISTANCE

4 COUPLER FORCE

$U = T_E$ (TRACTIVE EFFORT)

$= -B_E$ (ELECTRICAL BRAKING EFFORT)

T_{RR} = ROLLING PORTION OF TRAIN RESISTANCE

T_{RA} = AERODYNAMIC PORTION OF TRAIN RESISTANCE

C = CURVE RESISTANCE

G = GRADE RESISTANCE

M_E = EQUIVALENT MASS

$\frac{dv}{dt}$ = ACCELERATION OR DECELERATION

◉ DRIVER WHEEL

○ NON-DRIVER WHEEL

Figure G-2. Diagram of forces acting on a train.

uniformly distributed between 0 and 1. Figure G-3 provides the probability density funciton $f(x)$ and probability distribution function $F(x)$ for RAN(IDUM).

For the purpose of simulation, it was better to use the negative exponential distribution because uniform random numbers provide large changes more often, and thus lead to a higher probability of suboptimal results. Negative exponential distribution, on the other hand, provides a tapering in the density function. Figure G-3 provides the probability density and probability distribution function for negative exponential distribution.

Now, in order to generate negative exponential distributed random numbers, it is necessary to use $F^{-1}(x)$ where x is a uniformly distributed random number. For negative exponential distribution,

$$F(O) = 0$$

$$F(\infty) = 1$$

$$F(x) = -e^{\mu x/\mu}$$

Hence, if the random number selected from a uniform distribution is y, then:

$$y = \log x/\mu$$

or

$$x = -\mu \log \mu y$$

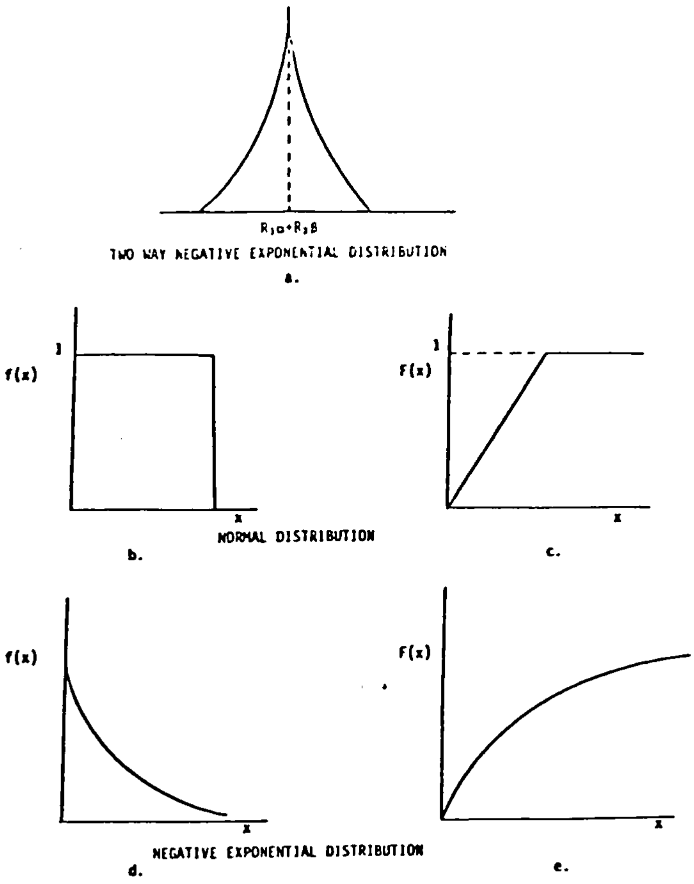


Figure G-3. Distributions used in Monte Carlo simulation.

G.4 THE TRAJECTORY OPTIMIZATION ALGORITHM

The purpose of this algorithm is to minimize $J = E$, subject to all the constraints of the system, and $T = T_1$ where T_1 is a specific travel time assigned to route.

The steepest descent method is used in the minimization procedure because of its simplicity in programming and because, for this specific problem, it converges in a reasonable amount of time. The algorithm is summarized as follows.

1. Generate a feasible trajectory to serve as an initial guess.
2. Discretize with respect to distance (divide the distance to be covered into appropriate intervals).
3. Calculate δJ_i for $i = 1, 2, \ldots, n\text{-}1$. Here $J = E$.

$$E = \frac{x_1 - x_0}{v_0} p(v_0, u_0) + ½ \sum_{i=1}^{n-1} \frac{x_{i+1} - x_{i-1}}{v_i} p(v_i, u_i)$$

$$+ \frac{x_n - x_{n-1}}{v_n} p(v_n, u_n)$$

$$T = \frac{x_1 - x_0}{v_0} + ½ \sum_{i=1}^{n-1} \frac{x_{i+1} - x_{i-1}}{v_i} + \frac{x_n - x_{n-1}}{v_n}$$

Subject to $T = T_1$, where T_1 is a specific travel time assigned so that the solution of the problem generates a point on the convex portion as shown in Figure G-4, then

$$\frac{\partial E}{\partial v_i} = ½ \left(\frac{x_{i+1} - x_{i-1}}{v_i} \frac{\partial P(v_i, u_i)}{\partial v_i} - \frac{x_{i+1} - x_{i-1}}{v^2_i} P(v_i, u_i) \right.$$

$$+ \frac{x_i - x_{i-2}}{v_{i-1}} \frac{\partial P(v_{i-1}, u_{i-1})}{\partial v_i}$$

$$\left. + \frac{x_{i+2} - x_i}{v_{i+1}} \frac{\partial P(v_{i+1}, u_{i+1})}{\partial v_i} \right)$$

because u_{i-1}, u_i, u_{i+1} are functions of v_i,

$$u_i = M_E a_i + G + C + T_{\mathrm{RR}} + T_{\mathrm{RA}}$$

$$i = 1, 2, \ldots, n-1$$

and

$$a_i = v_i \frac{v_{i+1} - v_{i-1}}{x_{i+1} - x_{i-1}}$$

Again,

$$\frac{\partial p}{\partial v_i}(v_i, u_i) = \left.\frac{\partial p}{\partial v_i}\right|_{\substack{u_i \\ \text{const.}}} + \left.\frac{\partial p}{\partial u_i}\right|_{\substack{v_i \\ \text{const.}}} \frac{\partial u_i}{\partial v_i}$$

$$\frac{\partial p}{\partial v_i}(v_{i-1}, u_{i-1}) = \left.\frac{\partial p}{\partial v_i}\right|_{\substack{u_{i-1} \\ \text{const.}}} + \left.\frac{\partial p}{\partial u_{i-1}}\right|_{\substack{v_{i-1} \\ \text{const.}}} \frac{\partial u_{i-1}}{\partial v_i}$$

$$\frac{\partial p}{\partial v_i}(v_{i+1}, u_{i+1}) = \left.\frac{\partial p}{\partial v_i}\right|_{\substack{u_{i+1} \\ \text{const.}}} + \left.\frac{\partial p}{\partial u_{i+1}}\right|_{\substack{v_{i+1} \\ \text{const.}}} \frac{\partial u_{i+1}}{\partial v_i}$$

and

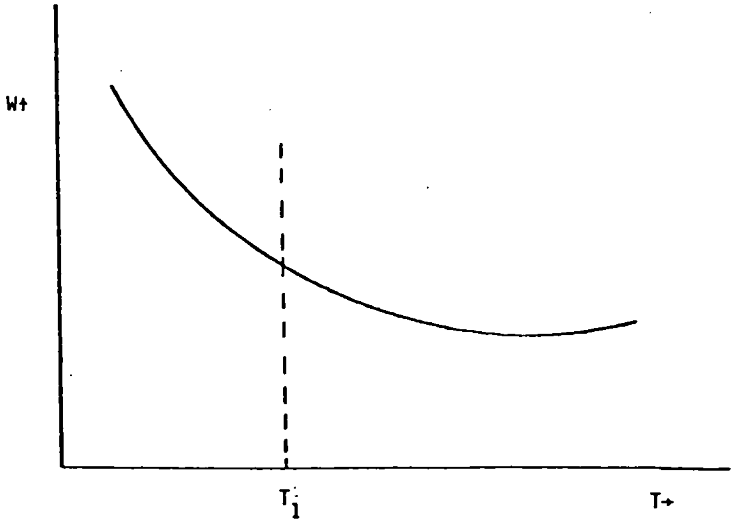


Figure G-4. A point on the noninferior portion of the curve with travel time $T = T_1$.

4. Determine C^j such that $C^j = T(v^j)/T_1$.
5. Calculate $v^{j-1/2}$ such that $v^{j-1/2} = C^j v^j$.
6. Calculate $\delta J_i = \partial E/\partial v_i^{j-1/2}$.
7. Calculate new v_i^j by taking a small step in the direction of the gradient, i.e., set

$$v_i^j = v_i^{j-1/2} - a\,\delta J_i$$

where v_i^j is the velocity, i, in j^{th} iteration and a is a constant which gives suitable step which minimizes the objective function J.

The step size a has been calculated using the quadratic approximation for the objective function described in the next section.

8. The gradient projection method is used to test all the constraints, i.e.,

- Verify if v_i^j abides by the speed restriction. If not, set v_i^j equal to the speed restriction.
- Calculate ai and β_i velocities corresponding to the minimum and maximum tractive force.

$$\text{If } v_i^j < a_i \text{ set } v_i^j = a_i$$

$$\text{If } v_i^j > \beta_i \text{ set } v_i^j = \beta_i$$

9. Test for convergence using the following criterion:

$$\|\delta J\| = \Sigma\,(\delta J_i)^2 \leq \epsilon$$

and

$$|C^j - 1| \leq \delta$$

where ϵ and δ have a prefixed value. If process has converged, stop; otherwise, return to 4.

The algorithm for discretization and minimization is summarized in Figure G-5.

G.5 ALGORITHM FOR SELECTING OPTIMAL STEP SIZE

Consider approximating the function $J(a)$ by a function $\mu(a)$ which has an easily determined minimum point. The simplest 1— variable function possessing a minimum is the quadratic:

$$\mu(a) = a + ba + ca^2$$

the minimum of which occurs where

$$(d\mu)/da) = 0 \Rightarrow \mathrm{b} + 2\mathrm{c}a = 0$$

$$\text{or} \qquad a^* = (-\mathrm{b}/2\mathrm{c})$$

The constants b and c for the approximating quadratic can be determined by sampling the function at three different a values, e.g., 0, t and $2t$ where t is the preselected trial step and evaluating the functions at these three a values at:

$$a = 0 \qquad f_1 = a$$

$$a = t \qquad f_2 = a + \mathrm{b}t + \mathrm{c}t^2$$

$$a = 2t \qquad f_3 = a + 2\mathrm{b}t + 4\mathrm{c}t^2$$

The above equations give

$$a = f_1$$

$$\mathrm{b} = (4f_2 - 3f_1 - f_3)/2t$$

$$\mathrm{c} = (f_3 + f_1 - 2f_2)/2t^2$$

therefore,

$$a^* = (-\mathrm{b}/2\mathrm{c}) \simeq (4f_2 - 3f_1 - f_3)/(4f_2 - 2f_3 - 2f_1)$$

Also, for a^* to correspond a minimum it must satisfy

$$(d^2\mu/da^2)|_{a^*} > 0 \Rightarrow C > 0$$

For $C > 0$ we should have

$$f_3 + f_1 > 2f_2$$

This means that the value of f_2 must be below the line connecting f_1 and f_3.

The logic for the quadratic interpolation described above is given in Figure G-6.

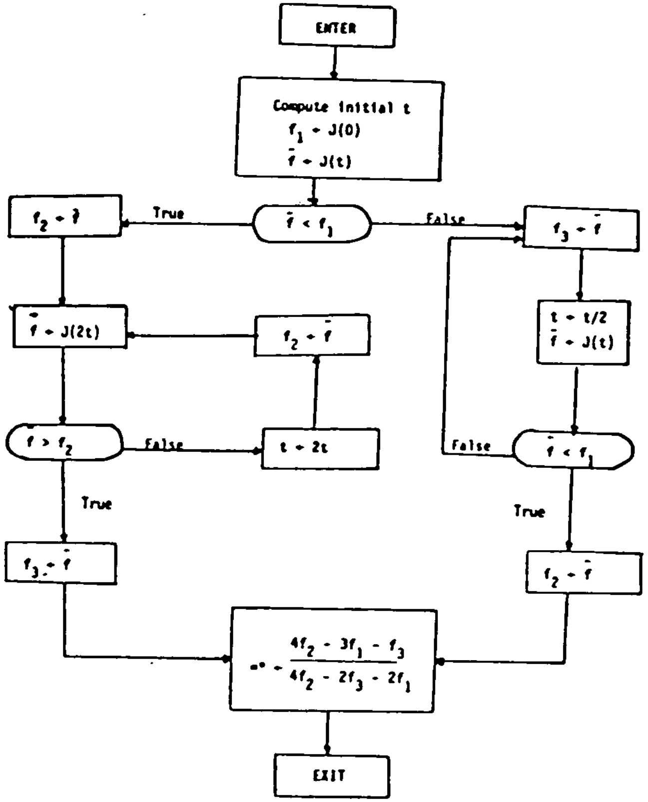


Figure G-5. Discretization and minimization flow chart.

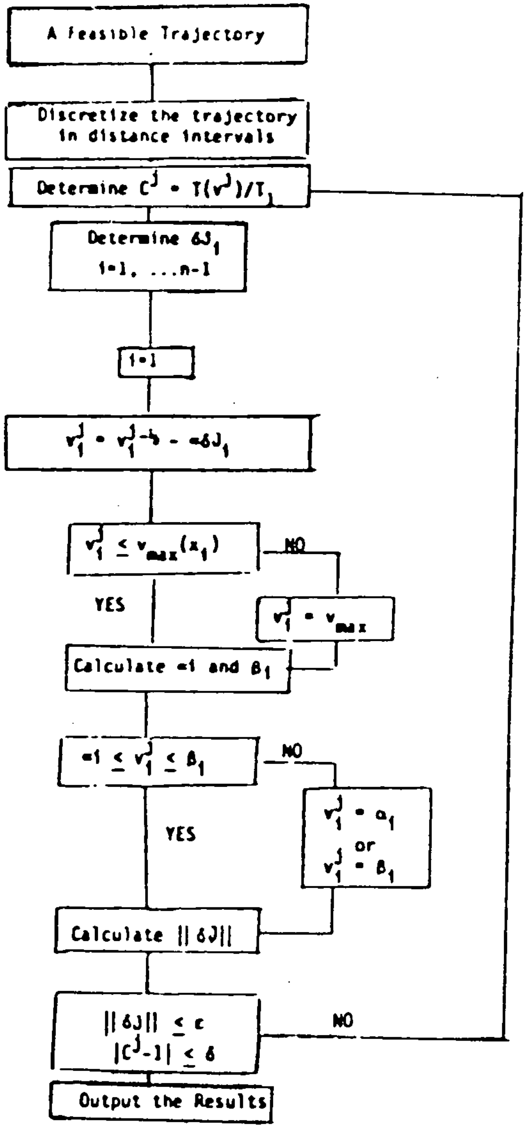


Figure G-6. Algorithm for selecting optimal step size.

Example

The WMATA Red Line running from Dupont Circle to Silver Spring was selected for the optimization purpose.

Using the actual motor and brake curve, the total run of 9.81 miles was optimized using Monte Carlo and Steepest Descent. The results are summarized in Tables G-1 and G-2, respectively.

Table G-1. Monte Carlo results for WMATA Red Line.

ENERGY CONSUMPTION KWH/CAR MILE	TIME (min)	% REDUCTION IN ENERGY	% INCREASE IN SCHEDULE TIME
6.60	19.1	-	-
5.50	19.3	16.7	1.1
5.35	20.0	19.0	4.6
5.31	19.5	19.6	2.1

Table G-2. Steepest descent results for WMATA Red Line.

ENERGY CONSUMPTION KWH/CAR MILE	TIME (min)	% REDUCTION IN ENERGY	% INCREASE IN SCHEDULE TIME
6.60	19.1	-	-
5.47	19.3	17.1	0.84
5.16	19.7	21.8	2.72
4.88	20.1	26.1	4.81

APPENDIX H VALIDATION PLAN

This validation plan has been developed for load management. The plan includes the preliminary information that must be developed by the transit authority, the validation procedure, which includes the equipment necessary for the prototype operation and documentation requirements.

H.1 PURPOSE

The purpose of validation is threefold: to verify, through actual prototype operation, the cost/benefit of load management on a U.S. transit property; to prove the value of simulation as a tool for future cost/benefit studies in energy conservation; and to develop algorithms for prediction and subsequent control of peak power demand.

The cost/benefit of load management must be verified in order to reduce the technical and financial risk that is inherent in such a system. In this connection, more data are required from those nondomestic transit organizations that presently employ some kind of load management program. Montreal and Hamburg are good examples of such rail transit systems.

Testing by simulation of energy conservation strategies that are appropriate to load management systems and that include vehicle performance modification, passenger load factor improvement during peak operating periods, and reduction of support power on and off-board for the trains should be verified as the least expensive method. The alternative method, which is actual testing on the system, involves a higher order of expense than simulation.

Although cost/benefit and simulation methodology must be verified, it will also be necessary to develop the algorithms for peak demand prediction and control as well as to specifically study the conditions under which peak demand varies from day to day. Such algorithms would involve prediction of future demand from present demand in the demand interval, times at which decisions must be made for strategy application and mixes of strategies to be applied so as to minimize the reduction of system performance.

H.2 REQUIREMENTS FOR TRANSIT AGENCIES

It will be necessary to select one or more rail transit systems to implement the validation procedure of a load management system. There are certain requirements that must be met by a transit agency before a load management system can be validated.

The first requirement is that an energy management study be completed, which shows that a load management system is cost beneficial, i.e., that payback of the initial investment in energy savings can be made within 3 years. It is not useful to demonstrate load management where cost benefit is marginal, i.e., long payback periods.

The second requirement is that a part of the transit system can be isolated for the purpose of the demonstration. Since the demonstration must be carried out without disturbing revenue operation, a natural isolation, such as one route of a transit system which is electrically isolated from the rest of it, is ideal.

The third requirement is that it be a low cost demonstration, but still be complex enough, that the results can be applied to other systems which are more complex. Rail transit systems which have demand monitoring equipment in place would be preferred over those which do not, if all other requirements are met.

The fourth requirement is that the transit property have a strong presence in the rate negotiation arena with the electric utilities and public utility commission. Such representation is necessary to avoid increased demand rates as a result of reallocation of demand which may be initiated because of the load management procedures of the rail transit system.

Finally, the last requirement is that the management of the transit property be actively supportive of the success of demonstration effort. It is not wise to attempt such a demonstration, if no or even passive support is given to the program.

The degree to which these requirements can be met would determine which transit properties would be selected for a load management demonstration.

H.3 VALIDATION PROCEDURE

Load management systems can be viewed at three levels of sophistication depending on available data, the degree of performance reduction which can be tolerated in the system, and the initial investment which the transit agency is willing to advance. The validation procedure of all three, beginning with the most sophisticated, is discussed in the following.

H.3.1 Real-Time Load Management

Load management in real time involves real-time power-demand monitoring with quick response to avoid high peak demand charges. Since it will involve installation of a demand monitoring system, similar to the one described in Chapter Two of this report, it is expected to be the most costly. It also has the lowest probability of reducing transit system performance because an energy conservation strategy that would involve either vehicle performance modification, or comfort performance reduction by reducing support power, would only be applied when peak demand was predicted to exceed some critical level.

The first step in validating a real time monitoring system involves its detailed design. In this step, hardware is selected for the demand monitoring system and the vehicle performance modification and support power reduction strategies identified. This step also involves using simulation to determine the expected results. It is at this time that the initial algorithms are developed for prediction and control of peak demand. It is important that the demand monitoring system be microprocessor based, so that it can be reprogrammed as more information is obtained. These algorithms should be based on both the voltage and the power at each meter because of the sensitivity of power draw from individual substations to the voltage at the substations.

The second step in the validation plan is a preliminary operation phase during which the load management system can be fine tuned and optimized. This period, which should last approximately one year after operation has been started, would involve a learning phase. During this time, information would be obtained on the exact nature of the causes of peak demand, through correlation with abnormal operation. It is also during this time that the algorithms would be changed and tested as required by the development of historical information. The response of the utility company can be ascertained at this time as well, and negotiation techniques can be developed to counteract any adverse reaction that may tend to reduce the benefit of the system.

The third step involves running the fine-tuned load management for the period of about a year to determine the actual cost/benefit. The historical data as developed by the monitoring system will provide the information to make this assessment. It is at this time that final verification of the simulation techniques can also be established. An energy audit update is undertaken at the same time.

H.3.2 Batch Processing Load Management

In this form of load management, power demand monitoring is accomplished by using metering information supplied by the utility, after the fact, to determine the occurrence of peak demand generation and to correlate this information with data from transit operation to ascertain cause. This kind of power demand monitoring requires metering information at time intervals less than or equal to the demand interval. Since this analysis is not done in real time, application of corrective measures in the form of energy conservation strategies cannot be accomplished until after the data are analyzed, and as a consequence, the corrective measures are applied in the dark. Because the corrective action must be applied in this way, a greater degradation of system performance results than in the case of real-time load management. The procedure begins with analysis, followed by corrective action, followed by analysis, followed by corrective action, etc.

The advantage of this system is in its low cost operation. However, its success depends on the ability of the transit agency to access the necessary metering information on a timely basis, and to be able to report accurately on events that are contributing to the creation of peak demand.

The first step in validating a batch process monitoring system involves accessing and reading magnetic tapes that are generated by the electric utilities. The computer programs that analyze the information must also be developed. An information gathering system must be developed so that events contributing to peak demand generation can be identified. Simulation is used at this point to determine the seriousness of the event in terms of its abnormal power consumption. Such events would be train delays followed by subsequent catchup, abnormal ambient temperatures, and conditions of abnormal voltage variation.

The second step involves the application of energy conserving strategies during periods of abnormal operation followed by further analysis and refinement of analysis techniques. If metering information was analyzed on a monthly basis, a lag of 2 months would probably be expected before strategy modification could occur. A year of operation would pass before this type of load management could be assessed in terms of its effectiveness. At each stage, simulation techniques are useful in pointing the way to strategy refinement.

As in the case of real-time load management, negotiation techniques should be developed to counteract any adverse reaction by the utility companies which could neutralize the energy cost savings potential of the load management system.

H.3.3 Electric Bill Analysis-Based Load Management

The least effective and least costly of load management systems is one which is based on monitoring electric bills. The procedure for validation is the same as for batch processing monitoring except that much less information on power demand on which to base strategy application is available. If the electric bill contains information on the time at which peak demand occurred, some attempt might be made to correlate the peak demand with the operational event that caused it.

Because of the sparce information available on power demand using this method, it may be cost effective for a transit agency that is forced to rely on it to entertain installing some form of batch processing demand monitoring.

H.4 DOCUMENTATION

Documentation of the validation experiment should begin with the initial energy management study and end with the operational phase. The following items are of particular interest:

- Initial prediction of load management cost/benefit as applied to the validation demonstration.
- Initial load management algorithms developed and tested as part of the demonstration.
- Initial selection of strategies to be used as responses to limiting peak demand.
- Evaluation of algorithms as the demonstration is conducted together with operational conditions which caused the changes.
- Initial reactions of the electric utilities and their subsequent responses. Strategies developed by the transit property as a consequence of electric utility response should be documented as well.

APPENDIX I

LOAD MANAGEMENT GUIDELINES

CONTENTS

INTRODUCTION

The purpose of this appendix is to provide a set of guidelines for electric rail transit managers in the discipline of energy management. It outlines a step-by-step procedure that will allow the application of energy cost reduction to be carried out in a cost/effective manner, through structural, operational, and institutional changes in the system.

Energy management is a process to understand the factors that determine system energy cost and to use this knowledge to determine the cost-benefit and overall effectiveness of energy cost reduction. The factors that determine electric energy cost are related not only to variables of equipment and system design and operating practices (referred to as the *energy use pattern*), but also to the *power rate structure* of the electric utilities that serve the system. The energy use pattern is controllable within limits by transit management. The power rate structure, which sets the schedule for electric facility, power demand, and energy consumption charges, may be a matter of negotiation between the transit authorities and the electric utilities that serve them. The cost of electricity on rail transit systems is made up of facilities, power demand, and energy consumption components. The facilities charges are fixed and cannot be controlled by transit management. The energy consumption and power transit aspects result from operating the system. Energy consumption is the actual use of power integrated over time, and it is measured by electric meters in units of kilowatt-hours (kWh). Power demand represents the generation, transmission, and distribution facilities which the electric utility reserves for its large customers, and is determined using the electric meter readings together with a complex mathematical formula. Power demand has units of kilowatts (kW). A typical electric bill for a rail transit operation is 50 percent demand.

Load management consists of reducing the demand component of energy cost by monitoring, predicting, and controlling power demand during the peak operating periods of the transit system. Although the research effort which resulted in these guidelines was principally concerned with load management, the steps toward overall energy cost reduction, which are more general and contain load management as a subset, are outlined here.

The first four steps are grouped under the general topic of energy management study. These steps are:

- Energy Audit.
- Simulation of Normal Operation.
- Verification of Normal Operation.
- Energy Reduction Cost and Effectiveness.

The energy management study must be carried out before any implementation of energy cost reduction can take place. If conducted properly, it will develop all of the necessary facts that the decision-maker will need to implement energy cost reduction on the system.

After the energy management study has been completed, the implementation phase of energy cost reduction begins. It is under this phase of the program that the predictions of the energy conservation cost and effectiveness through testing under prototype operation are validated.

There are several analysis tools that are used during the study phase. One such tool is the Energy Management Model (EMM), a series of computer simulation programs, developed for the electric rail transit industry. A set of tools that are useful for the analysis of power metering data can also be used.

The following definitions will be useful to the reader in the interpretation of the sections that follow.

1. Specification of a demand interval, which is a time interval measured in minutes over which electric power, as recorded on the meters, is averaged.
2. A method of demand consolidation. A way to combine the recordings of several meters for computing maximum demand. Maximum demand is determined coincidentally when in a given customer class and/or jurisdiction, it is the maximum of the sum of the average powers recorded on all electric meters in the same demand interval; and, noncoincidentally, when it is the sum of the maximum average powers recorded on all electric meters in any demand interval.
3. Computation of the monthly demand, which is the maximum demand as determined using the demand consolidation method in a monthly billing period.
4. A ratchet demand, simply called ratchet, calculated by a predetermined formula, which represents a minimum demand level for billing purposes.
5. Computation of the billing demand which is the maximum of the monthly demand and the ratchet.

A survey of the power rate structure of ten rapid transit agencies in the United States has shown that the demand interval varies from 15 min to 60 min. In this same survey, it was found that there are 28 rates under which U.S. rapid rail transit systems are billed for power furnished by 15 electric utilities in 11 states. All of the transit agencies have some form of contract with the supplying utilities.

ENERGY MANAGEMENT STUDY STEPS 1–4

The energy management study constitutes the beginning of any energy management program. It is here that the components of energy cost, obtained by the marriage of the energy use pattern with the power rate structure, are understood. The cost and benefits realizable by application of energy conservation and load management strategies are also predicted. This is accomplished in four steps.

Step 1—Energy Audit

Through the use of an audit procedure, the actual energy use pattern of the rail system is established. If the data are available, this audit should take the form of a detailed computer analysis of metering information (which can be obtained from the electric utility) at each power delivery point over successive demand intervals over a long period of time (typically a year or more), and a detailed estimate of energy end use, which flows through each meter. The audit must include traction energy, used to run the trains and provide auxiliary support power aboard them, and support energy, used to provide support services such as lighting, heating and cooling in passenger stations, tunnels, repair shops, and office buildings as well as signalling and substation power.

If detailed metering information is available, a statistical summary should be completed, a sample of which is shown in Figure I-1. This figure shows the mean, standard deviation, and maximum demand as a function of time (demand intervals) over the morning rush of Washington Metropolitan Area Transit Authority (WMATA) Red Line for the year 1980. The maximum can be interpreted in terms of transit system operational abnormalities.

A second useful analysis, if detailed metering is available, is regression relating energy consumption to rate of accumulation of car-miles and ambient temperature, which is available from the weather bureau. A graph which shows such a regression is presented in Figure I-2. In this case, the graph represents power as metered at the WMATA office building during the year 1980.

A useful, but lower level type of analysis, which can be conducted if detailed metering information is not available is electric bill analysis. This method provides information on a monthly basis rather than on an hourly or daily basis. An example of a histogram of peak power demand on a monthly basis is shown in Figure I-3 from data from the Greater Cleveland Regional Transit Authority (GCRTA). Regression analyses of energy and peak power vs. car-miles and ambient temperature can also be carried out here.

The data requirements from the transit operation, necessary to perform the analyses just described, are car-mile information on an hourly, daily or monthly basis. Ambient temperature can be obtained from the weather bureau.

The analysis methods and data requirements just described will aid in the understanding of the energy use pattern. The second important element is a listing of the detailed power rate structure that can be obtained from the power contract or agreement with the serving electric utilities. Future trends expected in the power rate structure should also be determined at this time. Such information as the power demand/energy use ratio trends, time-of-day and time-of-year rates, and possible changes in rates should energy conservation be undertaken, should be documented.

Finally, an investigation should be conducted into the level of participation of the transit agency in rate design. It is important to determine the depth and interest demonstrated during the past rate cases.

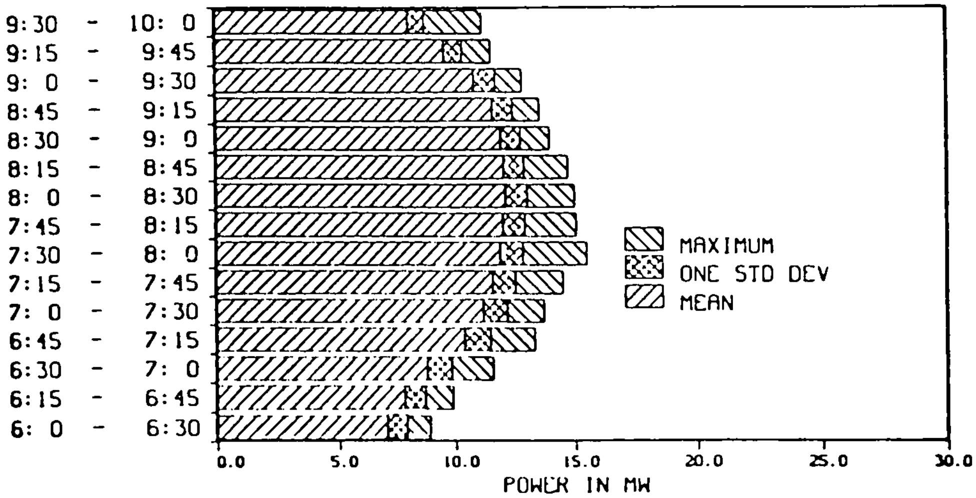


Figure I-1. Summary statistics—WMATA Red Line, AM peak.

The cost of this step will be determined principally from the availability and depth of data obtained from transit system and electric utilities. This cost can range from $10,000 to $40,000 depending on whether electric bill or detailed metering information is used as the basis. The difficulty of obtaining the data also plays a vital role in determining the cost.

Step 2—Simulation of Normal Operation

It is necessary to determine the power as seen by each meter (or groups of meters in the case of coincident demand) under normal operating conditions in order to provide a base for the reduction of power caused by application of energy conservation and load management. The support power and traction power backgrounds as determined in the energy audit are treated as constants (which may have ambient temperature and time of day variation), while the traction power of actual train operation is estimated by simulation using the EMM. (The Energy Management Model is available to the transit industry from the Rail Systems Center at normal magnetic tape reproduction costs.) The traction power which is simulated represents 60 to 85 percent of total energy use.

Using the EMM, studies should be conducted under conditions of average daily operation in order to predict energy use and abnormal daily operation in order to predict peak demand. Typically, several time intervals would be simulated depending on the level of detail that is desired. These time intervals are weekday peak (morning and evening), weekday off-peak (midday and evening), weekday startup and shutdown, Saturday, Sunday, and nonoperating.

Since the EMM can only simulate traction power during train operation time, other power, which can appear as traction power, must be estimated independently. This power would include auxiliaries aboard the car during turnaround time at terminals and layover during off-peak and nonoperating times and traction backgrounds such as no load losses of substations and switchpoint heating fed from the third rail. An example of such background power as determined on the WMATA Red Line is shown in Table I-1.

Simulation using the EMM provides two pictures of the operation of single trains on the system. These illustrations are shown for the Port Authority Transit Corporation (PATCO) Lindenwold Line. Figure I-4 shows a speed profile, while Figure I-5 shows a power profile for the same train. The latter can be

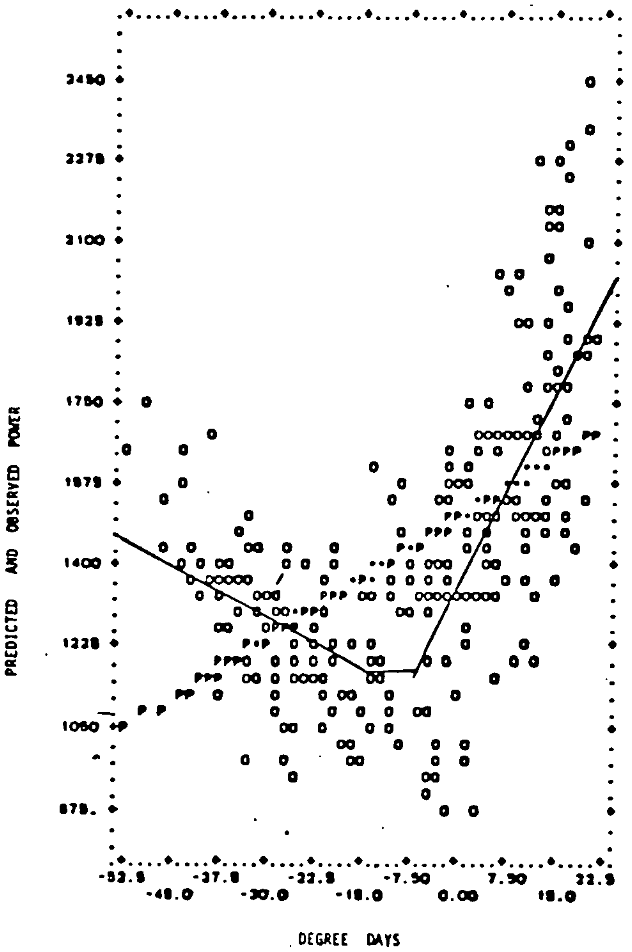


Figure I-2. Average temperature dependence of the average power recorded at one support meter (office building) at WMATA.

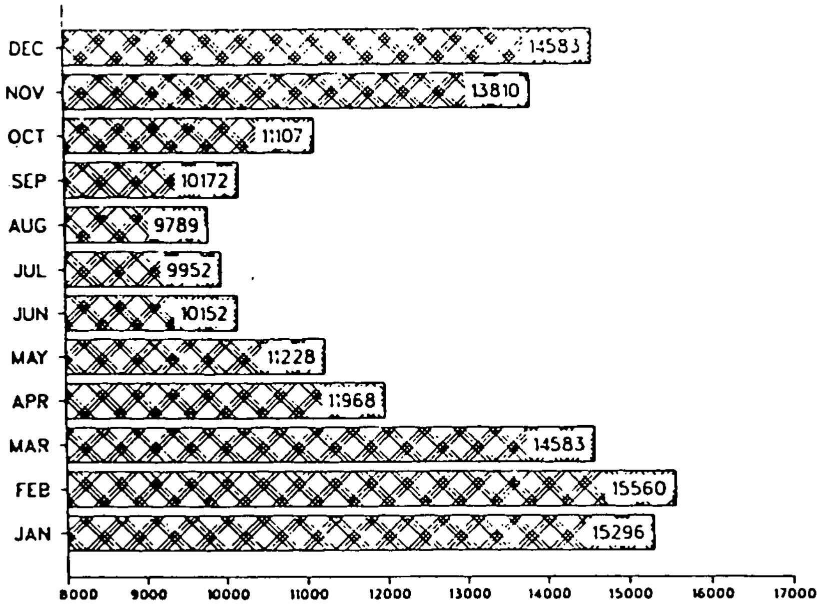


Figure I-3. GCRTA kilowatt demand histogram.

easily correlated to the former, and with an elevation profile on the same scale (shown in Fig. I-6), the power density on the transit system can easily be determined.

The prediction of traction power during actual train operation can be summarized in a table, similar to Table I-2 for the WMATA Red Line. This table when added to the background of Table I-1 represents all of the traction power to be used to compute energy use.

It was determined in an energy management study of WMATA that catchup operation of the system after train delays was responsible for generating peak demand. Thus, simulation of this method of operation resulted in the predictions of Table I-3, which when added to the appropriate peak background represents the traction portion of the peak demand. To obtain the total energy use and the overall peak demand, the support energy and power demand must be added to the traction components.

The cost of the simulation of normal operation can range from $10,000 to $20,000. This cost is principally determined by the data gathering task and simplifying assumptions.

Step 3—Verification of Normal Operation Simulation

To provide a framework for the credibility of the estimates of the effectiveness of the application of energy conservation strategies, the verification of the simulation of normal operation conducted in Step 2 should be made. This is accomplished by comparing the results with the metering information obtained in Step 1, the energy audit.

No cost is incurred in this step. It is merely a comparison of simulated vs. actual to verify the simulation.

Step 4—Energy Reduction Cost and Effectiveness

Energy use and peak demand reduction strategies can be tested for cost and effectiveness. The EMM is particularly useful at this stage. Using the power rate structure of the utilities and anticipated future trends in the rate structure, estimates can be made of energy cost savings in both the energy use and power

Table I-1. Derived background of PEPCO traction meters on Red Line.

METER NAME	LINE	LOCATION (MILEPOST)	SYMBOL	AUXILIARY RATED KW	NUMBER OF 2000 KW TRANSFORMER-RECTIFIER UNITS	NO LOAD LOSSES (KW)	NON-REVENUE SERVICE TIME POWER (KW)	CAR LAYUP POWER (KW)	MINIMUM BACKGROUND (KW) (AM-PM PEAK)	MIDDAY & EVENING BACKGROUND (KW)
Farragut North	Red	0.434	MA1	-	3	24	88		88	88
Gallery Place	Red	1.504	MB1	-	3	24	98		98	98
Union Station	Red	2.508	MB2	-	2	16	133		133	133
New York Avenue	Red	3.610	MB3	150	2	16	321	200	121	241
Rhode Island Avenue	Red	4.468	MB4	-	3	24	84		84	84
Brookland Avenue	Red	6.029	MB5	150	3	24	306		306	306
New Hampshire Avenue	Red	7.199	MB6	150	2	16	250		250	250
Takoma Park	Red	8.730	MB7	-	2	16	124		124	124
Silver Spring	Red	9.984	MB8	-	3	24	388	180	208	328
									1412	1652

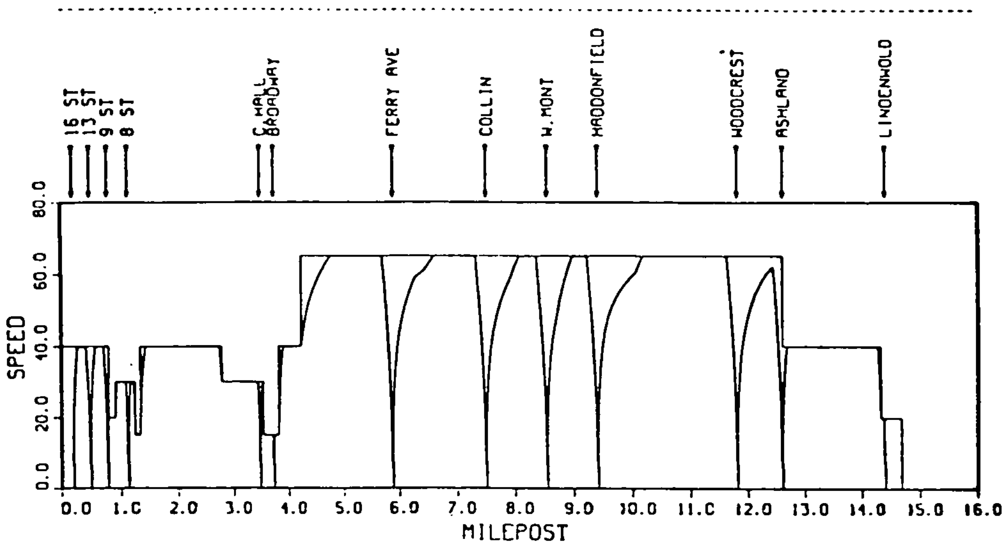


Figure I-4. Speed profile and restrictions—PATCO 6-car train, eastbound.

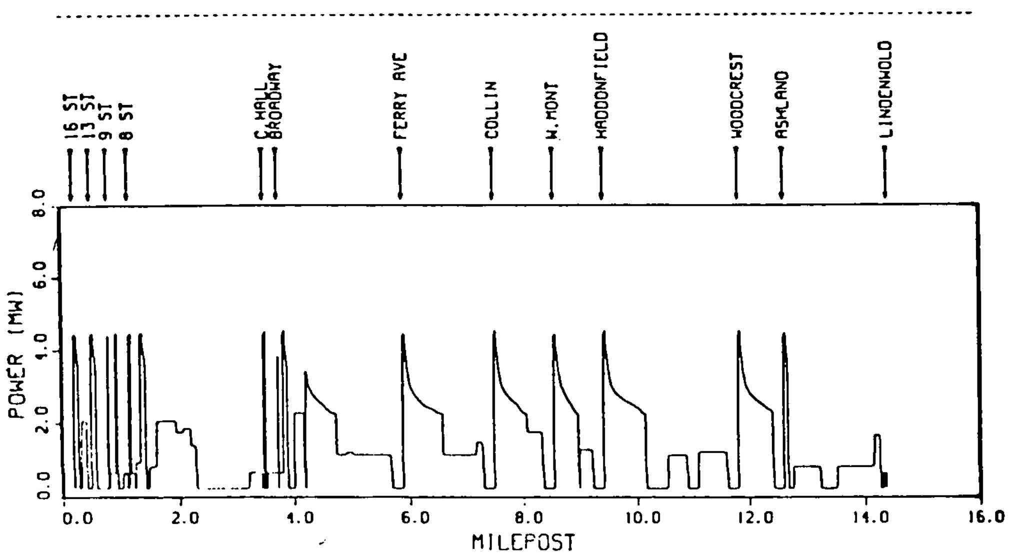


Figure I-5. Power profile—PATCO 6-car empty train, eastbound.

demand components. Thus, the overall benefit of these strategies may be determined. The cost of implementing the strategies must also be considered. These costs are generally transit agency specific, but some guidelines were developed here. Finally, if it is desirable to have load management, the cost of a power demand monitoring system must also be included. The guidelines for estimating strategy effectiveness and cost and demand monitoring cost are discussed below.

Energy Reduction Strategies

Classes of strategies whose effectiveness should be estimated are:

- Vehicle performance modification.
- Passenger load factor improvement.
- Reduction of auxiliary power aboard cars during operation and storage.
- Reduction of support power during transit operating and nonoperating periods.
- Regeneration of braking energy.

Some of these strategies are appropriate with load management to reduce peak demand, while others are used to reduce overall energy use.

Vehicle Performance Reduction. Rolling stock is used so that running time between stations is minimized, subject to speed restrictions, traffic interference, and operating policies of the

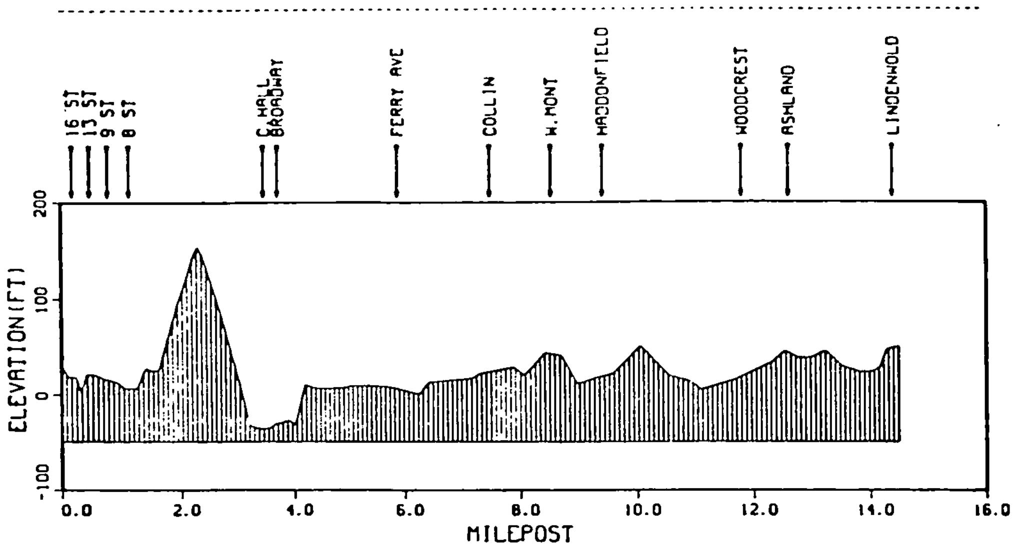


Figure I-6. Elevation profile—PATCO car, eastbound.

transit authority. In some cases, full performance would not be used, but held in reserve to catchup because of train delays.

Energy consumption by performance modification can be illustrated using Figure I-7. The accessible region is the area in the energy consumption vs. running time plane which represents points that can be achieved by identical trains running on the system just by varying their performance. The curve which borders this region is called the noninferior curve, because it represents the extremum of energy consumption for any fixed running time greater than the minimum running time. Within the accessible region is an operating region in which identical trains typically operate. Because of operational and equipment variances, most running times and corresponding energies will vary within the closed curve shown within the accessible region in the figure. Application of a vehicle performance modification strategy results in a shift of the closed curve in the accessible region to the right and downward, representing an increase in running time and a decrease in energy consumption. The quantities (percent energy decrease and percent time increase) can be calculated for such strategy application. A set of these quantities is a measure of how well employment of the strategy is expected to reduce both energy and performance, the latter in terms of schedule time increase. Several vehicle performance modification strategies are available for testing with the EMM. Among the useful ones are top speed reduction, coasting, and optimum performance modification.

Reduction of maximum speed is generally the most inefficient strategy in terms of energy reduction per increased schedule time, but it has an advantage in that it is easy to implement, through changes in operating rules or signals on manual train control systems and through speed command changes on automatic train control systems. It is especially effective on lines where top speed is seldom reached and the pattern of operation is acceleration followed by braking.

Coasting is a proven method to reduce energy consumption with minimal increase in running time. Coasting can be applied in several ways, two of which are identified here. In *anticipatory coasting*, the train accelerates to the top speed restriction, remains there and begins coasting in anticipation of a station stop or lower speed limit down the line. The second method is *sawtooth coasting*, in which the train accelerates to the speed restriction and alternately coasts and accelerates within a speed band whose maximum speed is the speed limit. In practice, sawtooth coasting is easier to implement and the energy reduction effects approach those of anticipatory coasting as running time is allowed to increase.

An optimized vehicle performance modification strategy is one for which energy consumption is a minimum for a fixed increase in running time, over the minimum running time. In practice, this strategy is achieved by varying tractive effort in such a way that minimum energy consumption results. The energy consumption and running time which results by application of the technique will lie on the lower curve bounding the accessible region in Figure I-7.

All of the above vehicle performance modification strategies can be simulated using the EMM. Figure I-8 shows an example of all the strategies applied to the WMATA Red Line. Two techniques for finding the optimized trajectories are shown: steepest descent, which finds the true optimum, and Monte Carlo, which approaches the true optimum.

The vehicle performance modification strategies can be used with load management; namely, as a real time response to the prediction of high peak demand. They can also be applied under all conditions to provide reduction of both peak demand and energy use.

Since the vehicle performance modification strategies do reduce system performance by increasing running time, they are only useful for small increases in running time, typically 2 to 3 percent, where transit capacity is only slightly affected and no requirement for adding trains is generated. Normally, the increase in running time can be made up by reducing dwell times at the least busy stations and by reducing turnaround times at the ends of the line.

Passenger Load Factor Improvement. Two passenger load factor improvement strategies are specified: running shorter and/or less trains in off-peak hours and turning trains at intermediate stations during peak and off-peak hours. Both kinds

Table I-2. Results of the ENS for normal operation during 1980 for the Red Line.

	POWER (KW)			
METER NAME	AM PEAK	MIDDAY	PM PEAK	EVENING
Farragut North (MA1)	1070	450	1046	438
Gallery Place (MB1)	1372	583	1290	558
Union Station (MB2)	1264	530	1261	517
New York Avenue (MB3)	632	271	657	270
Rhode Island Avenue (MB4)	1602	660	1668	651
Brookland Avenue (MB5)	1522	596	1456	592
New Hampshire Avenue (MB6)	1175	480	1162	481
Takoma Park (MB7)	1428	602	1472	602
Silver-Spring (MB8)	474	229	544	230
Coincident Red	10540	4401	10556	4340
Car - Miles	1644	711	1639	712
KWHPCM	6.41	6.19	6.44	6.10

*Does not include on-board auxiliary power during turnaround.

of strategies, when applied, will reduce car-miles, and as a result, energy consumption. The energy use per car-mile will slightly increase because of heavier loads.

Application of both strategies will reduce overall energy use. During peak hours of transit operation, it only makes sense to turn trains at intermediate stations. This strategy must be carefully considered because of difficulties encountered with scheduling and traffic interference. Application of the strategy during the peak hour can reduce peak power demand.

Passenger load factor improvement can also improve transit productivity. It involves many considerations other than energy. It is also a scheduling problem.

On specific transit properties, hypothetical passenger load factor improvement strategies can be devised and simulated using the EMM. These strategies are not appropriate with load management systems that require quick reaction to limit peak demand.

Reduction of Auxiliary Support Power Aboard Vehicles. Auxiliary power aboard vehicles can be reduced during both operating and nonoperating periods to reduce energy. Some nondomestic transit systems reduce auxiliary power during peak periods to reduce demand. During operating time, this power can account for 10 to 15 percent traction power.

Reduction of auxiliary power during nonoperating time can also save energy use. WMATA reduces power automatically from 30 kW to 5 kW when a train goes from operation to layup (removal of operator's key). The estimate of savings does not require simulation; it is simply the number of car-hours in layup per unit time multiplied by the operating and layup power difference.

Reduction of Support Power. Support power can be reduced both during operating and nonoperating times. If done during the peak transit operating periods, it can be part of a load management system. Areas which are suitable for investigation are lighting, heating and cooling, ventilation fans and partial system shutdown during nonoperating times.

Table I-3. Results of the ENS for catch-up operation during 1980 for the Red Line.

	POWER (KW)	
METER NAME (SYMBOL)	AM PEAK	PM PEAK
Farragut North (MA1)	1668	1577
Gallery Place (MB1)	1909	1787
Union Station (MB2)	1631	1668
New York Avenue (MB3)	848	939
Rhode Island Avenue (MB4)	1957	1961
Brookland Avenue (MB5)	1796	1813
New Hampshire Avenue (MB6)	1349	1387
Takoma Park (MB7)	1722	1743
Silver Spring (MB8)	614	683
Coincident Red	13493	13557
Car-Miles	1643	1635
KWHPCM	8.21	8.29

*Does not include on-board auxiliary power during turnaround.

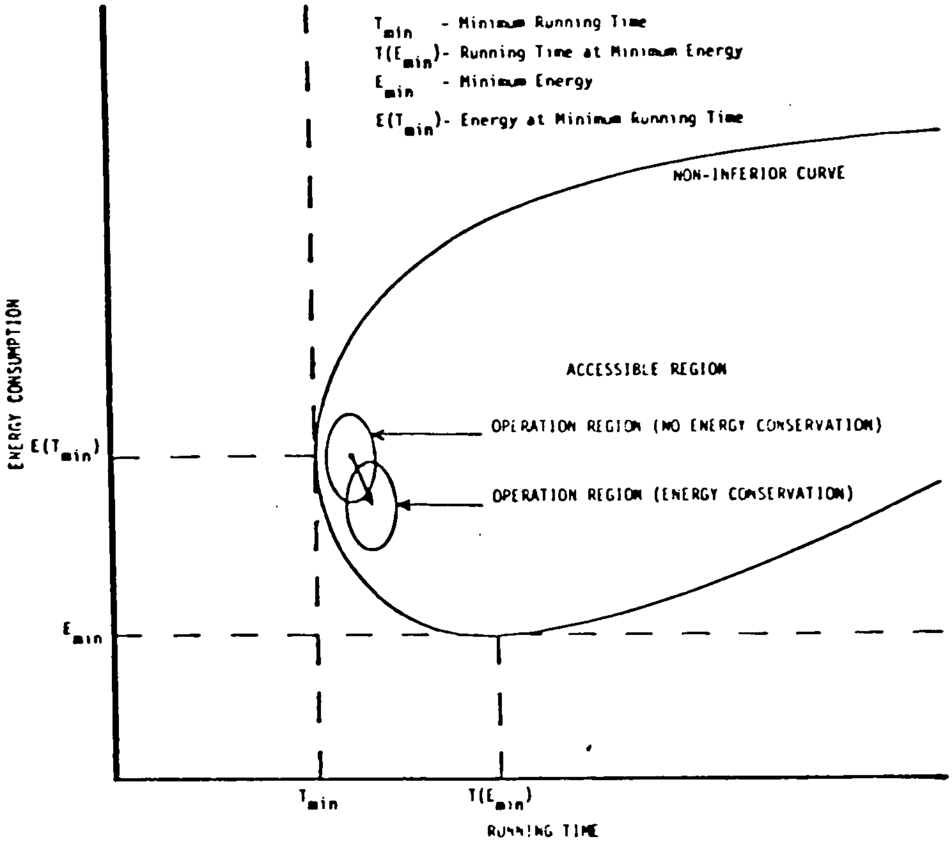


Figure I-7. Energy running time plane.

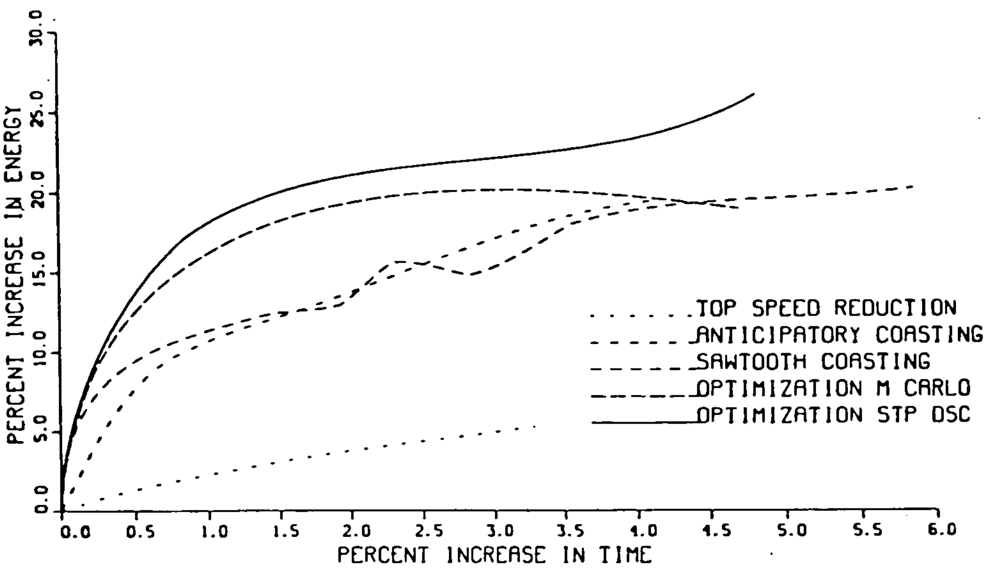


Figure I-8. Performance modification results—WMATA Red Line outbound.

Reduction of support power can work well with a real-time-based load management system. Although it does not interfere with the running of the trains, it does reduce the performance of the whole transit system in terms of comfort, and as such, should be considered carefully. Investigation of support power reduction does not require simulation, but simply a careful review of the energy audit completed in Step 1.

Regeneration of Braking Energy. Regeneration of braking energy has a large potential for energy cost savings on modern rail transit systems. In order to implement regeneration, it is necessary that cars be equipped with solid state propulsion systems, either choppers controlling DC motors or inverters controlling three-phase AC induction motors.

Two regeneration strategies may be considered. One strategy, which is in practical use today, is regeneration with natural receptivity, in which all of the trains on the system and other third rail or trolley loads, such as switchpoint heaters, capture the regenerated power. Other regeneration strategies, which are more futuristic and may have potential in terms of cost/effectiveness, are those with assured receptivity. These involve such things as on-board energy storage, off-board energy storage, and regenerative substations. In addition to solid state propulsion, the assured receptivity regeneration strategies involve other major investments in equipment.

All regeneration strategies may be simulated using the EMM to determine their effectiveness in terms of peak demand and energy use reduction. These are not appropriate strategies to use with load management because they are structural in nature and would be used at all times, not just during peak operating periods.

Cost of Implementation of Strategies

Certain costs are involved in the implementation of energy conservation strategies which have just been discussed. These costs can take the form of new equipment, modified equipment, engineering and/or labor manpower. Table I-4 presents some guidelines for these costs. These are only guidelines and the real costs must be worked out on a transit system specific basis.

Cost of Load Management—Power Demand Monitoring Component

Three forms of power demand monitoring can be considered as part of an energy management system:

1. *Real Time Monitoring.* Power demand monitoring in real time is required as part of a load management system. The objective is to monitor the demand over the early part of the demand interval and predict the demand level for that interval. If it appears that the demand will exceed a preset maximum, a warning will be issued so that transit management can take action to reduce performance.

For the purpose of estimates of real time demand monitoring cost, a generic demand monitoring system was designed which can handle large numbers of power feed points. Figure I-9 shows a schematic diagram of the monitoring system. In the main data collection computer, data from each meter are processed separately and examined over the early portions of the demand interval. The appropriate meter consolidations are made by summing the individual meter data into a total power curve. The slope and area under the power curve are evaluated over the early portion of the demand interval to predict the final demand for the interval. If a critical value of final demand is projected, an alarm will sound, and those meters contributing the largest to that critical demand will be displayed on a monitor. In the case of an ATC system, there is a capability to pass the warning information to the train control computer which in turn can take automatic action to reduce system performance. Since some experience is required before proper control algorithms can be developed, initial installation on ATC properties will involve the operator shaving the load manually.

All of the data for a given demand interval should be stored in a nonvolatile memory to prevent loss in the event of a power fluctuation at the data collection facility. At the end of each day, or other convenient time period, the data from the memory is archived on a tape cassette.

The historical information developed by the monitoring systems can be used for electric bill monitoring and rate case development.

2. *Batch Process Monitoring.* Electric utilities serving some of the U.S. rail transit agencies record metering information on magnetic tape for electric bill processing purpose. In these cases, batch process monitoring, which consists of certain types of analyses of the information on these tapes, can be used to understand the nature of peak power demand.

The first such analysis involves producing statistical summaries similar to the example shown in Figure I-1. This analysis will show how much larger the peak demand is than the average. Any correlation of the date-time of the peak with unusual events on the transit system, such as an increase in car-miles/hour or catchup operation, should be noted.

The second type of analysis to be conducted is a regression analysis relating power to car-miles/hour in the form:

$$P = P_0 + E_1(CM/H)$$

where the quantity P_0 is the background power (kW), the grouping CM/H represents the rate of accumulation of car-miles (car-miles/hour), and the coefficient E_1 stands for energy per car-mile. This will require gathering car-mile/hour data on a regular basis.

The third type of analysis which can be completed using the regression technique is the determination of the background power dependence on ambient temperature. This can be done by finding P_0 as a function of temperature. Figure I-2 shows an example of the results of this regression.

Batch process monitoring can also be used as a supplement to a real time monitoring system because the kind of detailed data needed is available.

3. *Electric Bill Monitoring.* For those transit agencies which cannot use batch process monitoring because they do not have the detailed data available, monitoring of electric bills is possible. Since the value, but not necessarily the time of peak demand, is presented on the electric bill, it is necessary to keep records of car-miles/hour and any abnormal operation to determine how this peak demand was generated.

Regression analysis using ambient temperature can still be conducted, but only on the basis of average monthly temperature. Likewise, regression analysis to determine monthly energy consumption as it relates to car-miles/month can also be carried out to determine the average monthly background power and the energy per car-mile.

Table I-4. Energy conservation strategy application implementation cost guidelines.

CATEGORY/STRATEGY	TRANSIT OPERATING PERIOD	IMPLEMENTATION COST GUIDELINES
*Vehicle Performance Modification		
Top Speed Reduction	Operating	Manual System: Operating Rule or Signal Change ATC System: Speed Command Changes
Coasting	Operating	Manual System: Operating Rule Changes Speed Regulator Changes ($100-200/lead car) Operator Training ATC System: Speed Regulator Changes ($100-200/lead car)
Optimized Performance Modification	Operating	ATC Only: Microprocessor Aboard Car ($1000-2000/lead car)
*Passenger Load Factor Improvement		
Turn Trains at Intermediate Stations	Operating	Labor manpower at terminals. Changes in Operators.
Shorter Trains	Off-Peak	Labor manpower (coupling/uncoupling).
Fewer Trains	Off-Peak	Savings in Operators
*Auxiliary Support Aboard Vehicles Turned Down	Operating	Manual Reduction by Operator. (No cost except switch $200/car)
	Non-Operating	Manual Reduction by Maintenance. Automatic Reduction on Lay up ($1000/car).
*Support Power Reduction	Operating	Automatic (Equipment Required) Manual - Labor Manpower
	Non-Operating	
* Regeneration Natural Receptivity	Operating	Cost of Chopper Propulsion: Cam Control $25-30,000/car rapid rail $20-25,000/car modern light rail
Assured Receptivity		Storage devices and Regenerative Substations on case of on-board storage, extra weight of vehicles.

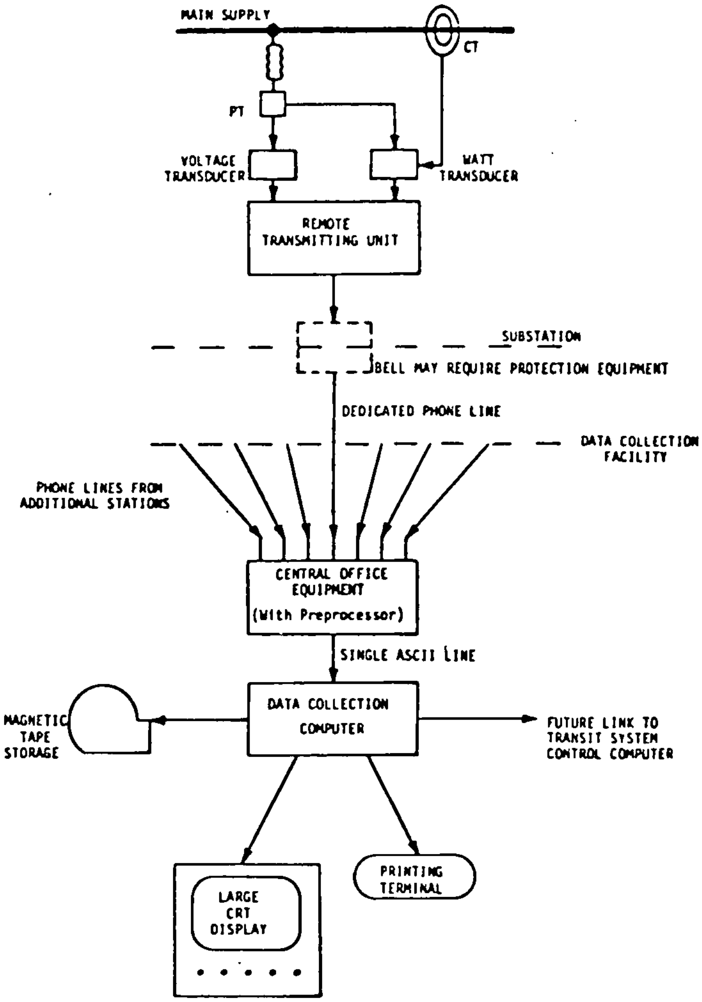


Figure I-9. Real-time power-demand monitoring system.

Estimates of cost were developed for the three types of demand monitoring methods. These estimates are presented in Table I-5. The costs shown in the table should be used as a guideline only. Site-specific considerations may change them.

A large investment item for real time demand monitoring is in the high voltage potential and current transformers necessary for isolation of the power meters and volt meters. Use of the electric utilities' transformers would substantially reduce the initial investment. The monitoring technician represents a person working full-time over the peak transit operating times, 5 days per week.

For the batch process monitoring, the initial investment is in the purchase and/or development of computer programs necessary to translate and analyze the metering information supplied by the electric utilities. Recurring costs include computer usage and manpower necessary to interpret the analyses. They would also include tracing and cataloging events which led to generation of the peak demand in order to correlate them with observations in the metering information.

Cost and Effectiveness Summary

Energy cost savings, which can result from implementation of energy conservation and load management, show up in reduced electric bills. This represents the effectiveness or benefit. The costs of implementation include both initial investment and recurring costs. They are:

- Engineering design.
- Equipment modification.
- Equipment installation.
- Manpower to operate.

Because a detailed study was completed for WMATA Metrorail, it was possible to use this system as the basis for a cost/effectiveness evaluation of a real time power demand monitoring and control system as an example. Because the demand interval at WMATA is 30 min, peak demand reduction was estimated for reactions at 10, 15, and 20 min into the demand interval (i.e., the performance modification strategy was initiated after 10, 15, and 20 min into the demand interval). It was also assumed that catchup operation was responsible for creation of the abnormal peak demand. Two strategies were considered: first, initiation of coasting for the remainder of the demand interval, and second, reverting back to normal operation. The energy cost savings are given in Table I-6. In the case of catchup operation with coasting, the increase in schedule time was 2.5 percent on the Red Line and less than 0.5 percent on the Blue and Orange Lines.

The previous estimates on energy savings were based on a simple application of performance modification, namely, reducing the performance of the whole system. Because of the nature (microprocessor-based) of the demand monitoring, it would be possible to apply performance modification on a local basis, when it might be most effective in reducing energy use per minimal increase in schedule time.

Table I-5. Power demand monitoring cost components.

Real Time Monitoring	
Initial Investment ($11,690/metering point less high voltage equipment	$24,560/metering point
Recurring Cost	
Telephone Lines	$32/month/metering point
Monitoring Technician (Independent of number of meters monitored)	$50,000/man-year
The initial investment is based on a sixteen metering point system:	
Hardware Cost (Less High Voltage Equipment)	$107,000
High Voltage Equipment	$206,000
Engineering Labor (1 man year)	$80,000
Total	$393,000
Batch Process Monitoring	
Initial Investment	
Computer Programs	20,000
Recurring Cost	
Computer Time	$500/month
Engineering Time (1/4 MY/Y)	$1670/month
Electric Bill Monitoring	
No Initial Investment	
Recurring Cost	
Engineering Time (1/10 MY/Y)	$670/month

Table I-6. Energy cost savings of real-time power-demand monitoring and control for WMATA.

STRATEGY	STRATEGY INITIATED AFTER ($K/MONTH) 10 MIN	15 MIN	20 MIN*
Catch-up Operation with Coasting	74.4	55.9	37.3
Revert Back to Normal Operation	62.3	47.6	31.2

DEMAND REDUCTION (MW)

JURISDICTION	CATCH-UP WITH COASTING			REVERT BACK TO NORMAL OPERATION		
	10 MIN	15 MIN	20 MIN	10MIN	15 MIN	20 MIN*
DC	4.9	3.7	2.5	4.5	3.4	2.3
MD	1.1	0.8	0.5	0.5	0.4	0.2
VA	0.8	0.6	0.4	0.6	0.5	0.3

---

*Time into demand interval during which strategy is initiated.

Table I-7 summarizes the cost of the demand monitoring and control system using the unit costs of Table I-5. Use of the catchup operation with coasting strategy requires a fleet modification to the speed regulator in the on-board ATO equipment. This modification was estimated at $40,000.

A summary of the cost/effectiveness of the real time power demand monitoring and control at WMATA is given in Table I-8. Normally, if the investment required is not too large, a payback period of less than 3 years is acceptable in the rail transit industry. Observation of Table I-8 reveals that the payback period is very sensitive to the time in the demand interval when the correction strategy is initiated. The lower this time, the higher the penalty to be suffered in reduced performance during the peak transit operating period.

WMATA already has a system where the power consumption information is brought to a central location. Therefore, the cost of a power demand monitoring and control system is expected to be much less if the present system can be used.

Rate Negotiation with Energy Management

Once a knowledgeable representation at the rate case hearings is established by the transit authority, techniques can be developed to incorporate arguments for rate relief because of the change of energy use patterns which results from load management.

Reduction of peak demand will shift the burden of rate increase toward the other customer classes serviced by the utility. The degree to which this shift occurs depends on many factors, in addition to the degree of peak demand reduction attainable.

1. The fraction of peak demand attributable to the transit system as a member of his customer class.
2. The fraction of peak demand attributable to the customer class of which the transit system is a member.
3. The relation of the time of peak demand of the agency to utility peak demand.
4. Facilities set aside for exclusive use of transit.
5. The ratio of peak demand to energy plus customer components in cost categories.

All of these factors must be incorporated into a new cost-of-service study which would be carried out by the transit agency in order to strengthen its position.

The degree to which rate relief can actually be realized is not certain. Since any rate relief realized by the transit agency increases the rate burden of customers in other classes, there is an inducement for them to initiate conservation policies to shed this burden and equalize the situation.

Perhaps a better way of viewing the situation is that the other customer classes will initiate conservation shifting the utility cost burden toward transit, forcing the issue of conservation at the transit agency.

IMPLEMENTATION OF ENERGY COST REDUCTION STEPS 5–6

Completion of the energy cost reduction study, outlined in the previous section, implies a decision point for transit management on which strategies to select for implementation. All of the theoretical estimates of cost and benefit are now available.

Step 5—Prototype Operation and Validation

This step is important to minimize the technical and financial

Table I-7. Summary of costs for real-time demand monitoring and control for WMATA Metrorail.

INITIAL INVESTMENT (72 metering points) ($M)	
With High Voltage Equipment	1.77
Without High Voltage Equipment	0.84
Coasting Modification to Fleet	0.04
RECURRING COST ($K/month)	
Telephone Lines	2.3
Monitoring Technician	4.2

risk of applying the selected conservation strategies. A low cost experiment should be conducted during which both the actual energy savings and performance changes can be measured under actual operating conditions. The results should be compared with the simulated case. Some considerations should be given to the following experiments.

Vehicle Performance Modification

To validate the simulation of coasting and optimum performance modification, a single train (preferably one or two cars) should be modified for the performance modification. The train should be instrumented to measure traction energy (recording watt meters) and running time (clock). Tests should be run during nonrevenue service time at several different performance modification levels. Simulations using the EMM should be done under the same conditions, for comparison. This simulation should be compared to the tests results for validation.

It is important that enough tests be conducted so that a solid average energy savings and running time increase can be established, since the (decreased energy, increased running time) points in the accessible region are statistical in nature.

Passenger Load Factor Improvement

The improvement of passenger load factor by proper scheduling of trains has an impact on transit productivity which is more than energy cost savings. The following steps should be taken to validate passenger load factor improvement strategies:

1. An internal committee should be established, consisting of scheduling, transportation, maintenance, and energy management personnel, to recommend strategies that can meet overall productivity requirements.
2. Each of the strategies should be simulated to determine energy savings and cost to operations.
3. A 3-month prototype test should be conducted during which energy use and/or peak demand is monitored, either via the electric bill or batch process monitoring of metering information.

Reduction of Support Power

The savings obtained by reduction of support power either aboard the vehicle or in the passenger stations, shops, and office buildings can easily be measured by monitoring the circuits that feed the support power. This can be done with both full and reduced support power using an integrating kilowatt-hour meter to determine the difference.

Regeneration of Braking Energy

Prototype demonstrations of regeneration either with natural receptivity or assured receptivity are expensive. If the transit system does not have solid state propulsion equipment, the first order of business is to procure a few cars, usually added onto an order of conventional cars. A prototype test program similar to that outlined in the case of applying the vehicle performance modification strategy should be conducted with some differences.

A train consisting of cars with solid state propulsion, and a train consisting of conventional cars, should be instrumented with recording kilowatt-hour meters and clocks to measure energy and running time. These should be run over the same routes during peak and nonpeak operation to determine energy savings. Simulation should also be conducted to which the test results can be compared. As in the case of vehicle performance reduction, enough measurements must be taken to establish average energy use with statistical confidence.

Load Management—Real Time Monitoring

A real-time power-demand monitoring system can be installed as an experiment and then expanded if verification of its operation is achieved. Since two of the major cost items are the potential and current transformers, some initial arrangement might be made with the electric utilities to use their equipment during the testing phase.

During the testing phase, it will be necessary to develop algorithms that can predict power demand given power samples in the early part of the demand interval. The EMM will be helpful in the development of these algorithms.

Step 6—Full Implementation and Monitoring

The prototype operation and verification outlined in Step 5 should reduce the technical risk for implementing energy conservation and/or load management on a wider basis. However, the program does not end here. Continued monitoring of the energy cost savings is still required, together with any system performance changes that result from the program.

It is at this stage of the program that the negotiation capability of the transit authority with the electric utilities must be strongest, since the reduction of revenue to the utilities because of the program will be felt. Changes in the power rate structure may bring other opportunities to reduce energy cost as well. Thus, the energy management study, outlined in Steps 1–4, should be updated from time to time, typically on a 3-year basis. If the original study has been conducted properly, updating should not be difficult.

Table I-8. Summary of cost/effectiveness analysis for real-time power-demand monitoring and control at WMATA Metrorail.

	CONTROL STRATEGY	
	REVERT TO NORMAL OPERATION	CATCH UP WITH COASTING
Initial Investment ($M)	1.77 (0.84)	1.81 (0.84)
Monthly Cost ($K)	6.5	6.5
Monthly Savings ($K)		
10 min•[a]	62.3	74.4
15 min•	47.6	55.9
20 min•	31.2	37.3
Payback Period(years)		
10 min•	2.6 (1.3)	2.2 (1.1)
15 min•	3.6 (1.7)	2.7 (1.3)
20 min•	6.0 (2.8)	4.9 (2.4)

( ) Without high voltage equipment.

Payback Period = Initial investment divided by Net Savings/year.

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[a] •Time into demand interval at which strategy is initiated.

ANALYSIS TOOLS

Brief Description of the Management Model

The package of simulation and energy management programs developed at C-MU was designed to meet two categories of objectives—functional objectives defining what the package is expected to do, and architectural objectives defining how the package is to be built.

Functional Objectives

1. Realistically model and simulate power flows, energy consumptions, and energy costs of existing and anticipated electric powered transportation systems.
2. Separate a system's overall energy consumption into its important end uses. Identify the cause-effect relationships governing these end uses and determine their sensitivities to changes in equipment, system design, and operating practices.
3. Provide the means to develop, refine, and test energy conservation strategies before they are implemented in actual systems.
4. Provide flexibility—allowing the package to be improved and upgraded as necessary to accommodate new models, new strategies, and new technology.
5. Provide an analysis tool for determining energy cost from the results of simulation.

Architectural Objectives

1. To be modular at all levels so that any module can be:
   a. Developed, tested, and verified independently,
   b. Inserted into the package or replaced without requiring a major retrofit affecting the package's integrity.
2. To be, as far as possible, machine independent and to be written in a widely used language. (No large package can come even close to being completely independent, but steps can be taken to minimize the effort required to move the package from one computer system to another.)

Approach

In essence, the approach to simulating a system, that is to determine its performance, power flows, energy consumptions, and energy costs, involves the following steps:

1. For each train in the system assemble data on its performance characteristics, the route and schedule it is to follow, and the characteristics of the track on which it is to run.
2. Assemble data on the electrical configuration of the network supplying power to the trains and/or the costs of energy.
3. Treating each train separately, calculate tables of its speed, position, and power demand against time.
4. From these tables assemble a master table which, for selected time instants, spanning the period under investigation, contains data on the locations and electric power demands of every train in the system.
5. At each of the selected time instants calculate the voltages, currents, and real and reactive power flows for all salient points in the electrical network.
6. Integrate the power flows to give energies and wattless flow, and process them in accordance with a selected power rate structure to obtain the energy costs.

In Steps 1–6, a system's total energy consumption is synthesized from its important end uses. (Examples of these end uses are the energy consumed by the auxiliaries and the energy dissipated as losses by the propulsion systems.) Thus, Steps 1–6 provide the means for identifying the end uses, the total energy consumption, and their sensitivities to changes in design or operating practices.

Thus, the addition of processes for strategy development and optimization to Steps 1–6 provides a scheme for meeting all of the previously listed "Functional Objectives." Such processes cannot, of course, be fully automated. Heuristics, creativity, and judgment are important ingredients in strategy development. Recognizing this, allowances are made for knowledgeable people to interact with the program package at two levels: first, through the identification and creation of strategies that are systematic enough to be automated and can then become permanent package features, and second, through direct interaction with the package in a time shared mode so that trial-and-error can be used to home in on a solution.

To meet the architectural objectives, the overall package was assembled from the principal modules shown in Figure I-10. All modules are written exclusively in FORTRAN. Each principal module is completely modular.

Principal Modules

The package consists of a transportation system model capable of simulating train performance and the power and energy flows in a system, together with components (modules) that support and utilize this model. These additional components are: supervisory programs, a data base, and an input file creation program which contains a propulsion performance model.

The EMM consists of four principal components: a Train Performance Simulator, an Electric Network Simulator, an Energy Cost Module, and an Input File Construction Module.

The deployment of the principal components (modules) of the package is shown in Figure I-10.

Train Performance Simulator (TPS). This program accepts as input vehicle parameters such as weight, propulsion system characteristics (tractive effort and efficiencies vs. speed), train resistance, numbers and types of vehicles in train, auxiliary electric loads, and passenger load factors; wayside parameters such as power distribution system type (DC, single phase AC, or three phase AC), voltage and right-of-way profile (grade, curve, and speed restriction as a function of location); and system operational characteristics such as acceleration and braking rates, maximum speed, and station dwell times. The program simulates the operation of a single train under the input conditions. Outputs include power profiles (real power for DC distribution and real and reactive power for AC distribution as a function of location). The program will accept trains with dynamic braking capability and the energy can be fed into storage devices aboard the vehicles (batteries or flywheels), dissipative devices aboard the vehicle (resistors) or to storage/dissipative devices, or other trains external to the train (regeneration) using the power distribution system.

There are many other programs that can perform some or

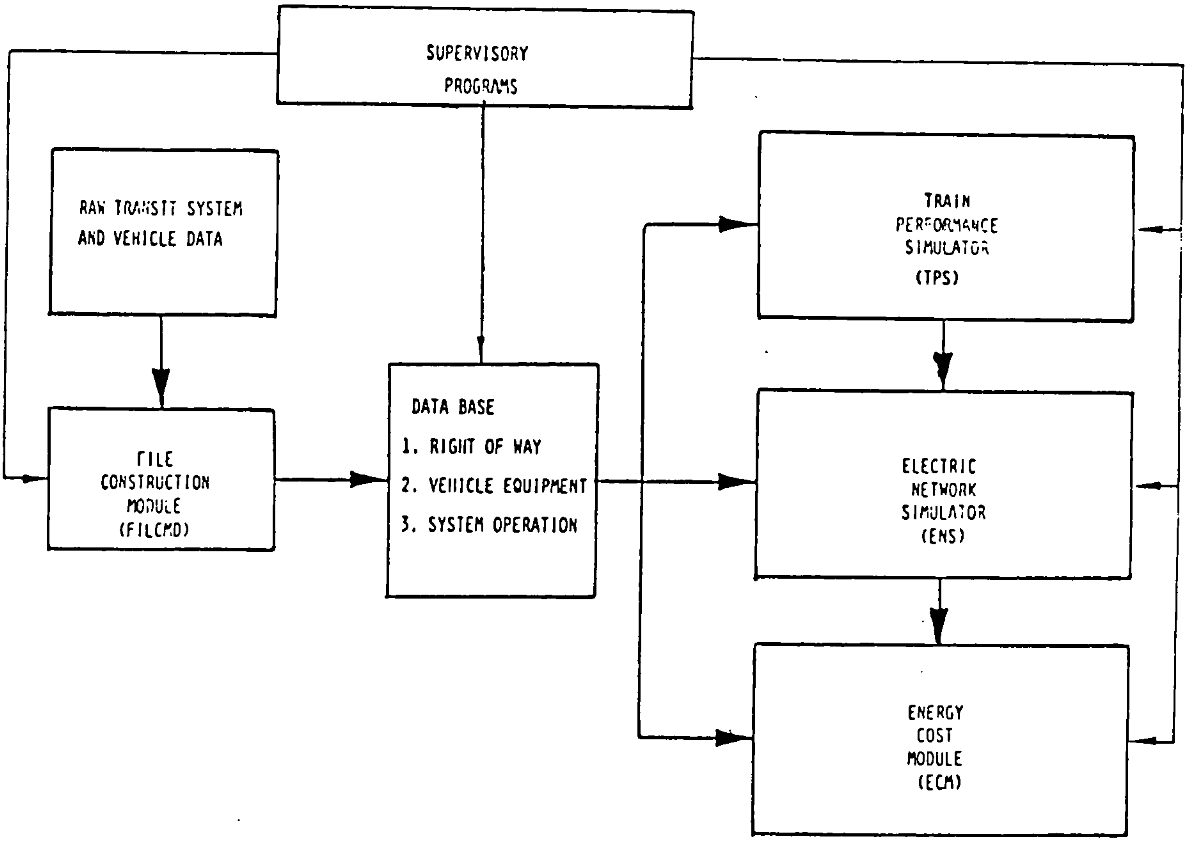

Figure I-10 Principal components of Energy Management Model (EMM).

all of these functions. The C-MU program is unusual not in terms of its functions, but in terms of its structure. First, it is modular and therefore can continue to grow easily. For instance, if new propulsion system models, or more accurate train resistance formulae are needed, the existing modules in which these are contained can easily be augmented or replaced.

Electric Network Simulator (ENS). The program accepts, as input, single train power and time profiles as a function of location along the right-of-way; timetables for movement of multiple trains; power rail, catenary or trolley impedances, running rail impedances; substation locations and characteristics; operating voltages, both nominal, maximum and minimum, characteristics of the distribution network; the substation feeders, and metering point locations. This program simulates the movement of the trains by taking snapshots of the entire system at fixed intervals of time. The calculated output of this program is a complete electrical picture of the system including power flows, voltages, currents, and losses at all salient points. In particular, power through metering points (forward and reverse), power distribution system and substation losses are computed. Capability for regeneration to other trains, to storage devices on the track side of substations, and/or through regenerative substations (even though metering points) is also included.

Energy Cost Module (ECM). The Energy Cost Module (ECM) consists of two computer programs which use the output of the ENS to compute such things as power demand at meters, consolidated power demand, and energy consumption. It does not compute energy costs directly, but rather provides the basis for a simple manual computation of these costs. This approach was taken because power rate structures vary greatly among transit agencies.

The two programs which constitute the ECM are the Appended and Consolidated Load Curve (APL) program and the Energy-Demand Consolidation (EDC) program.

The APL uses, as input, meter load curves that have been generated by the ENS. It appends these load curves and consolidates them by selecting only those meters that are designated for consolidation (i.e., they belong to the same power company or some other reason for consolidation).

The EDC uses, as input, a set of consolidated meter load curves and summarizes the meter readings over the stated demand intervals.

Data Base. To make a meaningful study, one needs a considerable amount of data on:

- The site or property under consideration.
- The equipment under consideration.

Obtaining and inputting these data are slow processes. Therefore, a library of relevant data is being assembled that can automatically be called on whenever necessary.

Input File Construction Module. The File Construction Module (FILCMD) uses raw transit system and vehicle data to create the files that can be used as input to the TPS and ENS, and that constitute the data base just described. This module operates in an interactive, time-sharing mode with a user at a terminal. This program also contains a propulsion model that can estimate efficiencies in power and electrical braking, and tractive and electrical brake vs. speed curves. These are subsequently used as input to the TPS.

Analysis of Metering Information

For those transit systems whose serving electric utilities record metering information on magnetic tape for the processing of electric bills and are willing to provide these data to the transit authority, it is possible to conduct some sophisticated analyses of this information. Usually such a tape contains average power or energy pulses for each meter over a time interval that is equal to or less than the demand interval. These data can be used as part of an energy audit or as input to a batch processing power demand monitoring system.

Figure I-11 presents a flow diagram of the processes and analyses methodology used in the analysis of this information. This system was developed at the RSC as part of its ongoing energy management work.

The raw data tape from the electric utility is read by a special executive level program that must be developed separately for each electric utility. The remaining programs work from data entered on the processed tape.

The principal inputs to do the complete analysis include the metering information, and car-miles and degree-day (ambient temperature) information. The principal outputs are summary statistics (sample contained in Fig. I-1), regression analysis results (sample contained in Fig. I-12) and various types of histograms (one sample contained in Fig. I-13).

A package **BMDP1R,** one of the computer packages of BMDP series, was used that estimates multiple linear regression relating a dependent variable (in this case traction power) to several independent variables (e.g., degree-day and car mile/hour in our case).

Let y represent the value of the dependent variable, and x_1, $x_2, \ldots, x_n$ the values of the independent variables, then the proposed relationship is:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \text{error}$$

The package estimates by least square the coefficient α, β_1, $\beta_2, \ldots, \beta_n$, that is, it finds a, b_1, $b_2, \ldots, b_n$, estimates of α, β_1, $\beta_2, \ldots, \beta_n$ that minimize:

$$\Sigma(y - a - b_1 x_1 - b_2 x_2 - \ldots - b_n x_n)^2$$

Here the summation is over the cases used in the analysis. The predicted value y for each case is:

$$y = a + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n$$

The residual for each case is $(y - y)$. Thus, a multiple linear regression equation can be written as:

$$E(y_j - y) = \beta_1(x_{1j} - x_1) + \ldots + \beta_n(x_{nj} - x_n$$
$J = 1, 2, \ldots$ n (number of cases)

In matrix notation:

$$E(Y^1) = X^1 B^1$$

where:

$Y = (y_j - y)$ is a row vector of length N;
$X = (x_{ij} - x_i)$ is a $N \times N$ matrix;
$B = (\beta_i)$ is a row vector of length n; and
X^1 and Y^1 are the transpose matrices of X and Y, respectively.

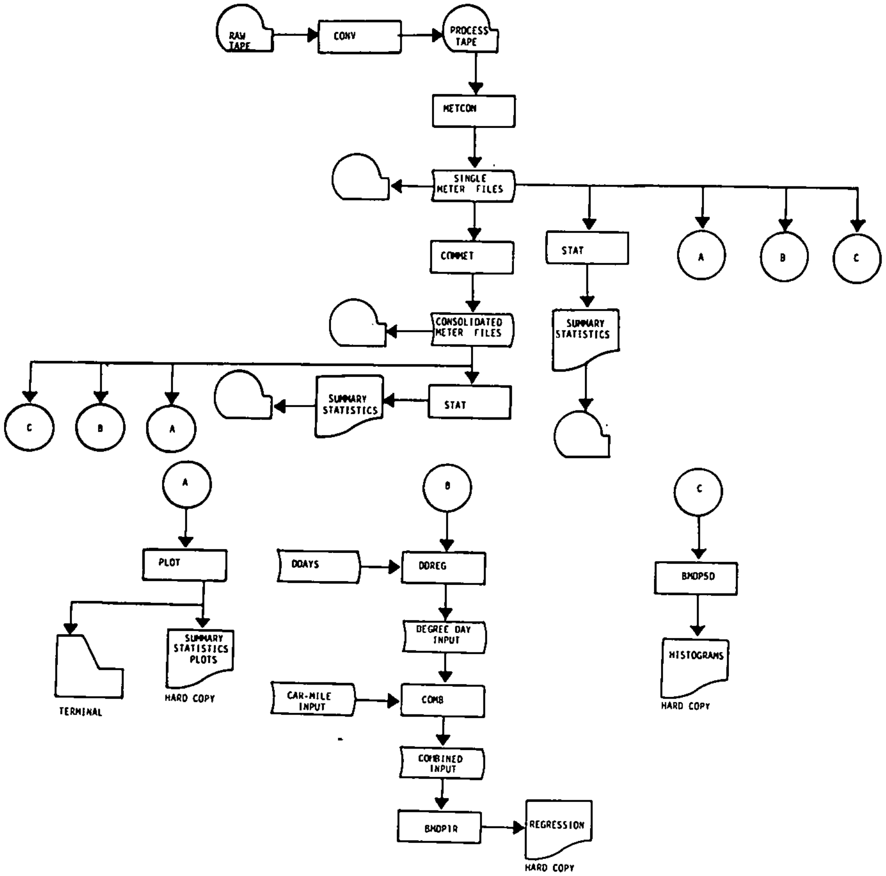

Figure I-11(a). Regression analysis flow chart.

CONV -	Executive level program which takes the magnetic tapes provided by the electric utilities and converts the information into Fortran readable format.
METCON -	Fortran program which is used to read the process tape and create one file for each meter for future processing.
COMMET -	Fortran program which is used to combine the single meter files into consolidations. The pulses from each meter which occur at the same times are added to obtain the consolidated pulse at that time. This is done for all times.
STAT -	Fortran program which is used to develop summary statistics, which are the mean, standard deviation and maximum for some specified period of time on weekdays, Saturdays, and Sundays.
PLOT -	Fortran program which is used to plot summary statistics.
DDREG -	Fortran program which takes degree-days by date as input and prepares the file for regression analysis.
COMB -	A Fortran program which combines input data of degree days as output from DDREG and car-mile data by date and stores it in a file for regression analysis.
BMDP1R -	A Biomedical Computer Program (BMDP) developed by Health Sciences Computing Facility of the University of California, Los Angeles, for regression analysis.
BMDP5D -	Same as above but for plotting histograms.

Figure I-11(b). Regression analysis definitions.

```
                    METER NAME - DUPONT CIRCLE TRACTION

VARIABLE          MEAN STANDARD DEVIATION COEFFICIENT    MINIMUM       MAXIMUM
                                          OF VARIATION
  1 DATE     160.79216          74.90992     0.46588    32.00000     289.00000
  3 MILES    774.75294         143.46292     0.18517   342.00000     991.00000
  4 POWER    926.46273         156.15845     0.16855   330.00000    1159.00000
  5 DDAYS     -3.67843          17.06283    -4.63862   -52.00000      21.00000

 CORRELATION MATRIX

             DATE      MILES      POWER      DDAYS
                1          3          4          5

DATE     1   1.0000
MILES    3   0.2545     1.0000
POWER    4   0.0592     0.7914     1.0000
DDAYS    5   0.7452     0.3314     0.1578     1.0000

MULTIPLE R            0.7991        STD. ERROR OF EST.      94.2560
MULTIPLE R-SQUARE     0.6385

ANALYSIS OF VARIANCE
                 SUM OF SQUARES     DF      MEAN SQUARE        F RATIO    P(TAIL)
     REGRESSION    3955092.500       2      1977546.300        222.692    0.00000
     RESIDUAL      2238815.100     252         8884.187

                                           STD. REG
   VARIABLE        COEFFICIENT   STD. ERROR   COEFF          T   P(2 TAIL) TOLERANCE

INTERCEPT           222.32089
MILES        3        0.90376       0.044       0.830    20.684     0.000    0.890164
DDAYS        5       -1.07441       0.367      -0.117    -2.925     0.004    0.890164
```

Figure I-12. Example of regression analysis summary.

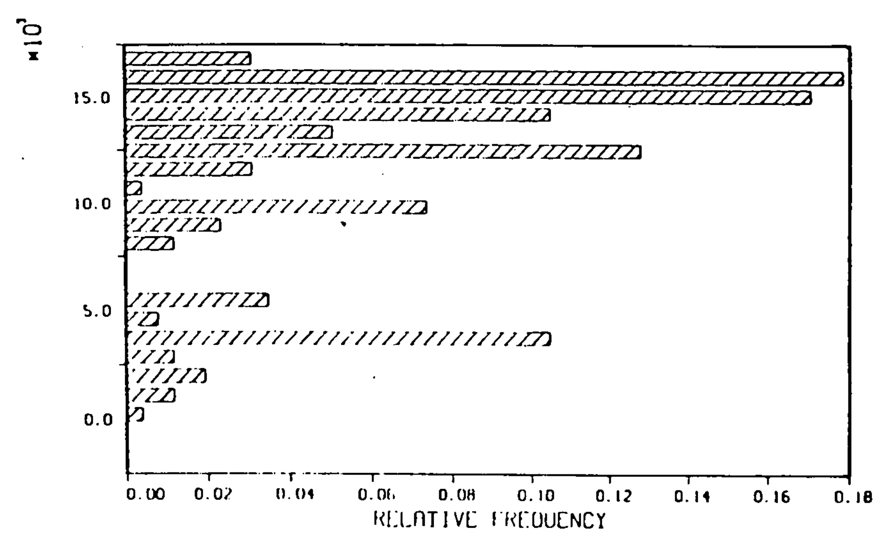

Figure I-13. Histogram—Red Line car-miles (Feb. 1–Oct. 15, 1980).

The least square estimate b of β is $b^1 = (XX^1)^{-1}XY^1$. The statistical descriptive package provides as output:

1. *Regression Coefficients*—A summary table for the regression is printed. It contains:

- The coefficients b_i
- The standard error of the coefficient $S(b_i)$
- The standardized regression coefficient $b_i S_x / S_y$
- t test for the coefficient $b_i S_x / S_y$

2. *Univariate Statistics*—

- Mean
- Standard deviation
- Coefficient of variation
- Minimum observed value
- Maximum observed value

3. *Correlation Matrix*—A correlation matrix of the dependent and independent variables is calculated which is used to test the multicollinearity among variables (an assumption for regression). The correlation of the dependent variable with the predicted value R is estimated as well as the multiple:

$$R^2{:}(1 - \Sigma(y_j - y)^2 / \Sigma(y_j - y)^2)$$

standard error of estimate:

$$\Sigma(y_j - y)^2 / (N - n)$$

4. *Analysis of Variance*—The analysis of variance table for the regression is printed. It contains:

- The regression sum of squares: $\Sigma(y_j - y)^2$
- The residual sum of squares: $\Sigma(y_j - y_j)^2$
- An F ratio that tests the significance of the regression.

5. *Tests for Significance*—The package provides three different tests for significance, namely:

- R^2
- t test
- F test

The R^2 tests the significance of overall regression equation (values of R^2 greater than 0.5 are significant for cases having two independent variables). The t test is used to test the significance of individual coefficients b_i. The summary table contains the t test for the coefficient $b_i/S(b_i)$ and the corresponding two tail probability value. Again, a t value with 95 percent confidence level (approximately 2.2 for most of the cases) has been chosen to test the significance of the independent variable in the given regression equation. An F value at 95 percent level of confidence (3.1 for two independent variable cases, and 3.9 for one independent variable case) is used to ascertain the significance.

SUMMARY OF DATA REQUIREMENTS AND UNIT COSTS

This section provides a listing of data requirements and unit costs for easy reference for the energy management study (Steps 1–4).

Step 1—Energy Audit

Data Requirements

- *Metering information*—For each meter, the average power for each successive time period less than or equal to the demand interval should be obtained for a period of not less than one year. If these data cannot be obtained, the electric bills should be used.
- *Load information*—All circuits fed through each meter should be identified and the loads associated with them should be tabulated. For each load, the average and maximum value and the time of occurrence of the maximum should be listed.
- *Power rate structure*—The present power contract and rates should be obtained. The latest cost allocation studies of the serving electric utilities should also be procured. Any utility studies that project future trends in the power rate structure should be reviewed.

Unit Cost

The cost of the energy audit is $10,000 to $40,000, which depends on the availability of data. If more data are available, the cost will be higher and the results of the audit will be more credible.

Step 2—Simulation of Normal Operation

Data Requirements

Input data for the EMM should be acquired.

- *Right-of-way* to include track plan, grade and alignment profile, speed restrictions and passenger station locations.
- *Vehicle* to include empty and crush load weight, length, cross sectional area, flange coefficient, and average auxiliary power.
- *Vehicle propulsion characteristics* to include type and number of motors, type of motor control, wheel diameter, and gear ratio.
- *Power distribution system* to include single line diagram showing substation and tiestation locations and configuration, substation average power rating of voltages and impedances, and third and running rail impedances.
- *Operational information* to include initial acceleration, deceleration and maximum speed, operating timetable for peak and non-peak operation, passenger load factor, dwell times, and number of cars per train.

Unit Cost

The cost of simulation for normal operation is $10,000 to $20,000. This cost is principally determined by the simplifying assumptions and the degree of difficulty encountered in obtaining the data.

Step 3—Verification of Normal Operation

Data Requirements

Output of Steps 1 and 2 is required.

Unit Cost

Very small—it involves the comparison of results of Steps 1 and 2.

Step 4—Energy Reduction Cost and Effectiveness

Data Requirements

This involves any expressed desires of the transit authority on details of applying energy conservation strategies; for example, in the case of passenger load factor improvement, by turning trains at intermediate stations during the peak period, the stations at which the trains are to be turned.

Unit Costs

The guidelines for cost of monitoring demand and applying strategies are contained in Table I-4. The cost of this step is typically $20,000 to $30,000.

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ADDRESS CORRECTION REQUESTED