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VOLUME 1

ENERGY COST REDUCTION STUDY OF THE WASHINGTON METROPOLITAN AREA TRANSIT AUTHORITY METRORAIL SYSTEM

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16. Abstract

The objectives of this study were to classify the energy used by the Washington Metrorail into its primary end uses, and to identify those energy conservation strategies which have the highest potential for reducing energy cost. The effort involved analyzing present energy costs, developing cost-effective energy conservation strategies, simulating the energy cost savings associated with these strategies, recommending the appropriate strategies for implementation and outlining a program for executing the recommendations.

The study is the first time that the Energy Management Model, developed for the transit industry by the Rail Systems Center at Carnegie-Mellon University, was comprehensively applied to a rapid transit property. The application was verified by comparing the simulated results to actual data. For all practical purposes, the simulated results agree to within 3% of the actual energy consumption.

Five energy conservation strategies were recommended for implementation based on high benefit and low cost. These are: coasting, passenger load factor improvement, planned catch-up operation, regeneration of braking energy and passenger station lighting improvement. All of these strategies have payback periods less than three years.

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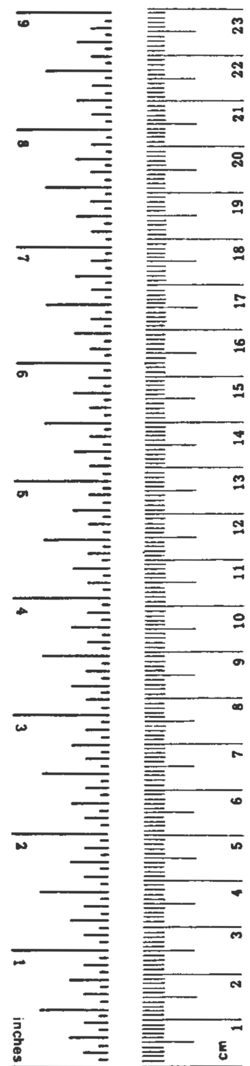
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

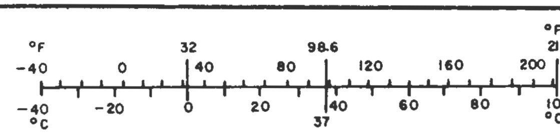
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

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



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1. EXECUTIVE SUMMARY

1.1. INTRODUCTION AND BACKGROUND

Rising energy costs and decreasing energy availability are exerting pressure on transit operators to reduce energy consumption. The Washington Metropolitan Area Transit Authority (WMATA) has been concerned with the increasing energy cost of its rail system. These costs are escalating because of the expansion of the Metrorail system and the absolute increase of the electric rates. The ratio of energy cost to operating cost is now 15-17% and is expected to increase in the future.

The WMATA has established a program for reducing its overall energy costs. This study was undertaken under the auspices of that program. The objectives of this effort were to classify the energy used by Metrorail into its primary end uses, and to identify those energy conservation strategies which have the highest potential for reducing energy cost. Although support energy (energy used in passenger stations, office building and maintenance shops) is considered in this investigation, the primary emphasis is directed toward traction energy (running the trains in revenue operation).

The work reported here was completed under WMATA contract M-41169 to Carnegie-Mellon University (CMU). It involved analyzing the present energy costs, developing cost-effective energy conservation strategies, simulating the energy cost savings associated with these strategies, recommending the appropriate strategies for implementation and outlining a program for executing the recommendations.

This study represents the first time that the Energy Management Model (EMM), which was developed for the transit industry by the Rail Systems Center (RSC) at CMU, was comprehensively applied to a rapid transit property. It is also the first time that such a comprehensive investigation on energy consumption was conducted on a North American rail transit system. The application to Metrorail was verified by comparing the simulated results to actual data obtained from the Potomac Electric Power Company (PEPCO) which is the major electric utility serving the system. For all practical purposes, the simulated results agree to within 3% of the actual energy consumption margin of error.

The availability of detailed information from PEPCO on their 1980 operations provided an ideal base for the investigation. An audit of energy usage was conducted using these PEPCO data. In assessing the cost-effectiveness of the energy reduction strategies, it should be pointed out that the use of 1980 operations is expected to result in a conservative estimate of energy savings since an expansion of service has occurred in the past year. Actual savings are expected to be larger.

Strategies Investigated

Several energy conserving strategies were investigated as part of this effort. These strategies are classified as performance modification, passenger load factor improvement, regeneration of braking energy, lighting load reduction and escalator load reduction.

The performance modification strategies initially considered were acceleration reduction, top speed reduction and coasting. All of them involve an increase in running time. This increase was kept to 2-3% of present running time so that the capacity of the system would not be significantly reduced.

During the investigation, it was discovered that the top performance level (PL1) of the system is not used for normal operation, but held in reserve for catch-up operation when train delays cause the system to fall behind schedule. When PL1 operation is used, a larger power demand results thus increasing energy costs.

Passenger load factor improvement strategies may be of two types: turning trains at intermediate stations during peak and off-peak periods, and reducing the cars per train during off-peak periods. Only the latter strategy was considered as part of this study.

Three regeneration strategies were considered in this investigation: regeneration with natural receptivity, regeneration with on board storage, and regeneration using regenerative substations. The overall potential of regeneration was assessed by assuming that the whole fleet had the capability to regenerate braking energy. A brief assessment was also made of the regeneration capability of the chopper cars being provided by BREDA Toning, Inc. as part of a new car order.

The lighting load reduction strategy, which was investigated by the General Manager's Task Force on Lighting, was summarized in this study. The effect of shutting off escalators as a support energy reduction strategy was also considered.

1.2. CONCLUSIONS

1.2.1. Results of Energy Audit

The analysis of traction and support energy, as metered by PEPCO, has resulted in the following conclusions:

1. A background power of 7-11% of peak power demand is registered on the traction meters even when the trains are not operating in revenue service operation. This background exists because of no-load substation losses, operation of car auxiliaries during layup, train testing and support services (metered through the traction substations) such as heating and ventilation of substations, chiller plants, tunnel ventilation, lighting and switchpoint heating.

2. A regression analysis on the Red and Blue/Orange Lines, using PEPCO traction metering information during revenue service time, shows that the power can be expressed as a sum of the background power plus an effect proportional to the number of car-miles. The coefficient of the car-mile effect is 6.87 KWHPCM (kilowatt-hours per car-mile) on the Red Line, and 5.73 KWHPCM on the Blue/Orange Line. Several of the substation metered powers exhibit an ambient temperature dependence. This effect was much smaller than the car-mile effect.

3. The energy metered at the support substations represents 30-35% of the total power bill of Metrorail. Of the total power metered through these stations, passenger station lighting accounts for 35-42% of these loads, while escalators account for 8-10%. The remainder of the power can be attributed to the office building, certain chiller plants, repair shops, signal and communications, tunnel lighting, heating and other support services.

4. The temperature dependence of the support power was of the order of 15-20%. Its effects were more pronounced on the Red Line and the office building.

1.2.2. Benefits and Costs of Energy Conservation Strategies

Certain energy conservation strategies show a high potential for energy cost savings at relatively low implementation expenditures.

<u>Careful Catch-up Operation</u>

Maximum peak demand is 30-35% higher than normal peak demand. The use of PL1 for catch-up operation as a consequence of train delays during the peak operating period can explain the difference between the maximum and normal peak demand. The indiscriminate use of PL1 can add $1M to the power bill in demand charges alone. The energy charges resulting from this operation are also higher than from normal (PL2) operation.

Performance Modification

Of the performance modification studies which were investigated, coasting offers the greatest potential for savings at a reasonable equipment modification expenditure. By spending $32,050 in modification of the speed regulator on the car, savings from $625,000 to $1,350,000 (4-9%) in energy costs are possible. The application of coasting would result in an increase of running time of 3% on the Red Line, and 1/2% on the Blue/Orange Line. These increases can probably be made up by shortening turnaround time so that overall schedule time can be maintained.

The use of coasting is also expected to reduce stress on the propulsion equipment, resulting in fewer on-the-road failures and, as a consequence, lower catch-up requirements and maintenance costs.

Reduction of top speed at the same performance level as the coasting strategy would result in less savings potential ($160,000 to $1,025,000). Reduction of accelerating rate would not result in energy savings.

Passenger Load Factor Improvement

Because of the nature of this study, only one passenger load factor improvement strategy was considered. It was based on the 1980 timetable and consisted of running alternate four- and six-car trains during the midday off-peak weekday period, and alternate two- and four-car trains during the evening off-peak weekday period, and on Saturdays and Sundays.

The result of applying this strategy is a reduction of the annual car-miles by 3.82 million, with an energy cost savings of $770,000. The cost to Metrorail in applying such a strategy is $68,000 which is the manpower cost of coupling and uncoupling operations associated with running the shorter trains during the off-peak periods.

A second class of passenger load factor strategies was not considered, namely, turning trains at intermediate stations during peak operating periods.

Data have been included in Chapter Five which would allow Metro engineering personnel to easily estimate energy savings of passenger load factor improvement strategies.

Regeneration

It is not known whether the cost of adding chopper control to part of the present fleet would provide a favorable rate of return in the form of energy savings achievable by regeneration. The estimated minimum annual savings in the power bill with the 1980 operating timetable is $2.5M with a fully regenerating fleet of 294 cars. This savings is $8,500/car/year at that level of operation.

Although not part of the original study, an estimate was made on the energy cost savings which would be realized by the placement of the eighteen chopper cars to be delivered soon. If the cars are used on the basis of two chopper cars per train, the savings would be $16,000/car. Without the rate relief that Metro obtained during the recent rate negotiation in the DC jurisdiction of PEPCO, this savings would have only been $8,200/car.

Because a regenerating car will feed the auxiliaries of the train of which it is a part, the use of two chopper cars/train will assure that much of the regenerated energy is utilized rather than dissipated in on-board resistors because of poor line receptivity under some circumstances.

Support Power Conservation

The General Manager's Committee on Lighting recommended that the indirect fluorescent lighting at the passenger stations be replaced with direct mercury vapor lighting. The energy cost savings is estimated at $675,000/year (4-5% of the power cost) with an additional savings in replacement lamps estimated at $41,000/year, or a total annual savings of $716,000. The estimated capital cost is $1,067,000 which would be payed back in 1 1/2 years.

Annual energy cost savings achieved by turning off all escalators with less than a 15 ft height of rise, and the third escalator in areas where three are serving the station from one entrance in off-peak periods, is $32,000 (< 1% of the total power cost).

1.3. RECOMMENDATIONS

Five strategies are recommended for reducing energy cost for future Metrorail operations: Coasting, Careful Catch-up Operation, Passenger Load Factor Improvement, Regeneration, and Lighting Improvement. A plan for a logical implementation of these strategies is outlined.

Coasting

Three steps should be undertaken in implementing coasting. The first step involves the testing of a two-car train which was modified for coasting. This testing should take place during non-revenue service time. The test results should be compared to the EMM simulation.

The second step involves the selection of a running time which does not increase schedule time significantly. Once this is done, the speed regulator boards on the Red Line cars should be modified for coasting at the selected running time level. Energy cost savings should be verified by examining metering records.

If the predicted savings are borne out in practice, the third step would be to modify the remainder of the fleet.

Careful Catch-up Operation

The implementation of catch-up operation should be done in two steps. The first step involves the comparing of a test period during which no catch-up operation is permitted with a similar period during which no restriction on catch-up was in effect. Having verified the savings possible using this approach, a policy which includes demand interval consideration, length of time that catch-up should remain in effect, and location of trains to which it is applied, should then be formulated and executed.

Passenger Load Factor Improvement

Proper scheduling of trains to improve passenger load factor has an impact on transit productivity which is beyond just energy cost savings.

A committee consisting of scheduling, transportation, maintenance and energy management personnel should be established. This committee should suggest strategies which would meet Metro constraints and, at the same time, increase the passenger load factor by reducing revenue car-miles. Each of these strategies should be evaluated using the EMM. Those which have high potential for energy cost reduction should be assessed for additional cost to WMATA. The strategies which have high benefit/cost paybacks should be tested and implemented.

Regeneration

In order to assure that the eighteen chopper cars received from BREDA Toning, Inc., are used to achieve the best energy cost savings compatible with operational and maintenance constraints, the energy savings on the chopper cars should be measured as soon as is practical after the cars are received. Once the energy savings predicted by the simulator have been verified in practice, alternative options should be studied using the EMM in order to maximize the energy benefit of the chopper cars.

After the verification phase has been completed, a study should be conducted to determine under what circumstances it might be cost-effective to modify cam-control cars into chopper cars. This work should be undertaken only after the energy savings and other operational costs of the chopper cars relative to the cam-control cars are known. The WMATA will be the first U.S. property with the opportunity to directly compare chopper vs. cam-control under the same operational conditions.

Lighting Improvement

The savings achievable by lighting improvements are of the same order as that of coasting. However, the capital costs to implement these improvements are much larger. A committee should review them again for possible implementation, on a prototype basis at first.

2. INTRODUCTION

2.1. BACKGROUND

Rising energy costs and decreasing energy availability are exerting pressure on transit operators to reduce energy consumption. Both existing and new rail rapid transit systems are feeling this pressure.

Concerned by rising energy costs, the operators of several rail transit systems have implemented energy conservation measures. The San Francisco Bay Area Rapid Transit District (BART) and the Metropolitan Atlanta Rapid Transit Authority (MARTA) incorporated regeneration of braking energy from the beginning into their rail system in order to improve overall energy efficiency. The New York City Transit Authority (NYCTA) is testing several energy cost reduction strategies including coasting, regeneration with on-board storage and substation battery energy storage to reduce peak demand.

The Washington Metropolitan Transit Area Authority (WMATA) has also been concerned with the rising energy costs of its rail system. Table 2-1 shows the cost of electric power for WMATA Metrorail from FY1979 through FY1981. Power costs are rising both because of the expansion of the Metrorail system, and because of the absolute increase in the cost of energy as is evident from the table. With the total operating cost increasing from $54M in 1979 to $90M in 1981, the ratio of power cost to operating cost is 15-17%. This ratio is expected to increase in the future as energy resources become more scarce.

The total electrical energy used by Metrorail operations is 17.3 KWHPCM (Kilowatt-Hour Per Car-Mile), and the traction energy (metered through traction meters) used is 11.4 KWHPCM. It is clear from observing WMATA operating information that 60-65% of the electric power cost is due to traction, while the remaining 30-35% is due to support services such as station lighting, tunnel ventilation, environmental conditioning, signal and communications, and escalators.

The objectives of this study were to classify the energy consumed by Metrorail into its primary end uses, and to suggest and analyze energy conservation strategies which have high potential for reducing future energy cost. The first objective was met by means of an energy audit using metering information from the Potomac Electric Power Company (PEPCO). The second objective was achieved by using the

TABLE 2-1 ENERGY COSTS OF WMATA METRORAIL

FISCAL YEAR	1979	1980	1981
KWH (Millions)	193	252	271
Total Electric Power Cost ($M)	9.1	11.4	15.2
Traction Energy Cost ($M)	6.0	7.8	10.4
Support Energy Cost ($M)	3.1	3.6	4.8
Cost/KWH ($/KWH)	0.047	0.045	0.056

Energy Management Model (EMM) which was developed for the transit industry by the Rail Systems Center (RSC) at Carnegie-Mellon University (CMU).

The application of certain energy conservation strategies to the WMATA rail system is expected to reduce the power bill. However, before such implementation of any strategy, it is important to assess the cost and benefit of each such strategy, and test its benefit under revenue operating conditions. The strategies can involve operational modification, procedural changes and/or equipment improvements.

The present work involves analyzing present energy costs, developing cost-effective energy conservation strategies, determining by simulation the energy savings associated with these strategies, recommend certain strategies for implementation and develop a program plan for executing them.

2.2. REPORT STRUCTURE

A description of the EMM which was used to simulate Metrorail operations is contained in Chapter Three. Both the Train Performance Simulator (TPS) which is used to determine power requirements and running time, and the Electric Network Simulator (ENS) which uses the output of the TPS and the operational timetable to determine power flows at the electric utility metering points, were used extensively in assessing the benefit of the energy conservation strategies.

Chapter Four provides a description of the Metrorail traction system in a way which is appropriate for application of the EMM to its study. This chapter is divided into several parts. Section 4.2 contains the general operating characteristics of the rail system including the operating timetable which was in effect during the time period (1980) selected for study. A description of the vehicle characteristics including physical data, propulsion data and braking information is presented in Section 4.3. Section 4.4 has an outline of the right-of-way characteristics including station locations, track profile and speed limits for the routes which were studied. The power distribution system from the metering points to the vehicle current collectors is described in Section 4.5. The power rate structure for the three jurisdictions of PEPCO and for the Virginia Electric Power Company (VEPCO) are outlined in Sections 4.6 and 4.7. These power rates were used to determine the energy costs from the simulated power demand and energy usage.

The material in Chapter Five is concerned with traction energy. Traction energy is the time integrated power registered by the electric meters in the traction substations. The actual traction energy consumed by Metrorail operations during 1980 was provided by PEPCO. These were the bases for an energy audit which is discussed in Section 5.1. Using the operating timetable for 1980 as the basis, simulation of the operation was conducted and is described in Section 5.2. Section 5.3 provides a comparison of simulated vs. actual running time and energy consumption for normal operation during the 1980 time period. Based on the results of the first three sections of Chapter 5.0, the traction energy conservation strategies of performance modification, passenger load factor improvement and regeneration were evaluated using the EMM. The results are reported in Section 5.4.

The material in Chapter Six concerns support energy which is the time integrated power registered by the electric meters in the passenger stations, the office building and the repair shops. A support energy audit, which is described and reported in Section 6.1, was conducted during the same 1980 time period as the traction energy audit. The results of this audit were used as the basis for analysis of conservation opportunities for support energy. These results are presented in Section 6.2.

Chapter Seven is devoted to the results of the cost and benefits of the application of conservation strategies to both traction and support energy use of Metrorail. Energy savings which result from strategy application are summarized in Section 7.1 The costs to WMATA to apply the strategies are detailed in Section 7.2. Section 7.3 presents a summary of the costs and benefits for all of the energy conservation strategies considered in the study. In addition to the energy cost reduction benefit obtained by applying the conservation strategies, there are other benefits, especially in the area of reduced maintenance and increased reliability which may be realized. Recommendations for strategy application to Metrorail operation are also incorporated.

A program plan for implementing the performance modification strategy of coasting, passenger load factor improvement and regeneration is outlined in Chapter Eight. This plan is designed to verify the results obtained using the EMM before full implementation of any strategy which involves equipment modification or purchase.

Chapter Nine contains the appendices to the report. The appendices contain details of the calculations which were presented in the report, summaries of TPS runs and data obtained from WMATA.

3. BRIEF DESCRIPTION OF THE TRANSPORTATION ENERGY MANAGEMENT MODEL

3.1. OBJECTIVES

The package of simulation and energy management programs developed at CMU 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.

3.1.1. 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.

3.1.2. Architectural Objectives

1. To be modular at all levels so that any module can be:

    developed, tested and verified independently,

    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.)

3.2. 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 energy-billing-schedule 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 the previously listed "Functional Objectives". Such processes cannot, of course, be fully automated. Heuristics, creativity and seat-of-the-pants 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 3-1. All modules are written exclusively in FORTRAN. Each Principal Module is completely modular.

3.3. 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 T ain 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 3-1.

3.3.1. Supervisory Programs

The program coordinates the activities of the other programs, ensuring that data flows adequately between them.

3.3.2. 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

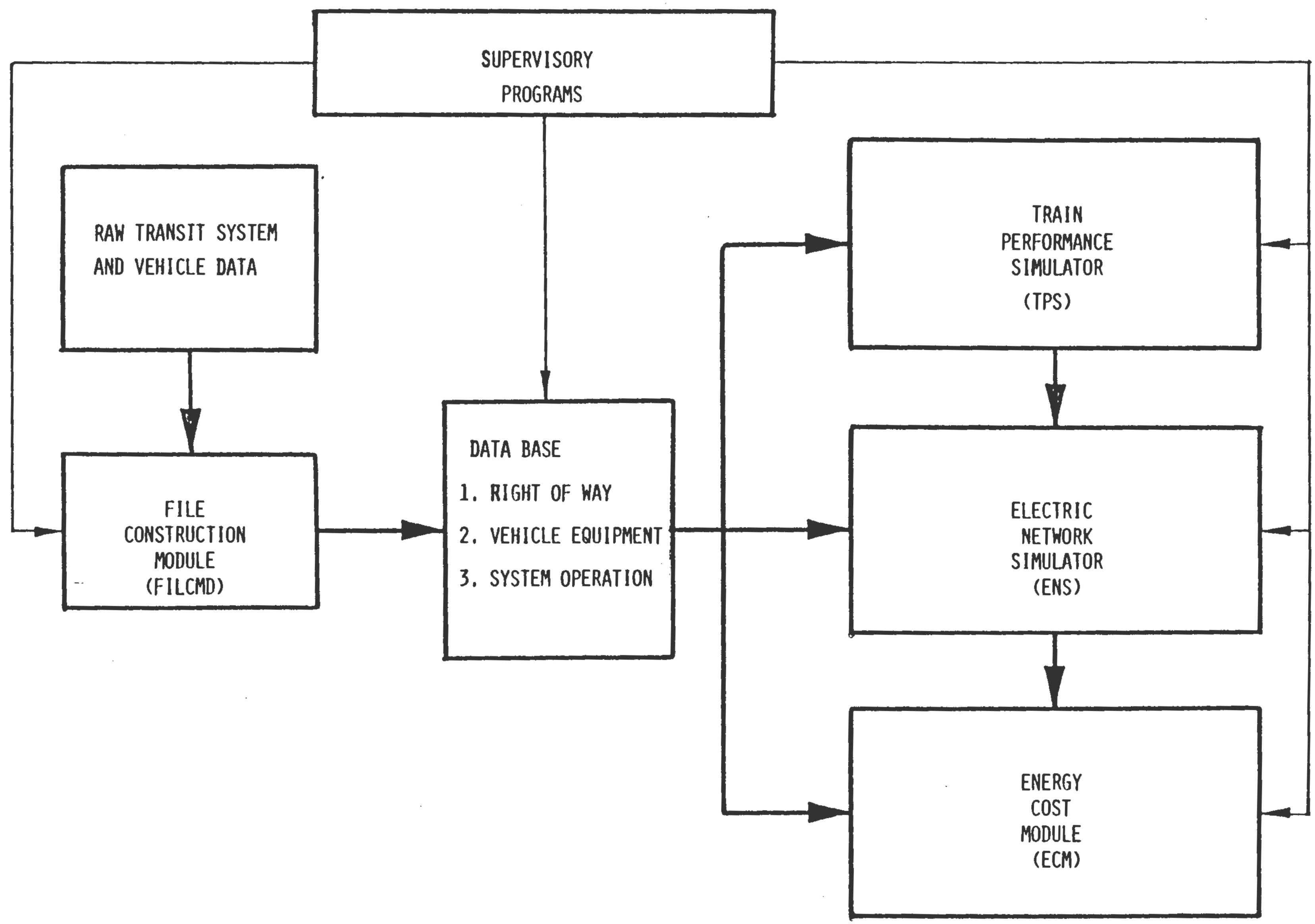


FIGURE 3-1 PRINCIPAL COMPONENTS OF ENERGY MANAGEMENT MODEL (EMM)

the power distribution system.

There are many other programs that can perform some or all of these functions. The CMU program is unusual not in terms of its functions, but its structure. First, it is modular and therefore can continue to easily grow. 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.

3.3.3. 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 fr 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.

3.3.4. 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 since power rate structures vary greatly among transit properties.

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 which have been generated by the ENS. It appends these load curves and consolidates them by only selecting those meters which 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.

3.3.5. Data Base

To make a meaningful study, one needs a considerable amount of data on:

- the site or property under consideration, and
- 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. Data from WMATA have been added to the files in the data base.

3.3.6. Input File Construction Module

The File Construction Module (FILCMD) uses raw transit system and vehicle data to create the files which can be used as input to the TPS and ENS, and which 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 which 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.

4. DESCRIPTION OF METRORAIL TRACTION SYSTEM

4.1. 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 4-1 shows a map of the system and its present status.

The present operation consists of the Red, Blue and Orange Lines. The Red Line extends from Van Ness Station to Silver Spring Station, a distance of 12 miles. The Orange Line runs from Ballston Station to New Carrollton Station, a distance of 16.6 miles, and the Blue Line extends from National Airport Station to Addison Road Station, a distance of 10.8 miles. The Blue and Orange Lines share common track from a point slightly west of Rosslyn Station to D/G Junction, a point east of the Stadium Armory Station. Passenger transfer between the Red Line and the common Orange and Blue Line occurs at Metro Center.

The electric power service to Metrorail is provided by two utilities: the Potomac Electric Power Company (PEPCO), and the Virginia Electric Power Company (VEPCO). The PEPCO services Metrorail in three jurisdictions:

1. District of Columbia (DC),
2. Maryland (MD),
3. the Rosslyn portion of Virginia (VA).

The WMATA is considered a separate customer class by PEPCO in the DC, MD and VA territories of PEPCO. The RT rate schedules have been developed and implemented for each of these jurisdictions. Service supplied by VEPCO for the balance of the WMATA system in Virginia is supplied under the Virginia State Rate Schedule which is generally applicable to state and municipal organizations chartered in Virginia.

Electric rates for WMATA (the RT tariff and others) service in DC and MD are established under the supervision of the DC Public Service Commission and MD Public Service Commission, respectively. The PEPCO VA-RT rates are not subject to similar supervision in Virginia; rates must be negotiated between PEPCO and WMATA. The Virginia State Rate is established under the supervision of the Virginia State

Status of 101 mile Metro system December 1980

Produced by WMATA Office of Public Affairs
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.

As of the end of 1980, a process was underway to revise the opening sequence of some of these segments

Total mileage—100.84

Total stations—86

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

M metro

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

FIGURE 4-1

Corporation Commission.

For the purpose of the Energy Management study, the Metro operation which was in effect during most of 1980 was selected as the system to be studied. This decision was made because metering data was available from PEPCO for the time period in question. This data was used to validate the performance of the EMM which was an integral part of the overall effort. This metering information was available from January 1980 through January of 1981.

4.2. 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 insures 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 ten 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 which was in effect from February through October 1980 is shown in Table 4-1. 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 4-1. 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 ten minute headways on the Red Line, and twelve minute headways on the Orange and Blue Lines. The common portion of the Orange and Blue Lines from Rosslyn to Stadium Armory Station have an effective headway of three minutes during the peak period, and six minutes during the off-peak periods. The Red Line peak period operation consists of running both six- and eight-car trains on a headway of five minutes. 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 operating periods on the Red, Blue and Orange Lines are presented in Appendix 9.1. Load factor information was not available for the operating periods on Saturday and Sunday. 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, which were compiled during this period, 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 shown in Table 4-2 for all three lines.

4.3. VEHICLE CHARACTERISTICS

4.3.1. Physical Characteristics

The vehicles which comprise the Metrorail fleet are assumed to all have identical physical characteristics from the point of view of train performance. Table 4-3 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

TABLE 4-1
SUMMARY OF 1980 TIMETABLE
FOR
METRORAIL OPERATIONS

(Effective February - October 1980)

Operating Period	Time Span	Headway(MIN)	Cars/Train
	RED LINE		
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
	ORANGE AND BLUE LINES		
Weekdays			
Midnight	12:00A - 6:00A	-	No Revenue Operation
AM Peak	6:00A - 9:30A	6	6
Midday	9:30A - 3:00P	12	6
PM Peak	3:00P - 6:30P	6	6
Evening	6:30P -12:00A	12	6
Saturday			
Midnight	12:00A - 8:00A	-	No Revenue Operation
Midday	8:00A -12:00M	12	6
Sunday			
Midnight	12:00A -10:00A	-	No Revenue Operation
Midday	10:00A - 6:00P	12	6
Evening	6:00P -12:00A	-	No Revenue Operation

*During peak periods on Red Line, six 6-car and five 8-car trains operate.

TABLE 4-2 SUMMARY OF EMPIRICAL DWELL TIME INFORMATION

Station	Average Dwell Time (in seconds)
RED LINE	
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
ORANGE LINE	
Virginia Square	16
Clarendon	19
Court House	23
Rosslyn	31
Foggy Bottom	25
Farragut West	26
McPherson Square	21
Metro Center	35
Federal Triangle	32
Smithsonian	32
L'Enfant Plaza	22
Federal Center, SW	26
Capitol South	25
Eastern Market	23
Potomac Avenue	24
Stadium-Armory	26
Minnesota Avenue	28
Deanwood	21
Cheverly	18
Landover	25
BLUE LINE (CRYSTAL CITY-ARLINGTON CEMETERY)	
Crystal City	22
Pentagon City	18
Pentagon	25
Arlington Cemetery	27

TABLE 4-3 VEHICLE PHYSICAL CHARACTERISTICS

Empty Weight (tons)	36.0
Crush Load Weight (tons)	52.5*
Vehicle Length (ft.)	[illegible].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

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

of actual train resistance measurements which were made on the cars. The development of these coefficients is outlined in Appendix 9.2.

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

4.3.2. Propulsion Characteristics

The Metrorail vehicle is a self-propelled rail transit car with four powered axles. The main propulsion characteristics are listed in Table 4-4. The power conditioning and control subsystem is presently cam controlled resistor switching. One new car order includes eighteen chopper controlled cars which have the capability to regenerate power back to the third rail. An option to that order provides for two hundred 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 Figure 4-2. 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.

<u>Cam Control Resistor Switching</u>

To control the motor circuit voltage in present cars, resistors are inserted between the line and motor circuit. Figure 4-3 shows the tractive effort-speed curves at each of the motor circuit modes, designated 1 to 8 in Figure 4-2. 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 MPHPS 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 4-4 VEHICLE PROPULSION CHARACTERISTICS

1.	Motors per Vehicle	- 4
2.	Motor Characteristics	- (W) Type 1462
3.	Control	- Cam Resistor Switching (Present Operation)
		- Chopper (Regeneration)
4.	Maximum Accelerating Rate	- 3.0 MPHPS
5.	Wheel diameter	- 28 inches
6.	Gear ratio	- 5.414
7.	Maximum speed	- 75 MPH
8.	Nominal line voltage	- 750 V
9.	Maximum line voltage	- 860 V
10.	Minimum line voltage	- 600 V

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

FIGURE 4-2 METRORAIL PROPULSION POWER LEVEL DEFINITION

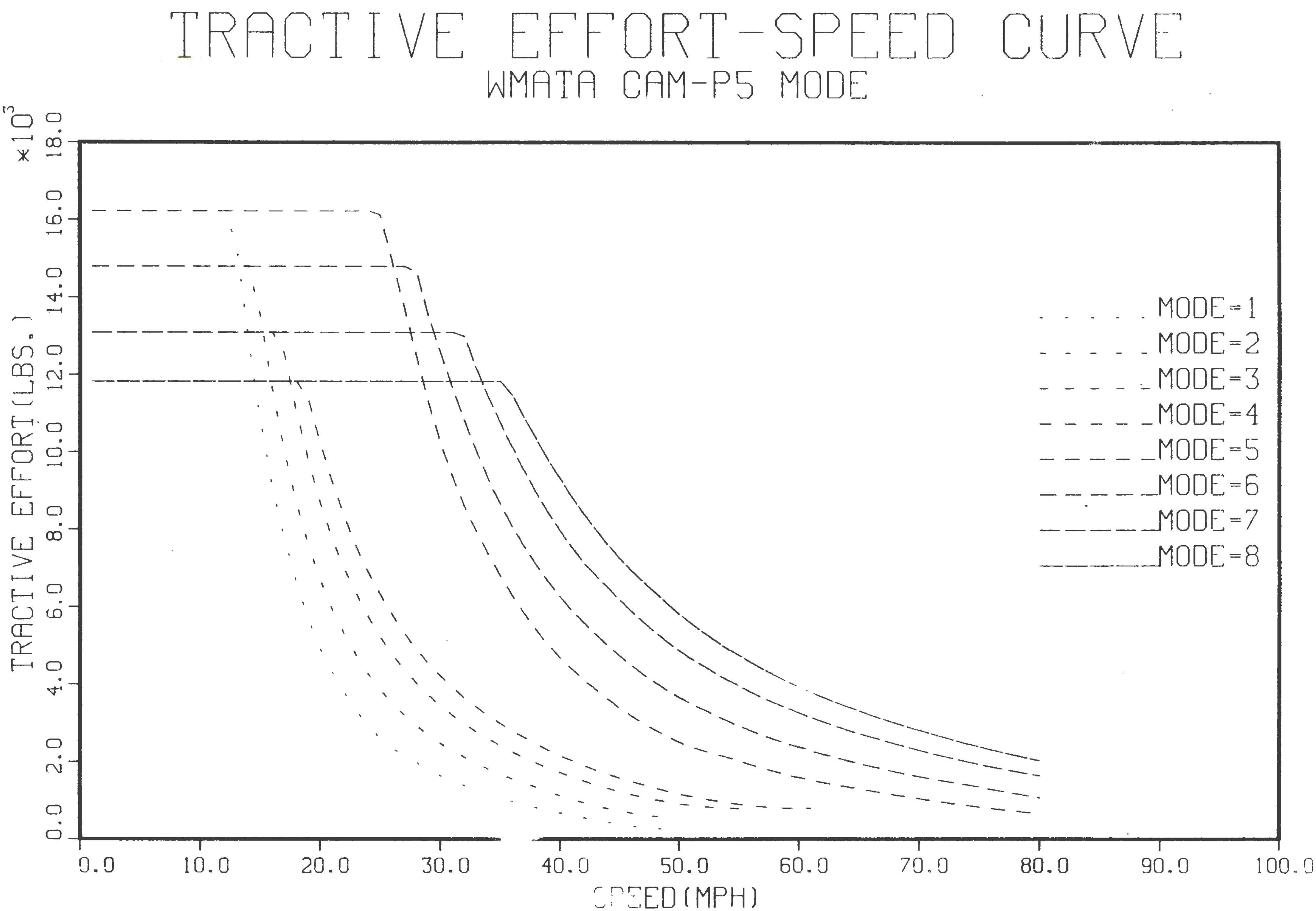

TRACTIVE EFFORT-SPEED CURVE
WMATA CAM-P5 MODE
TRACTIVE EFFORT(LBS.)
*10^3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
MODE=1
MODE=2
MODE=3
MODE=4
MODE=5
MODE=6
MODE=7
MODE=8
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
SPEED(MPH)

FIGURE 4-3

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 by 70%, then 60%, until 40% of full field is reached. The tractive effort follows the mode 8 curve which is shown in Figure 4-3.

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 4-3.

Figure 4-4 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. These numbers were calculated using the external propulsion model of the EMM.

Chopper Control

Metro has ordered a number of cars from BREDA with chopper control propulsion systems. Since one of the strategies 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 using the external propulsion model of the EMM. The parameters[1] used for this model are shown together with its description in Figure 4-5.

Figure 4-6 shows the tractive effort speed curves at each of the motor circuit modes (1-8) described in Figure 4-2. 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 MPHPS on level track.

---

[1] The parameters were obtained from the Transportation Division of Westinghouse Electric Corporation.

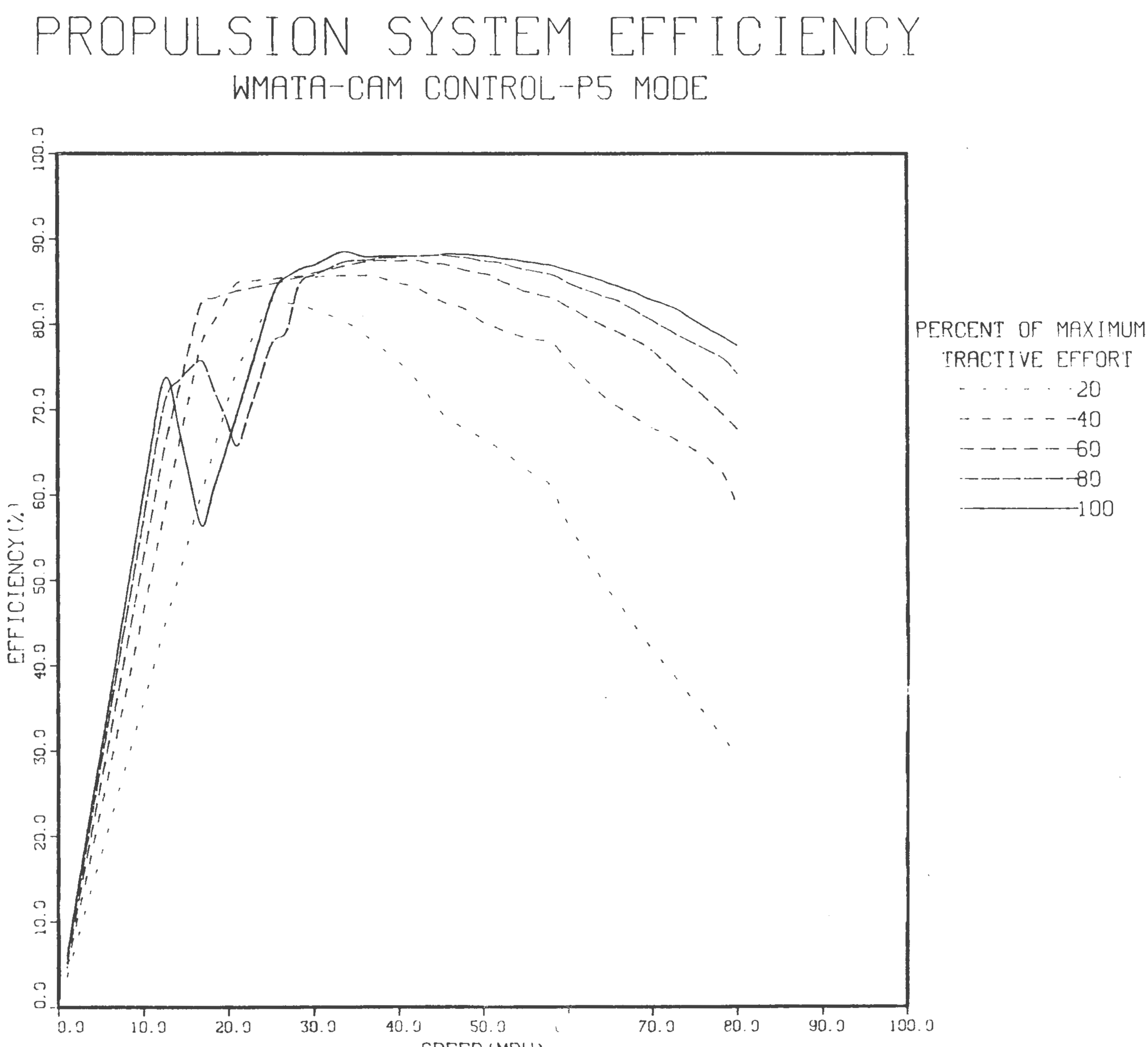
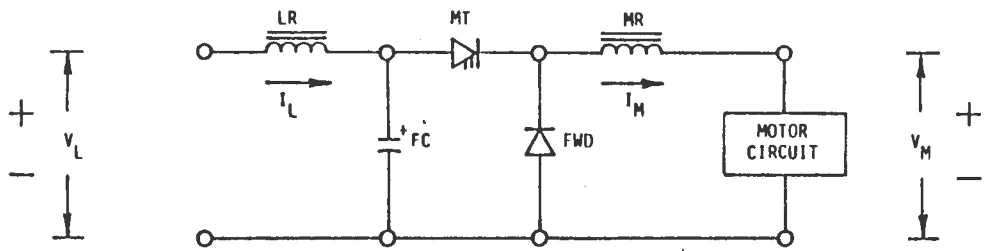

PROPULSION SYSTEM EFFICIENCY
WMATA-CAM CONTROL-P5 MODE
EFFICIENCY(%)
SPEED(MPH)
PERCENT OF MAXIMUM
TRACTIVE EFFORT
20
40
60
80
100
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0

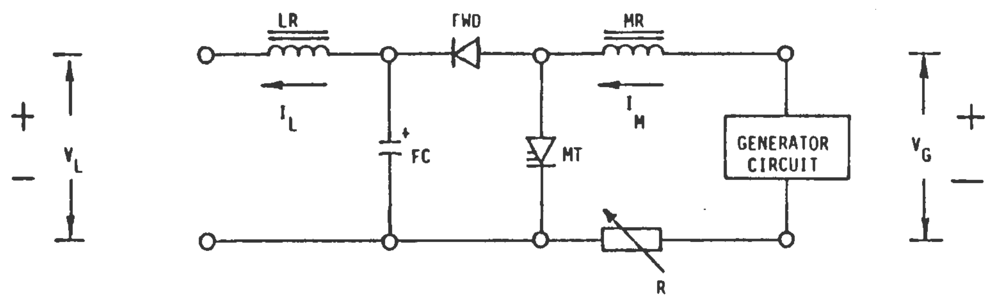
FIGURE 4-4

CHOPPER PROPULSION MODEL

1. POWER



2. BRAKING



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

$R_{LR} = 0.00185\Omega$

$R_{MR} = 0.012\Omega$

$R_{FC} = 0.0053\Omega$

$V_{MT} = 1.45$ 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

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

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 ($V_G < V_L$; $R = 0$)

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

where

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

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

FIGURE 4-5 CHOPPER PROPULSION MODEL

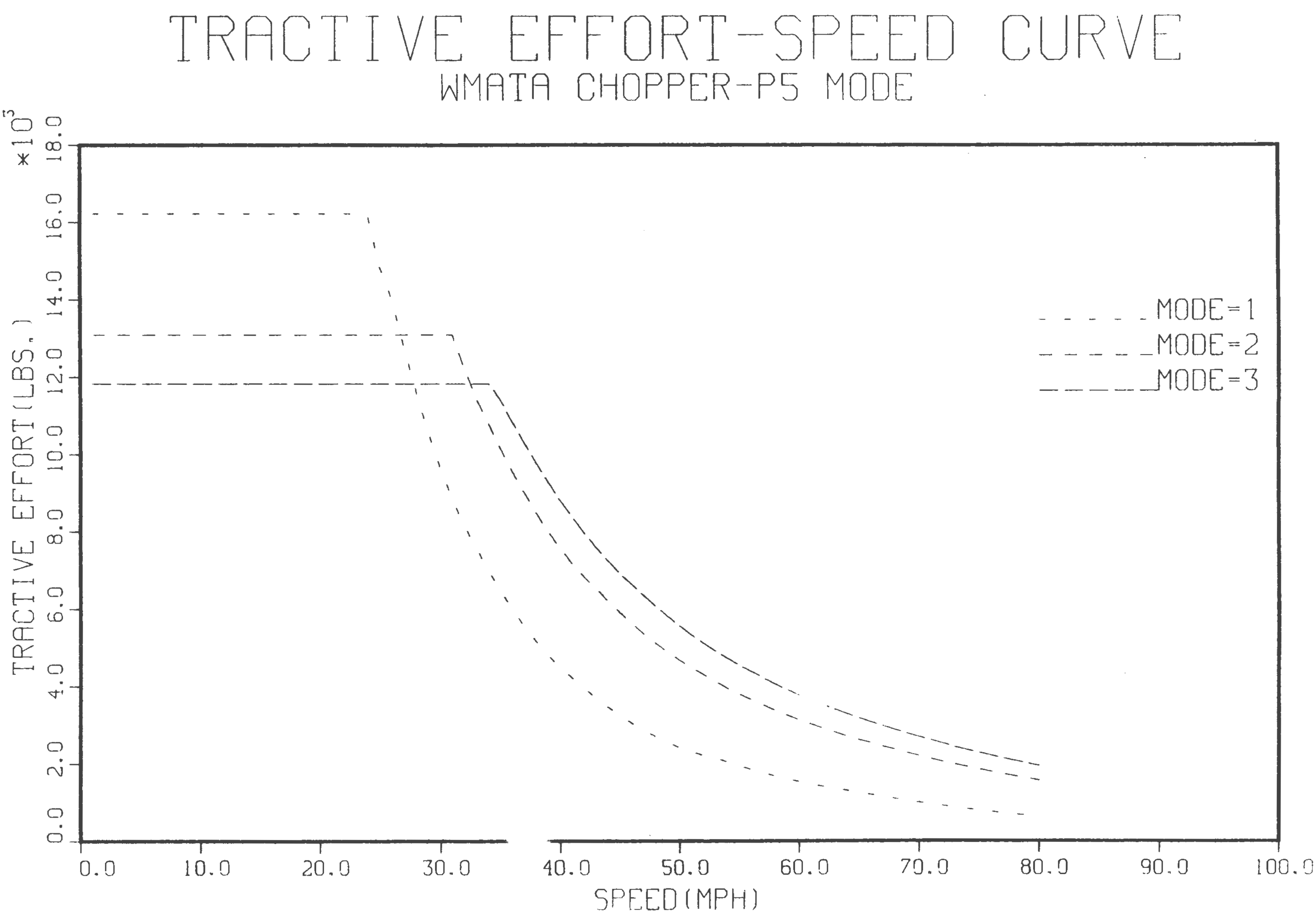

TRACTIVE EFFORT-SPEED CURVE
WMATA CHOPPER-P5 MODE
TRACTIVE EFFORT(LBS.)
*10^3
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
MODE=1
MODE=2
MODE=3
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
SPEED(MPH)

FIGURE 4-6

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 4-7.

Figure 4-8 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 4-9. This efficiency is the ratio of regenerated power at the line to power at the wheels.

4.3.3. Braking Characteristics

The brake rate has been set at 3.0 MPHPS. 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.

4.4. RIGHT OF WAY CHARACTERISTICS

The locations of the passenger stations on the Red Line and the Blue/Orange Line are shown in Figures 4-10 and 4-11, respectively. Both the station numbers, as defined by Metro, and the mileposts, as defined for use in the EMM, are shown in the Figures. In the case of the Red Line, the Dupont Circle passenger station was taken as milepost 0.00, and in the case of the Blue/Orange Line, the milepost 0.00 was assigned to the National Airport passenger station.

The grades were obtained from the maintenance-of-way track charts. Maximum grades are 4%. Elevation profiles of the Blue, Orange and Red Lines are shown in Figures 4-12 to 4-14. 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, the northbound and southbound directions of

PROPULSION SYSTEM EFFICIENCY

WMATA-CHOPPER-P5 MODE

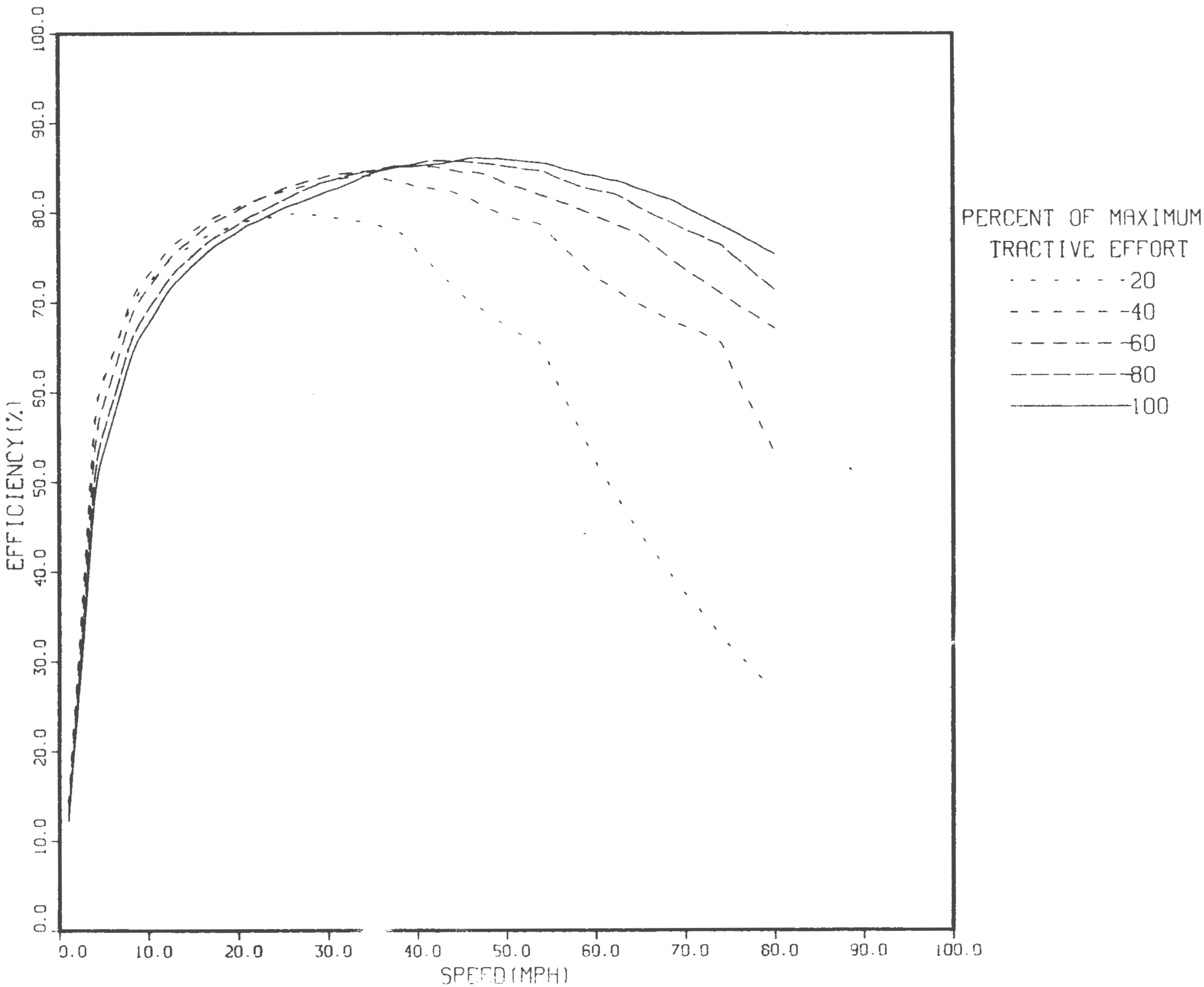


FIGURE 4-7

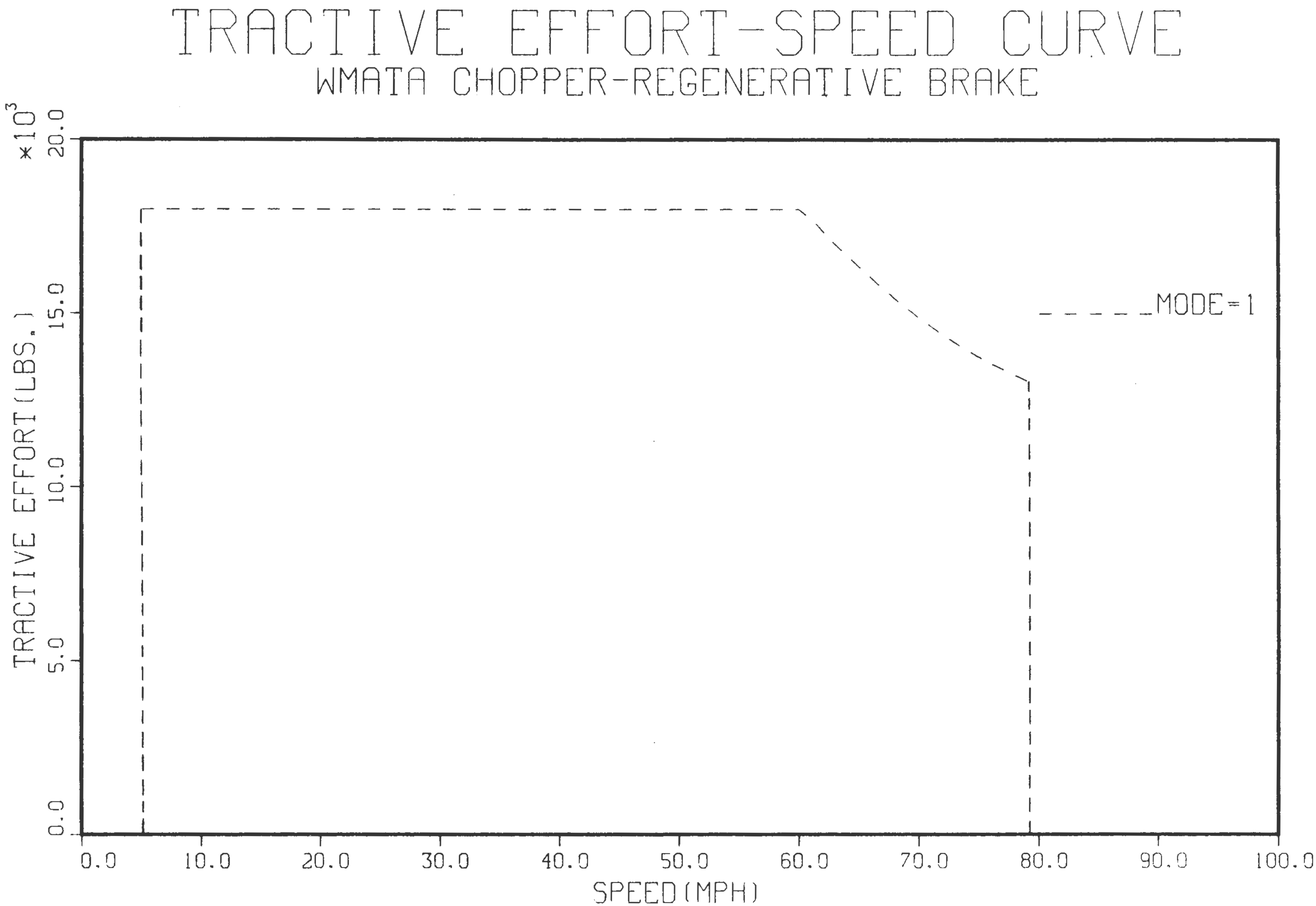

TRACTIVE EFFORT-SPEED CURVE
WMATA CHOPPER-REGENERATIVE BRAKE
*10^3
20.0
15.0
10.0
5.0
0.0
TRACTIVE EFFORT(LBS.)
MODE=1
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
SPEED(MPH)

FIGURE 4-8

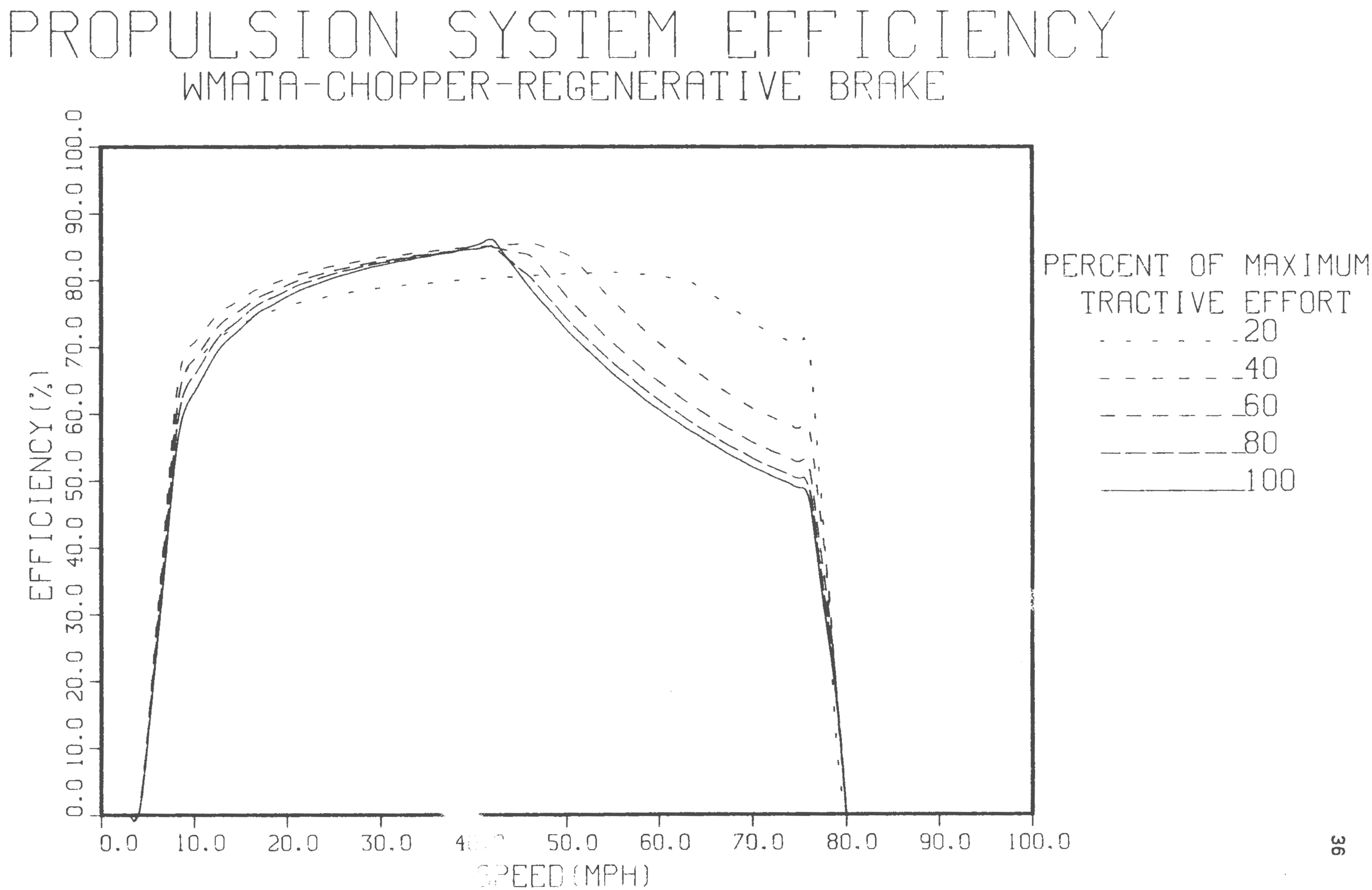
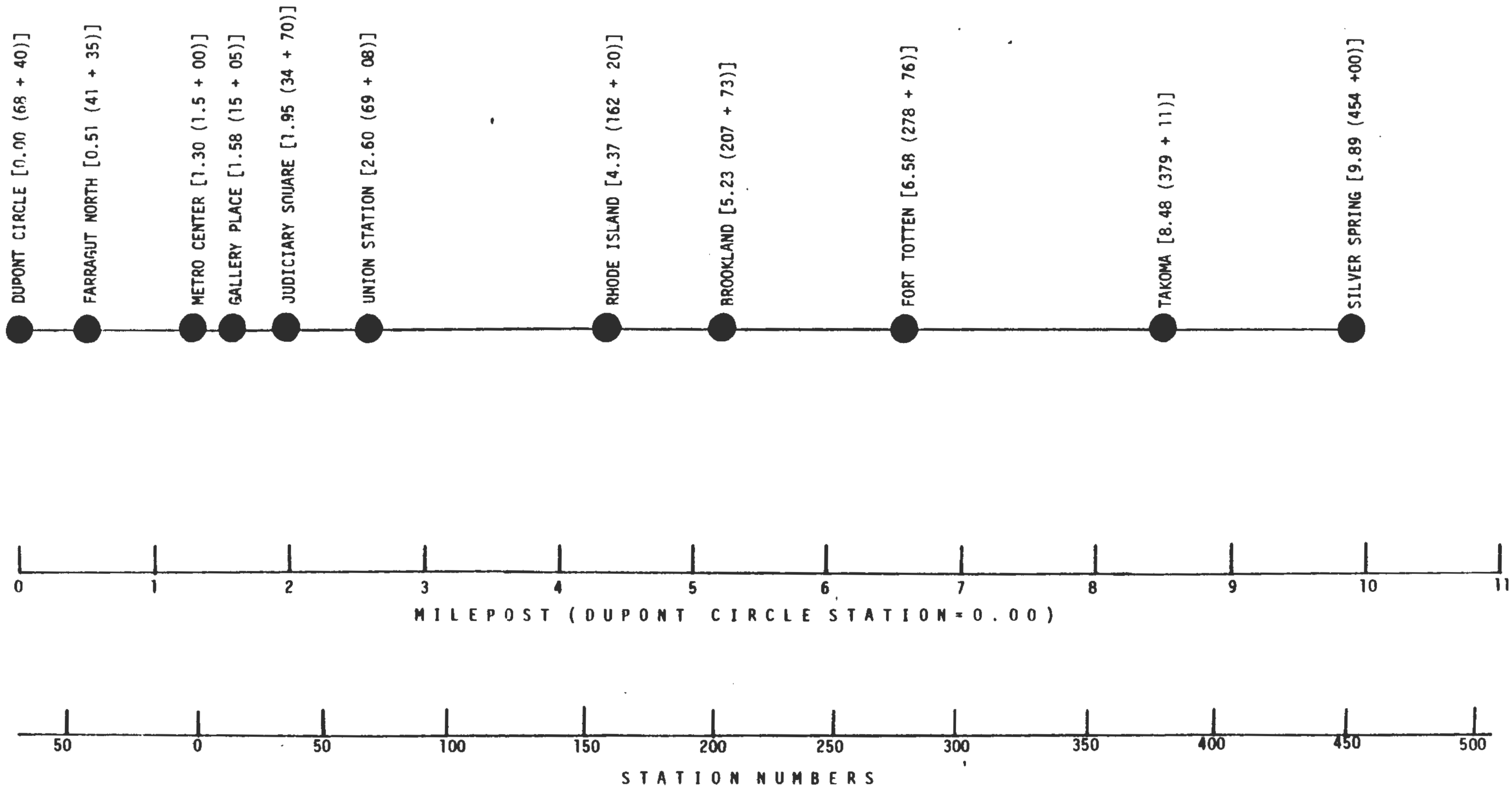

PROPULSION SYSTEM EFFICIENCY
WMATA-CHOPPER-REGENERATIVE BRAKE
EFFICIENCY(%)
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
100.0
SPEED(MPH)
PERCENT OF MAXIMUM
TRACTIVE EFFORT
20
40
60
80
100

FIGURE 4-9



KEY: [Milepost (Station Numbers)]

FIGURE 4-10 PASSENGER STATION CONFIGURATION - RED LINE

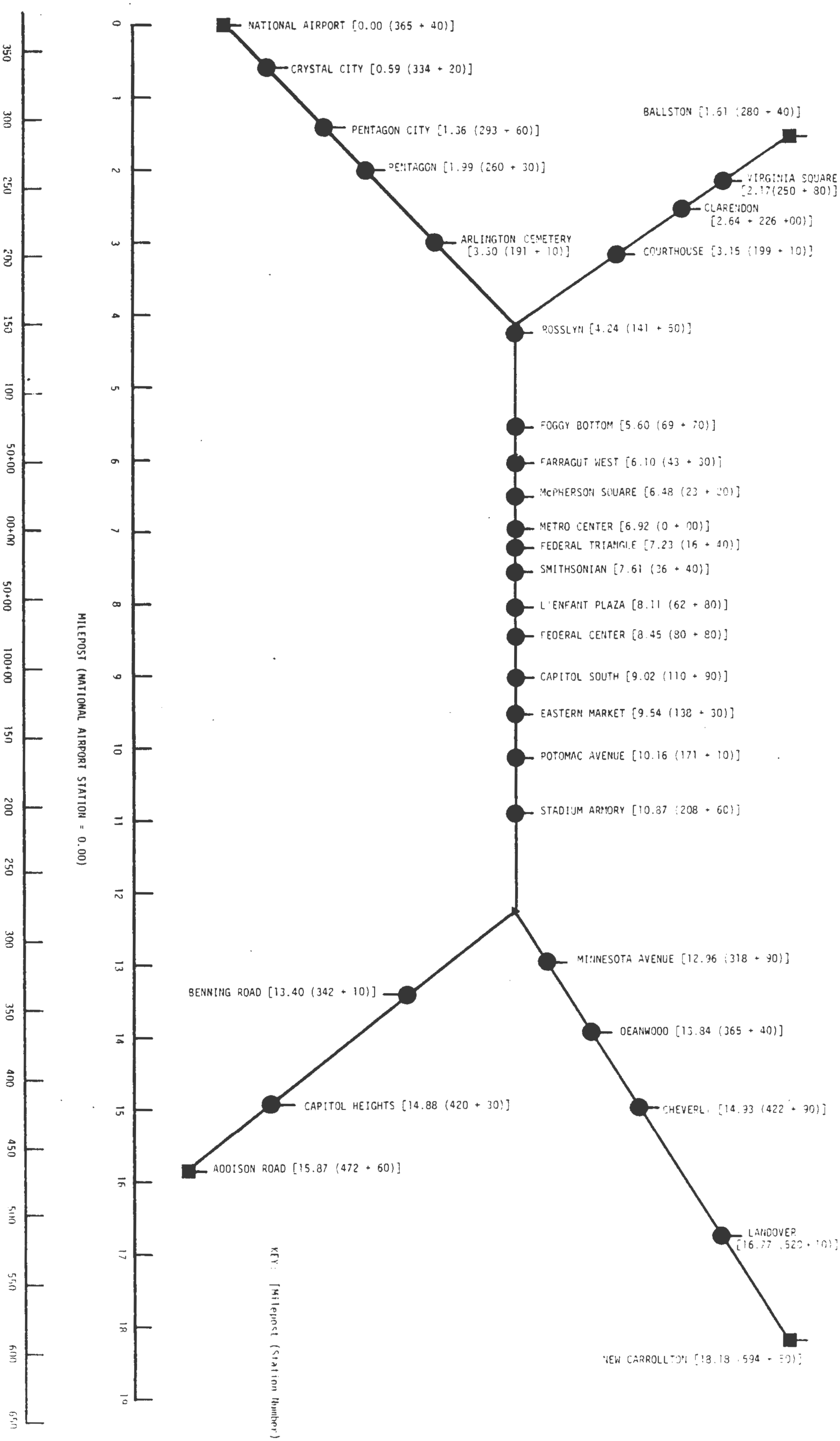


FIGURE 4-11 PASSENGER STATION CONFIGURATION
BLUE/ORANGE LINE

ELEVATION PROFILE
WMATA BLUE LINE

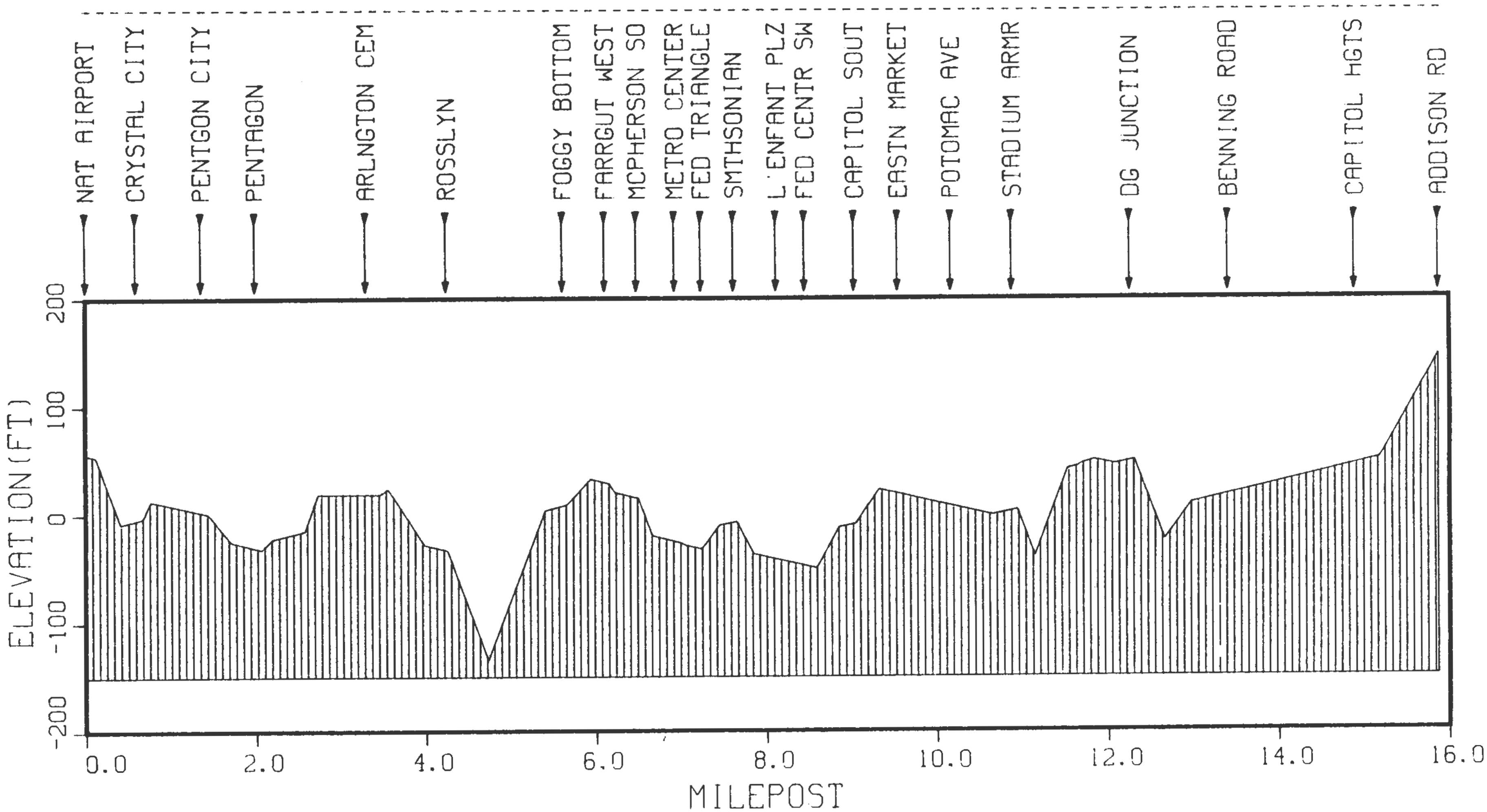


FIGURE 4-12

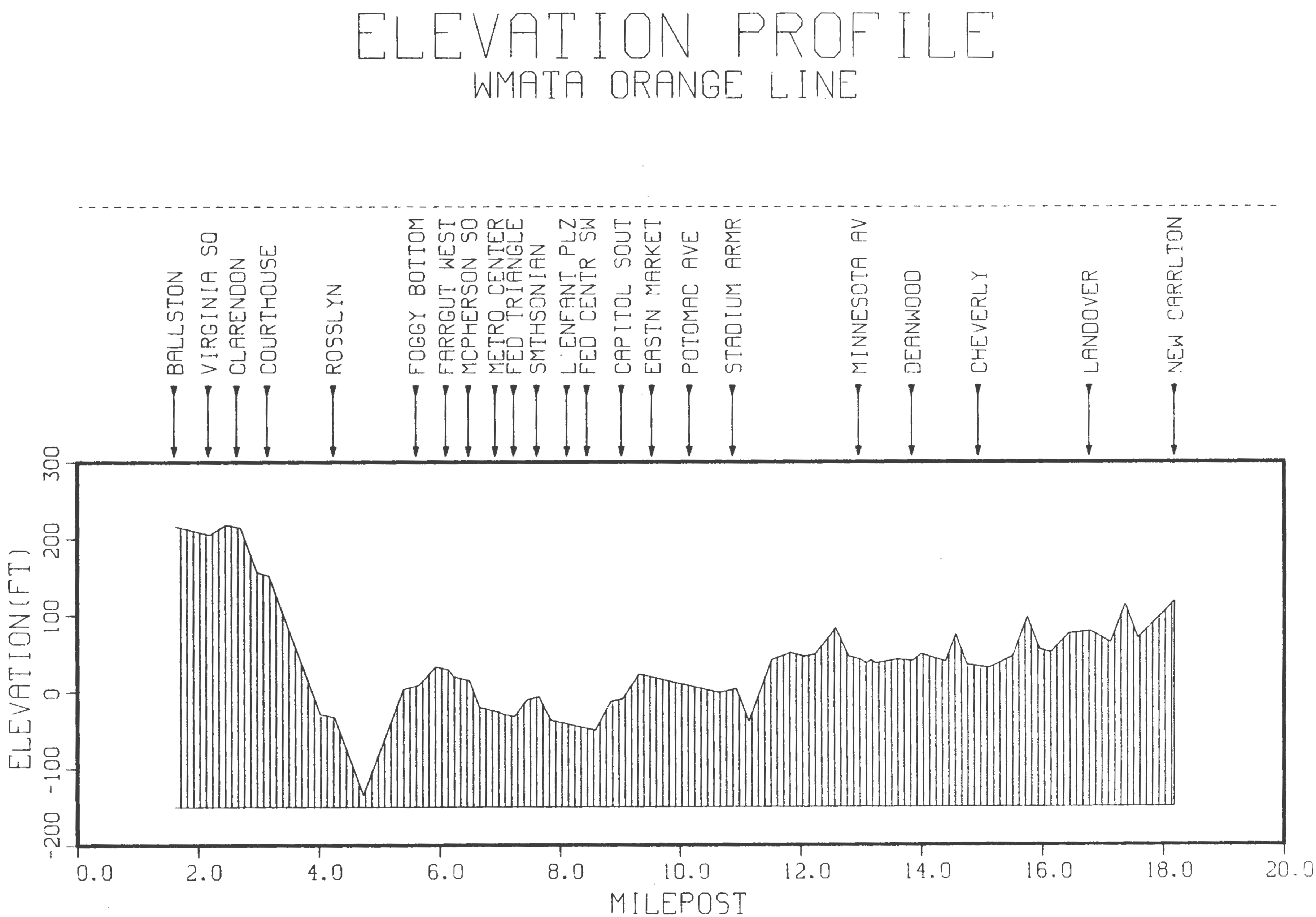

ELEVATION PROFILE
WMATA ORANGE LINE
BALLSTON
VIRGINIA SQ
CLARENDON
COURTHOUSE
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMTHSONIAN
L'ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
MINNESOTA AV
DEANWOOD
CHEVERLY
LANDOVER
NEW CARRLTON
ELEVATION(FT)
300
200
100
0
-100
-200
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
MILEPOST

FIGURE 4-13

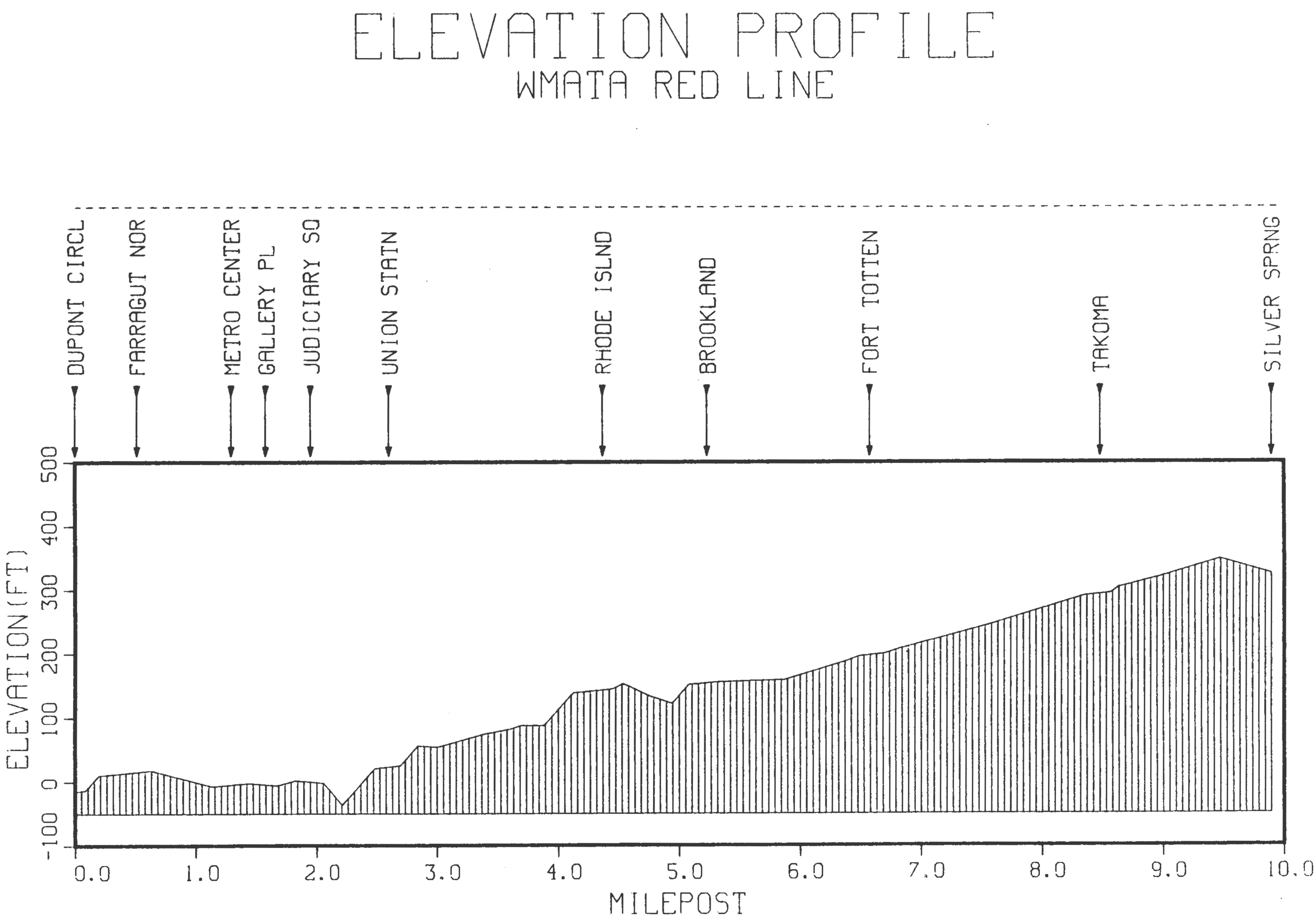

ELEVATION PROFILE
WMATA RED LINE
DUPONT CIRCL
FARRAGUT NOR
METRO CENTER
GALLERY PL
JUDICIARY SQ
UNION STATN
RHODE ISLND
BROOKLAND
FORT TOTTEN
TAKOMA
SILVER SPRNG
ELEVATION(FT)
-100
0
100
200
300
400
500
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
MILEPOST

FIGURE 4-14

the Blue Line, and the eastbound and westbound directions of the Orange Line in Figures 4-15 through 4-20. The speed restrictions for the catch-up (PL1) operation for the same lines and directions as normal operation are shown in Figures 4-21 through 4-26. 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.

4.5. POWER DISTRIBUTION SYSTEM

4.5.1. Network Description

The electric network of the Red Line is isolated on the D.C. side from that of the Blue/Orange Line. The electrical network for the Red Line is shown in Figure 4-27, while that for the Blue/Orange Line is shown in Figure 4-28.

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 V.

From Dupont Circle to Silver Spring, the Red Line is served by ten traction substations, each of which is metered by PEPCO. The Orange Line, from Ballston to New Carrollton, and the Blue Line, from National Airport to Addison Road, are served by twenty-one traction substations, each of which is metered by PEPCO, and by five substations which are joined on the AC side and are commonly metered by VEPCO. In 1980 operation, which was used as the basis for this study, the part of the network from D/G Junction to Addison Road (Milepost 12.25 to 15.87, in Figure 4-28) was not included. The meter designated MA2 (Belmont Road) was also not operational.

The Red Line is a two-track system with tiestations whose breakers are normally closed connecting the lines between substations. The Blue/Orange Line is mostly a two-track system with exceptions in the vicinity of D/G Junction (Benning Road tiestation) and Rosslyn. The lines between Rosslyn substation and Rosslyn tiestation include four tracks.

SPEED PROFILE AND RESTRICTIONS

RED-EMPTY 6 CAR TRAIN-OUTBOUND-PL2

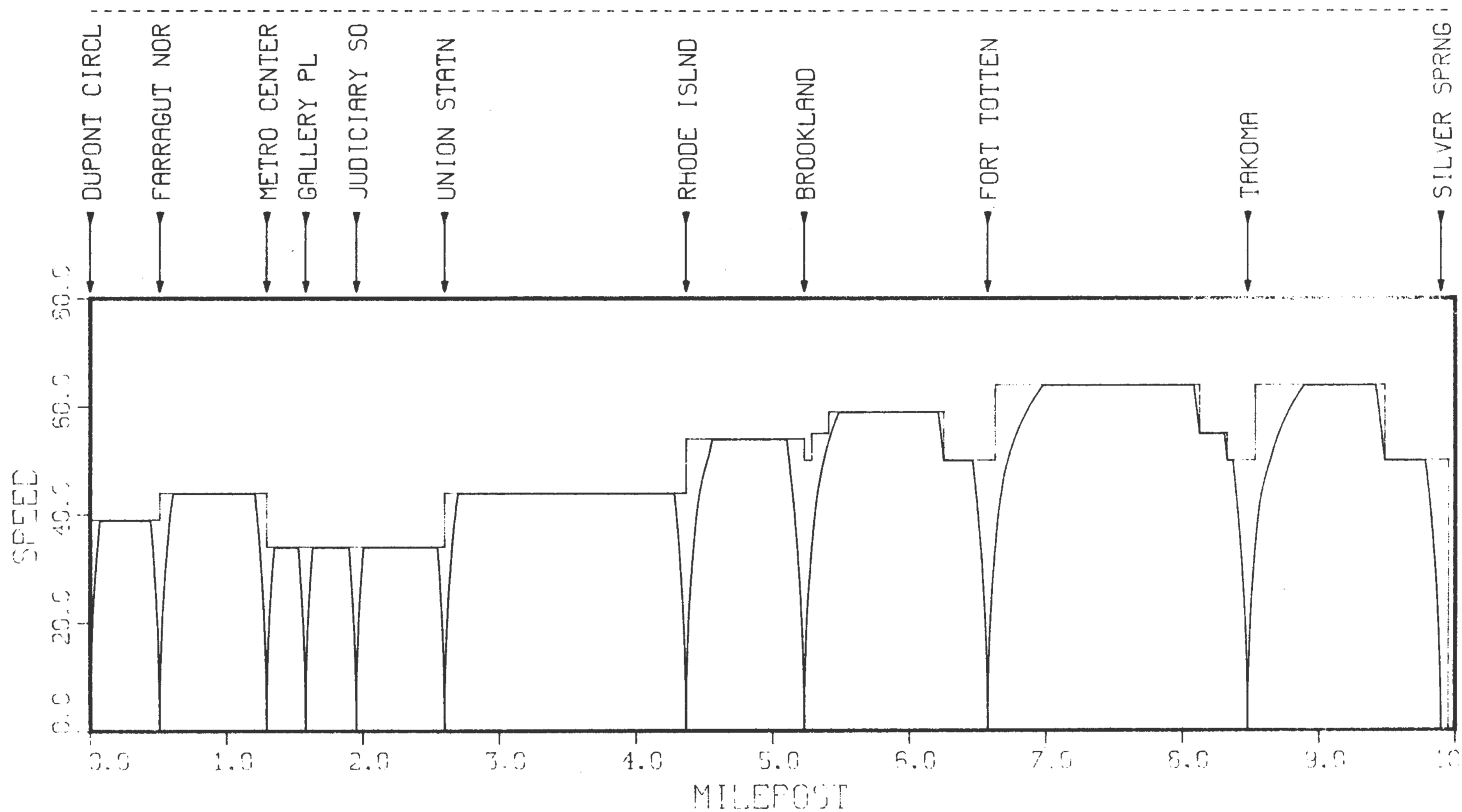


FIGURE 4-15

SPEED PROFILE AND RESTRICTIONS

RED-EMPTY 6 CAR TRAIN-INBOUND-PL2

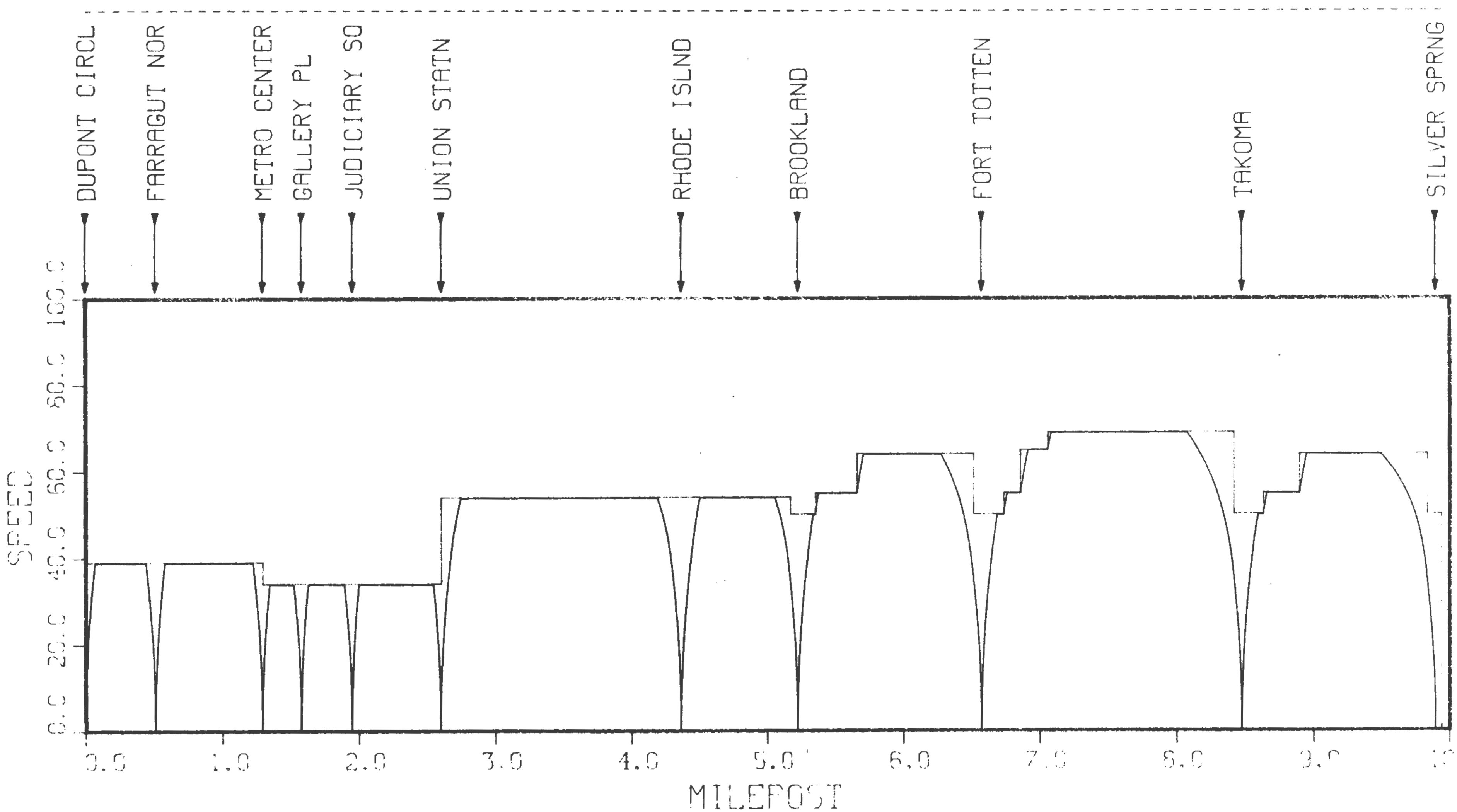


FIGURE 4-16

SPEED PROFILE AND RESTRICTIONS

BLUE-EMPTY 6 CAR TRAIN-NORTHBOUND-PL2

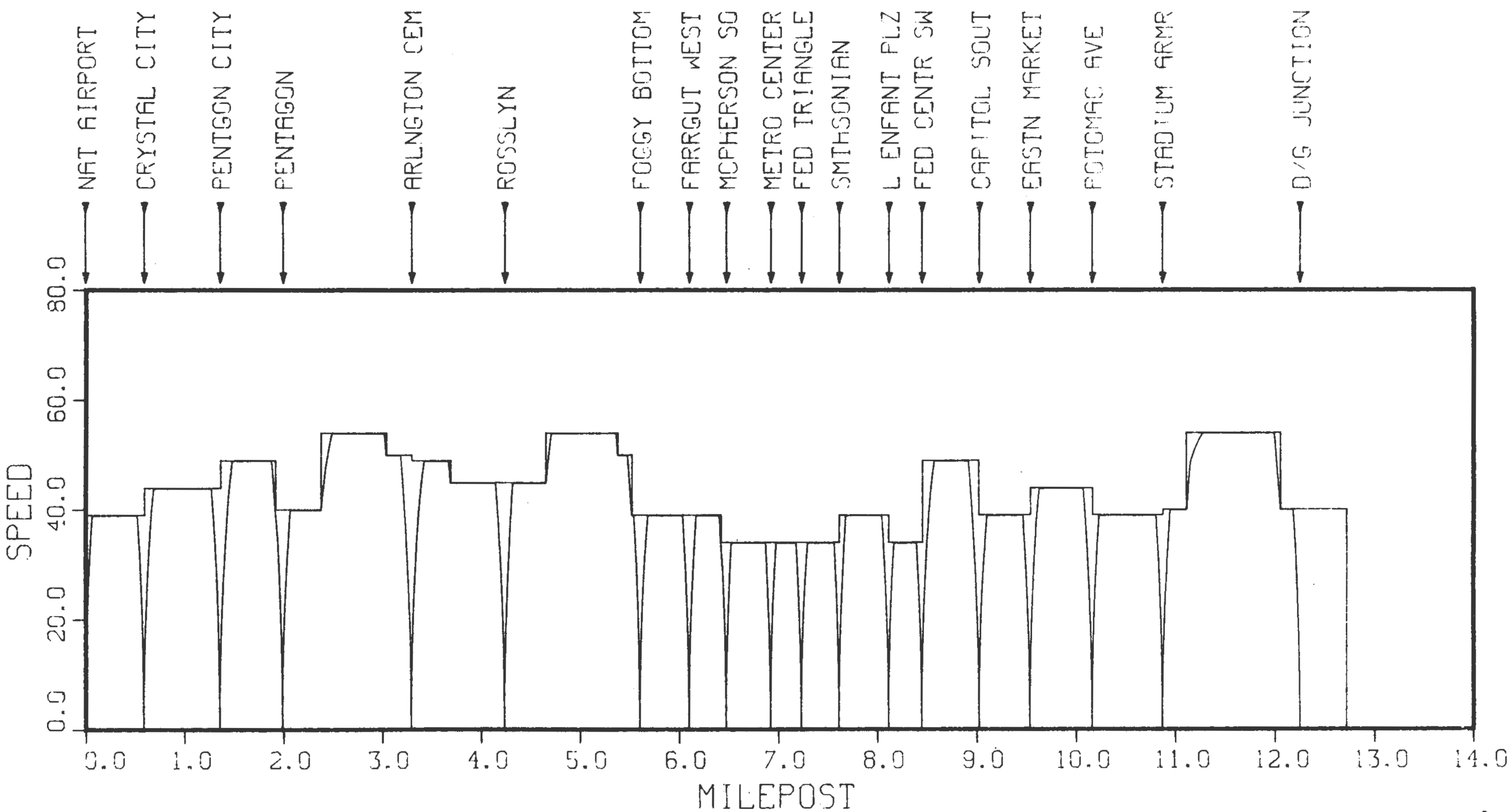
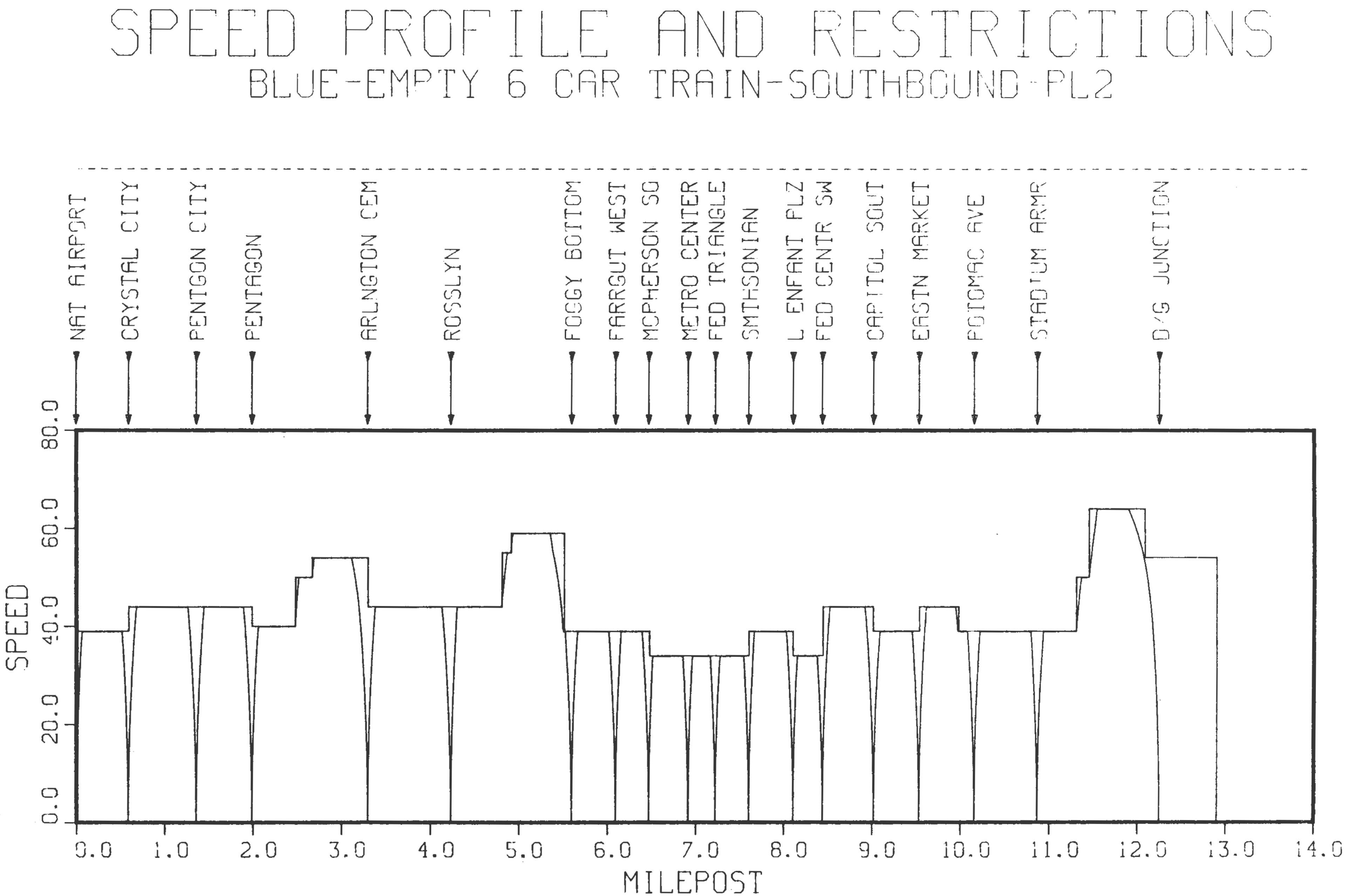


FIGURE 4-17


SPEED PROFILE AND RESTRICTIONS
BLUE-EMPTY 6 CAR TRAIN-SOUTHBOUND-PL2
NAT AIRPORT
CRYSTAL CITY
PENTGON CITY
PENTAGON
ARLNGTON CEM
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMTHSONIAN
L ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
D/G JUNCTION
SPEED
0.0
20.0
40.0
60.0
80.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
11.0
12.0
13.0
14.0
MILEPOST
FIGURE 4-18

SPEED PROFILE AND RESTRICTIONS

ORANGE-EMPTY 6 CAR TRAIN-EASTBOUND-PL2

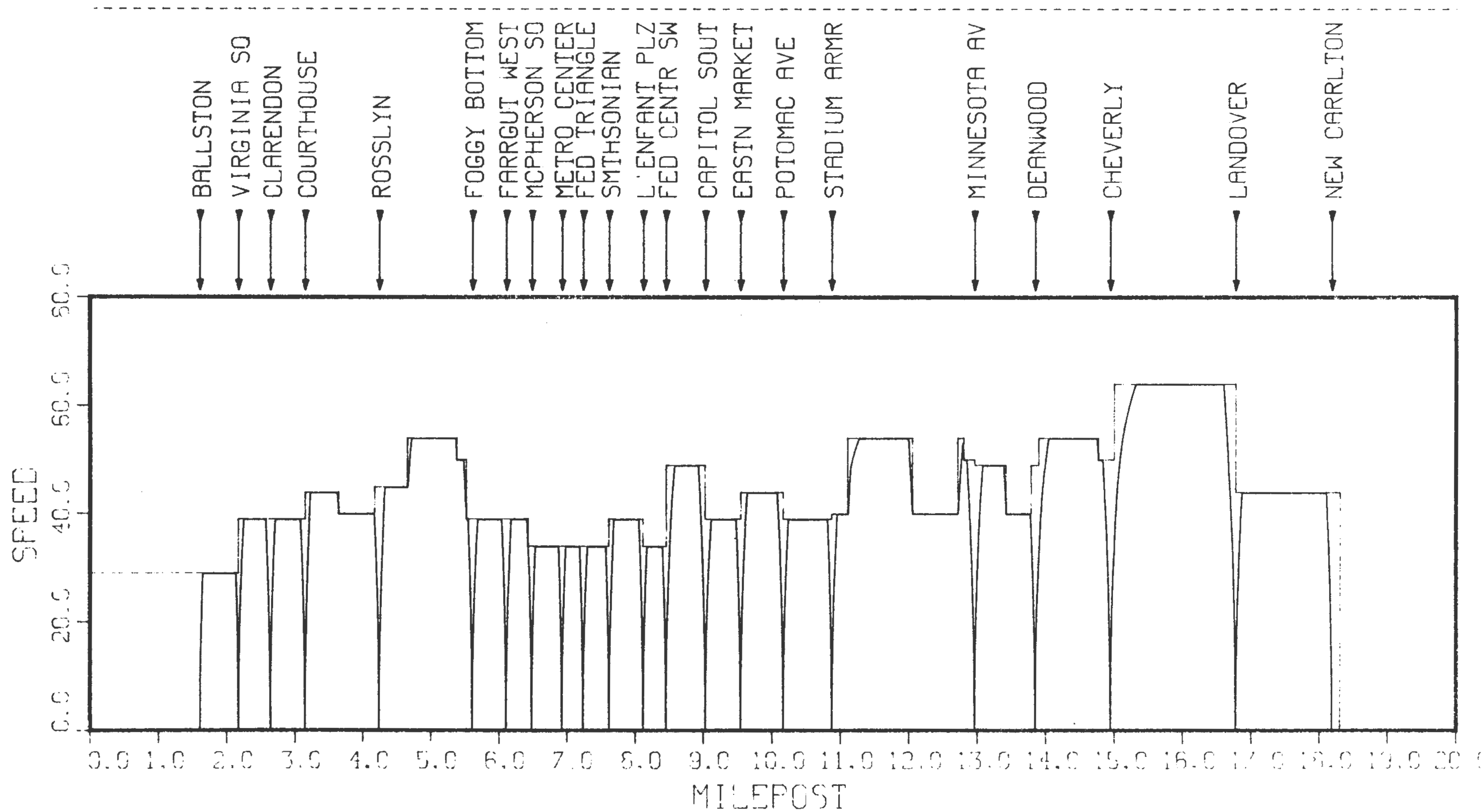


FIGURE 4-19

SPEED PROFILE AND RESTRICTIONS

ORANGE-EMPTY 6 CAR TRAIN-WESTBOUND-PL2

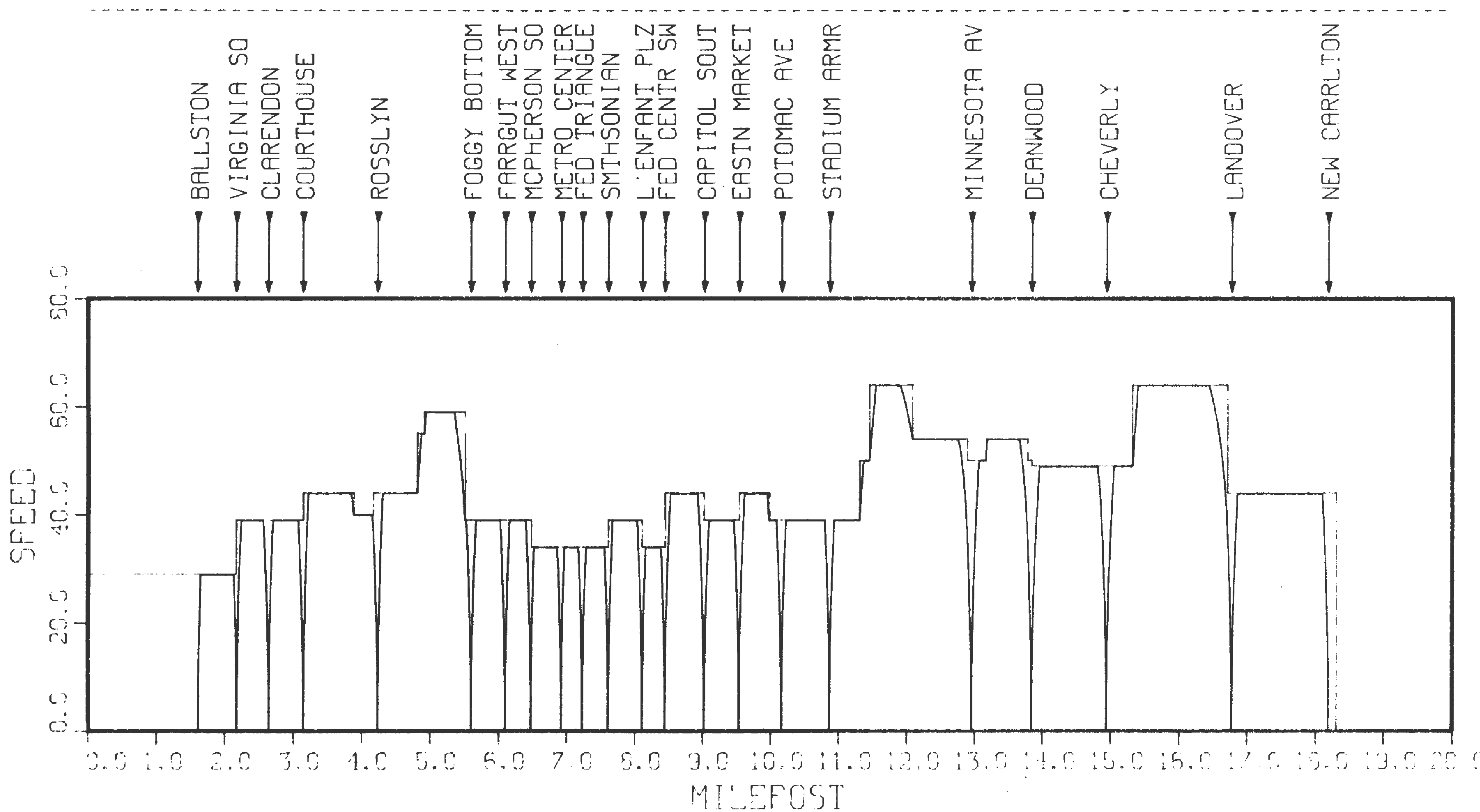


FIGURE 4-20

SPEED PROFILE AND RESTRICTIONS

RED-EMPTY 6 CAR TRAIN-OUTBOUND-PL1

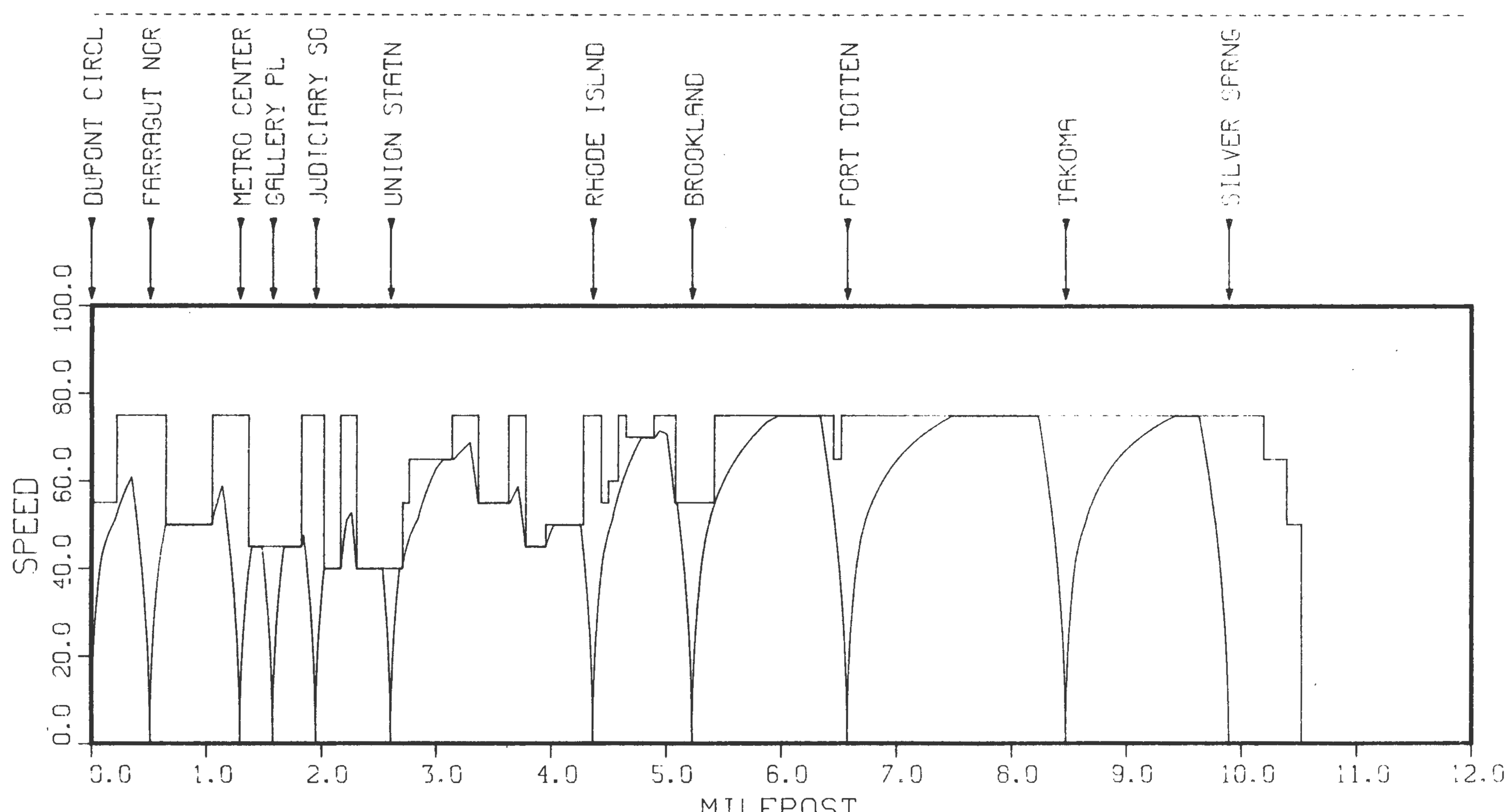


FIGURE 4-21

SPEED PROFILE AND RESTRICTIONS

RED-EMPTY 6 CAR TRAIN-INBOUND-PL1

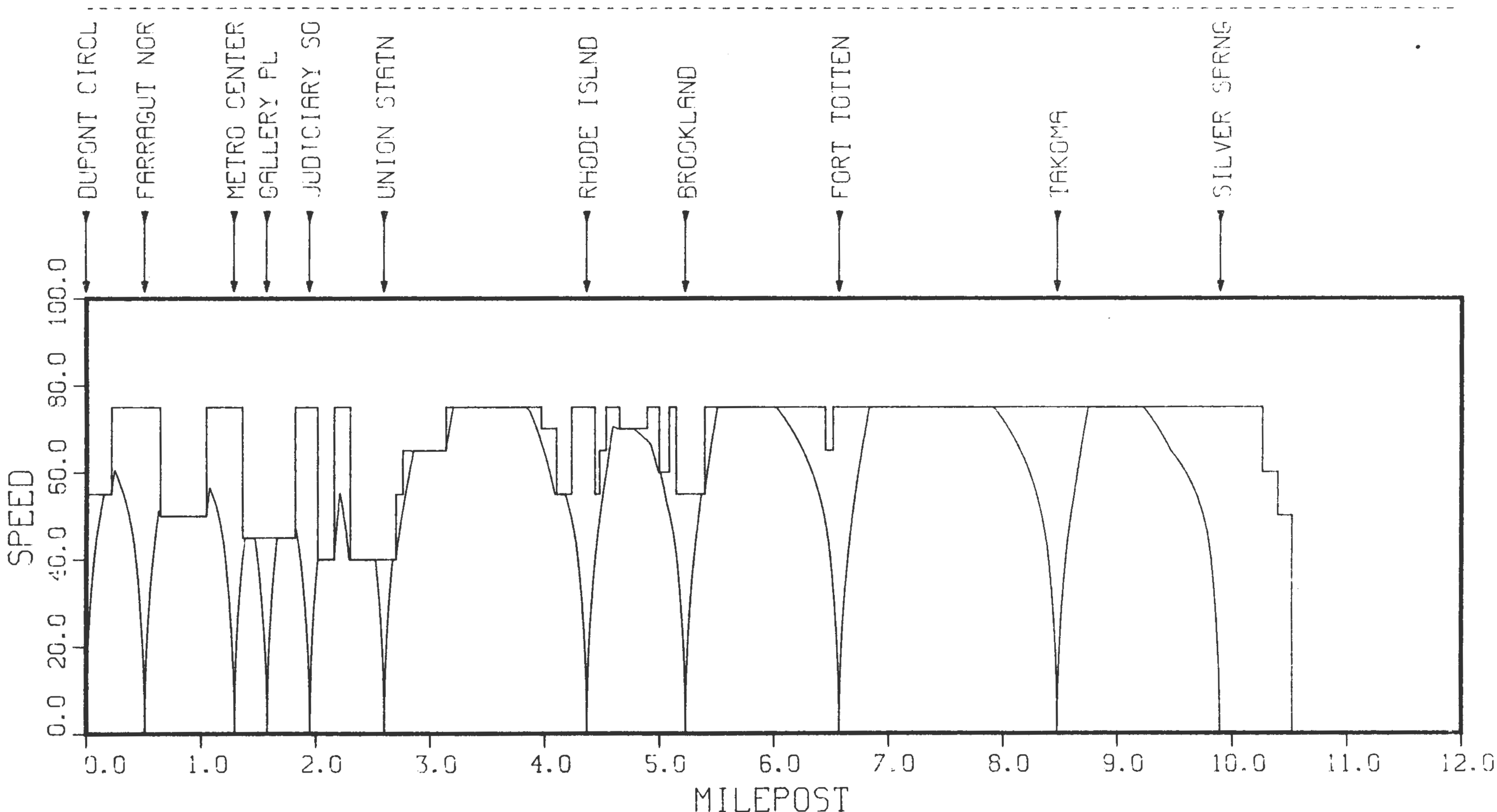


FIGURE 4-22

SPEED PROFILE AND RESTRICTIONS

BLUE-EMPTY 6 CAR TRAIN-NORTHBOUND-PL1

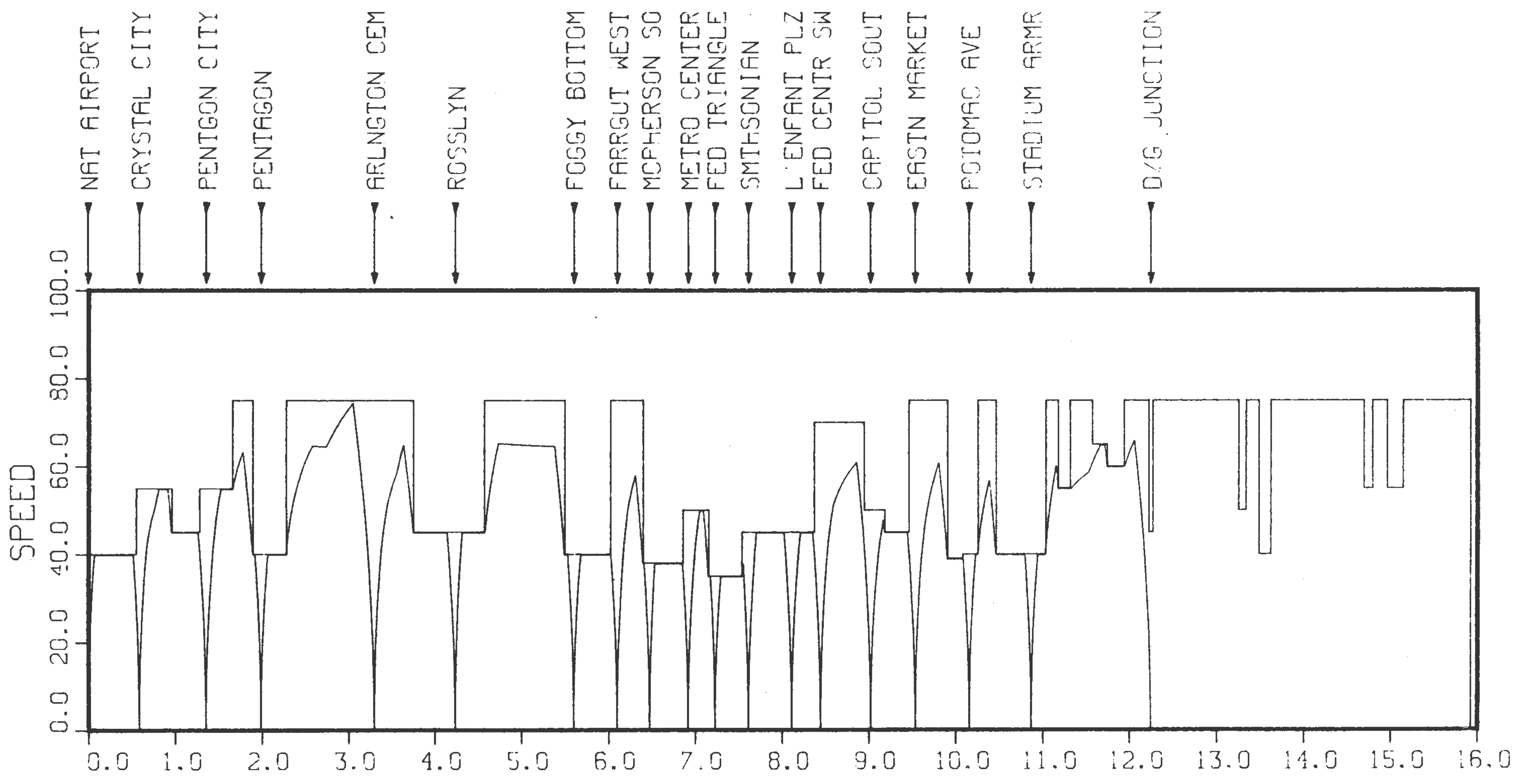


FIGURE 4-23

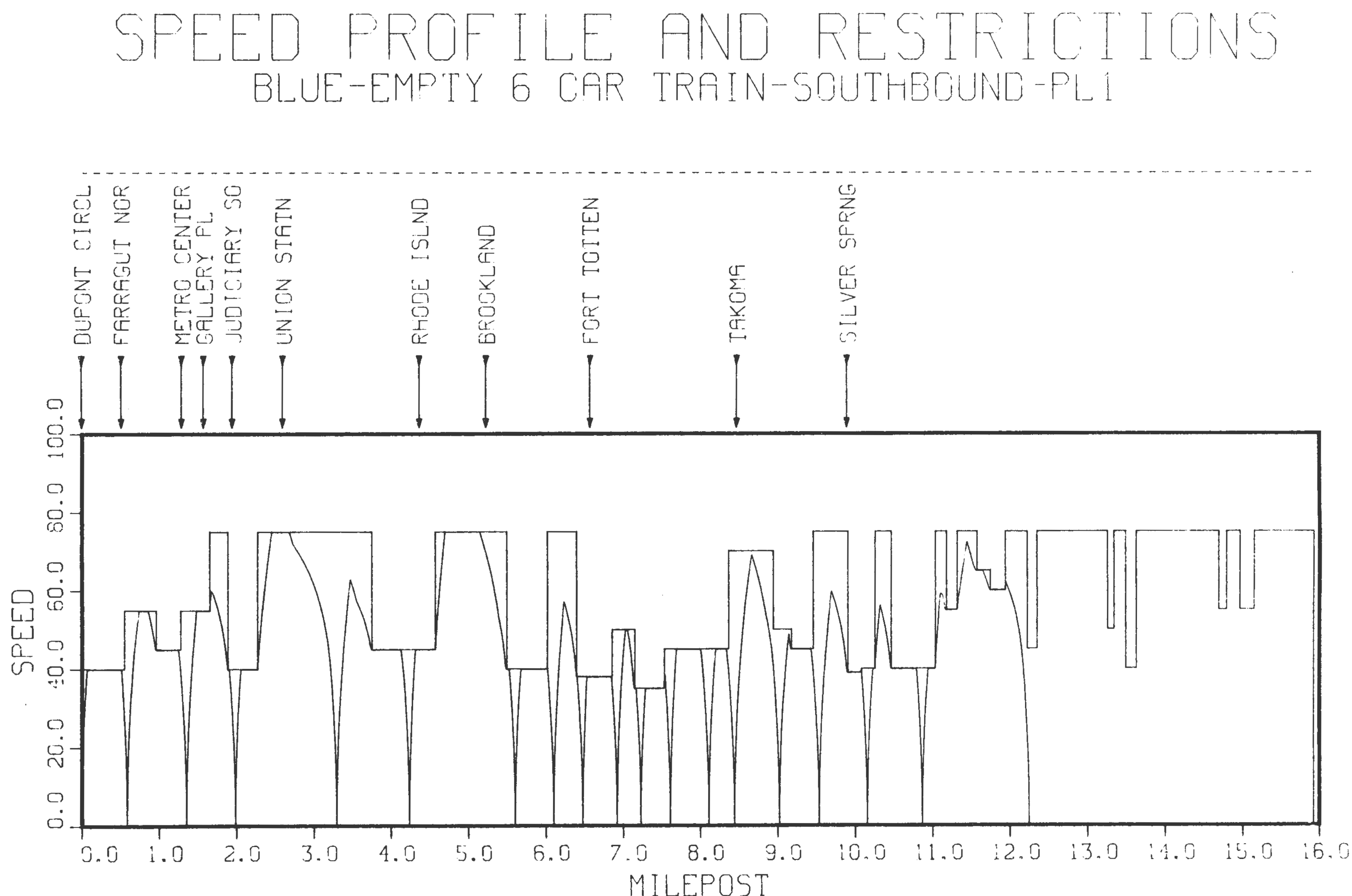

SPEED PROFILE AND RESTRICTIONS
BLUE-EMPTY 6 CAR TRAIN-SOUTHBOUND-PL1
DUPONT CIRCL
FARRAGUT NOR
METRO CENTER
GALLERY PL
JUDICIARY SQ
UNION STATN
RHODE ISLND
BROOKLAND
FORT TOTTEN
TAKOMA
SILVER SPRNG
SPEED
0.0
20.0
40.0
60.0
80.0
100.0
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0
MILEPOST

FIGURE 4-24

SPEED PROFILE AND RESTRICTIONS

ORANGE-EMPTY 6 CAR TRAIN-EASTBOUND-PL1

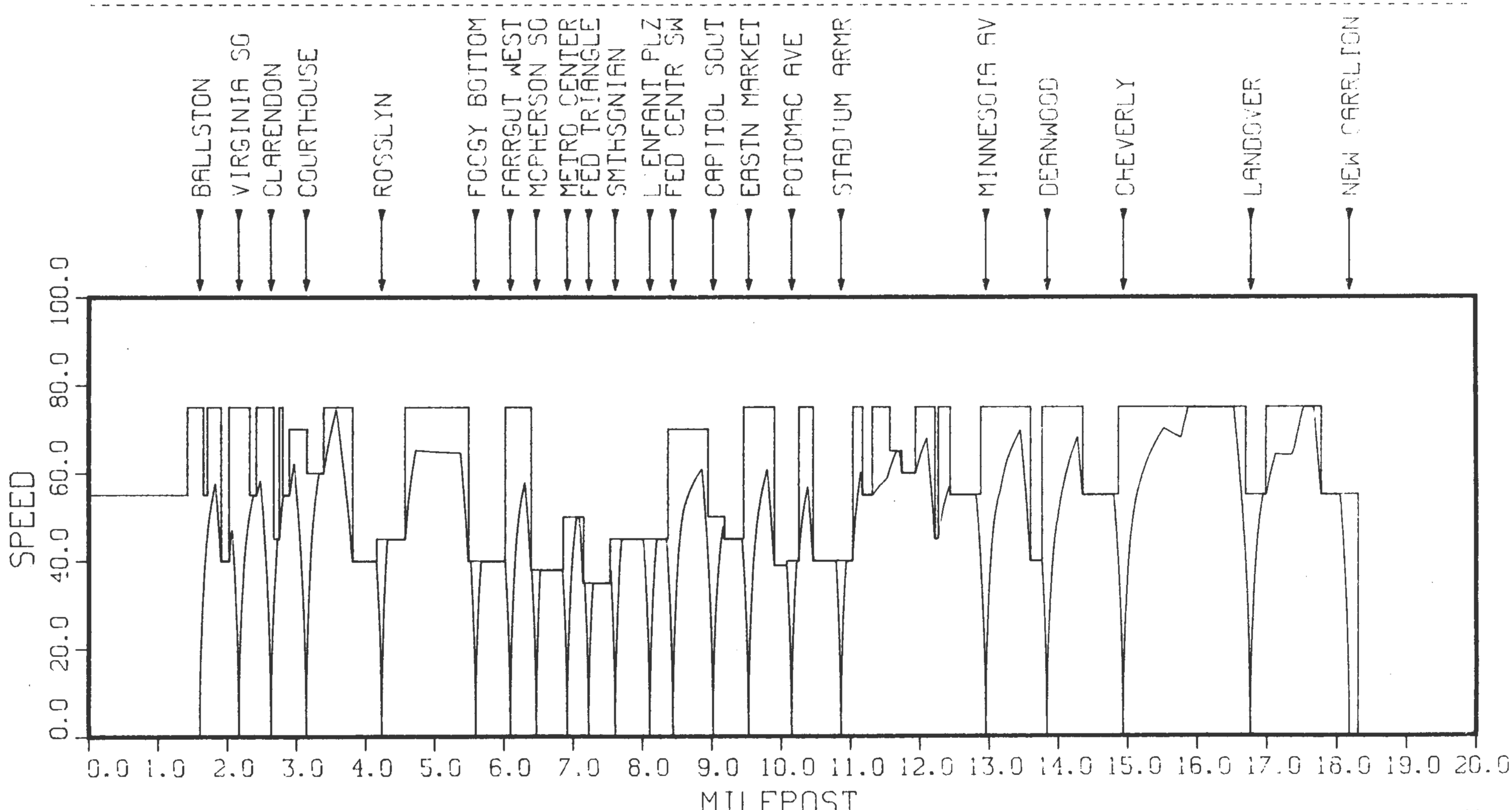


FIGURE 4-25

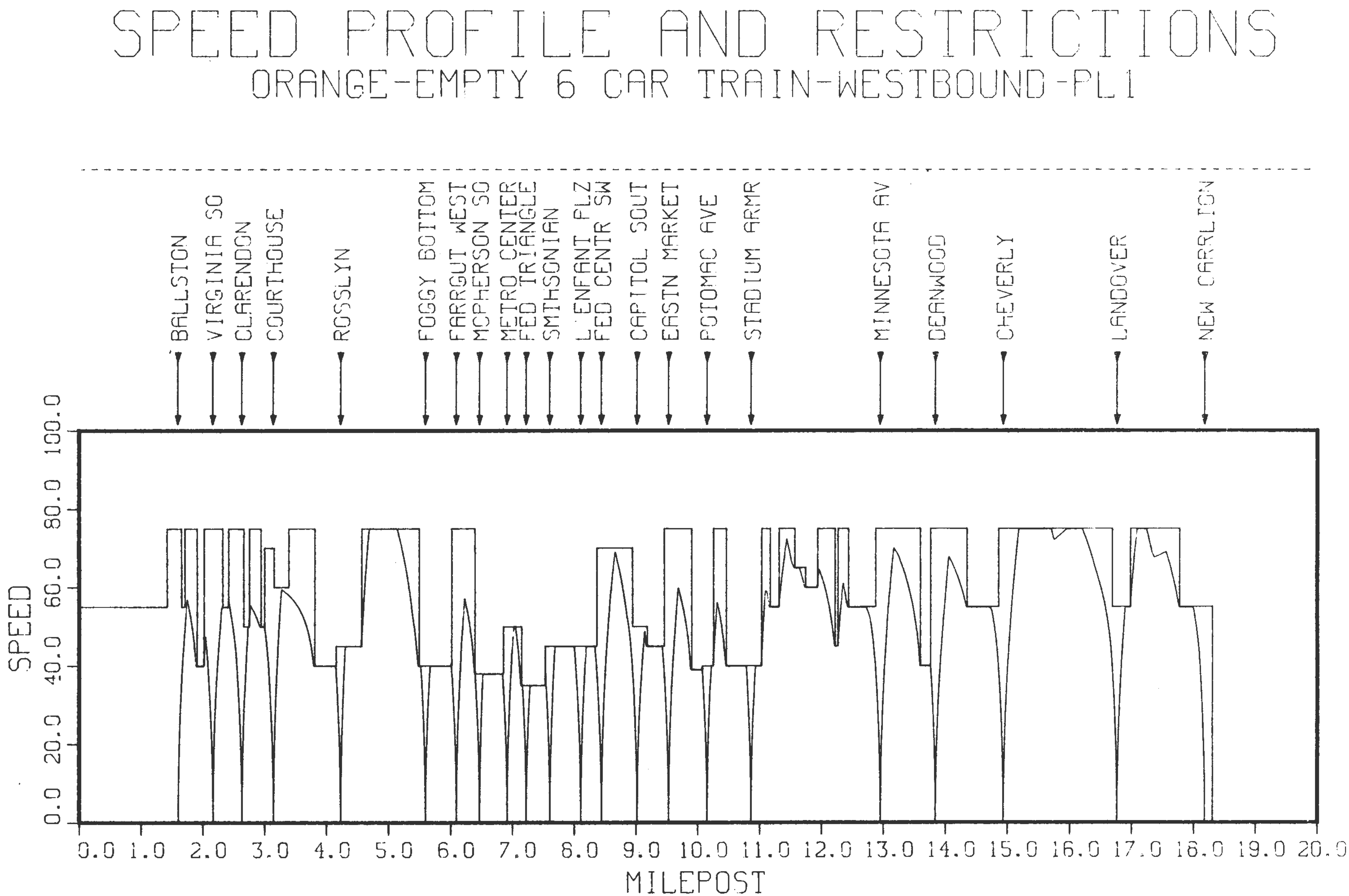

SPEED PROFILE AND RESTRICTIONS
ORANGE-EMPTY 6 CAR TRAIN-WESTBOUND-PL1
BALLSTON
VIRGINIA SQ
CLARENDON
COURTHOUSE
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMITHSONIAN
L'ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
MINNESOTA AV
DEANWOOD
CHEVERLY
LANDOVER
NEW CARRLTON
SPEED
0.0
20.0
40.0
60.0
80.0
100.0
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0 17.0 18.0 19.0 20.0
MILEPOST

FIGURE 4-26

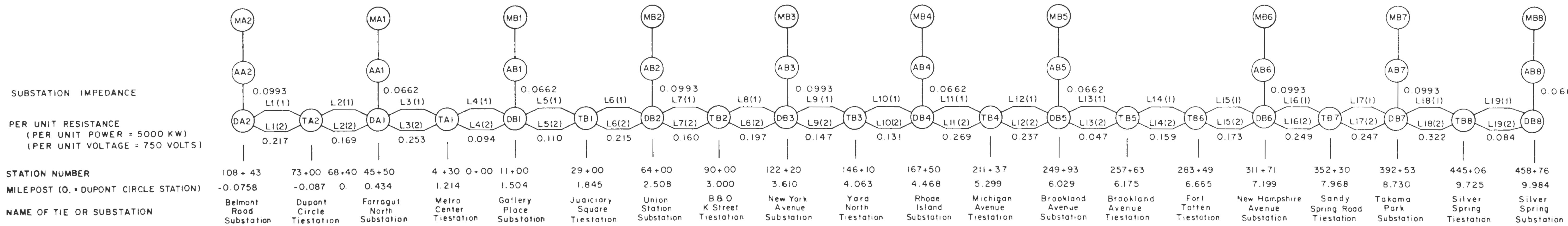


FIGURE 4-27 RED LINE
ELECTRICAL DISTRIBUTION NETWORK

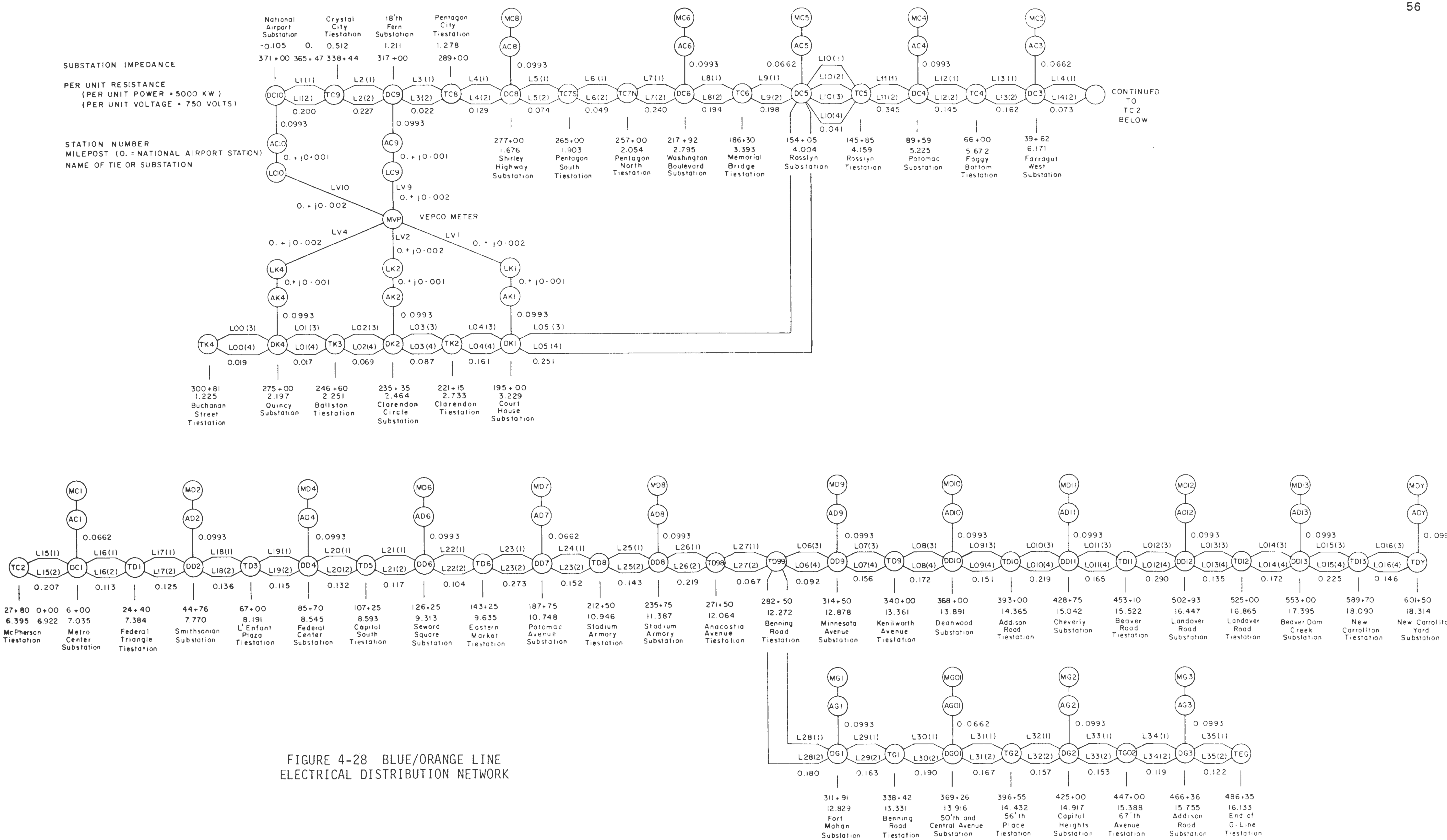


FIGURE 4-28 BLUE/ORANGE LINE ELECTRICAL DISTRIBUTION NETWORK

4.5.2. Substation Description

Table 4-5 lists the substation characteristics appropriate to the Red Line, and Blue/Orange 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.

4.5.3. 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.

4.6. 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 listed in Table 4-6.

The demand interval is 30 minutes, 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 non-traction power is based on a simple rate formula. There is no demand charge, and the rates are (effective October 1980):

$.04/KWH for energy,

$.0211/KWh for fuel adjustment.

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

TABLE 4-5 SUBSTATION CHARACTERISTICS**

SUBSTATION NAME	METER DESIGNATION	NUMBER OF 2000 KW T-R*	NO LOAD LOSSES (KW)	IMPEDANCE (PER UNIT)	RATING OF AUX. TRANSFORMERS (KW)
RED LINE					
Belmont Road+	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 Avenue	MB3	2	16	.0993	150
Rhode Island Avenue	MB4	3	24	.0662	
Brookland Avenue	MB5	3	24	.0662	150
New Hampshire Avenue	MB6	2	16	.0993	150
Takoma Park	MB7	2	16	.0993	
Silver Spring	MB8	3	24	.0662	
ORANGE AND BLUE LINES					
Shirley Highway	MC8	2	16	.0993	1500
Washington Boulevard	MC6	2	16	.0993	500
Rosslyn	MC5	3	24	.0662	750
Potomac	MC4	2	16	.0993	600
Farragut West	MC3	3	24	.0662	
Metro Center	MC1	3	24	.0662	
Smithsonian	MD2	2	16	.0993	
Federal Center	MD4	2	16	.0993	
Seward Square	MD6	2	16	.0993	
Potomac Avenue	MD7	3	24	.0662	500
Stadium Armory	MD8	2	16	.0993	225
Minnesota Avenue	MD9	2	16	.0993	
Deanwood	MD10	2	16	.0993	
Cheverly	MD11	2	16	.0993	
Landover	MD12	2	16	.0993	112.5
Beaver Dam Creek	MD13	2	16	.0993	75
New Carrollton Yard	MDY	2	16	.0993	1500
Fort Mohaw+	MG1	2	16	.0993	1000
50th & Central Avenue	MG01	3	24	.0662	300
Capitol Heights+	MG2	2	16	.0993	
Addison Road+	MG3	2	16	.0993	
National Airport	MVP	2	16	.0993	
18th & Fern	MVP	2	16	.0993	
Court House***	MVP	2	16	.0993	

*T-R Transformer-Rectifiers

**Obtained from George Care, WMATA

***VEPCO Meter (common to all substations)

+1981 Operation

TABLE 4-6 PEPCO POWER RATE STRUCTURE

JURISDICTION	DC	MARYLAND	VIRGINIA
Effective	12/81	6/81	4/80
Demand ($/KW)	11.70*	9.85**	7.85**
Energy (¢/KWH)	0.52893	0.5796	0.4244
Customer ($/delivery pt.)	150.75	145.00	140.00
Fuel Adjustment (¢/KWH)***	2.29257	1.8	1.8

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

**Billing demand is the maximum of the monthly demands including the present month.

***This represents an average for the period.

study.

4.7. PEPCO METER CONSOLIDATION

Tables 4-7, 4-8 and 4-9 present information on the consolidation of the meters for both traction and non-traction purposes for the D.C., Maryland and Virginia jurisdictions of PEPCO service.

TABLE 4-7 PEPCO METER CONSOLIDATION - DC JURISDICTION

METER LOCATION	METER DESIGNATION	METRO ACCOUNT #	LINE	CONVERSION FACTOR PULSES TO KWH
		Traction Power		
Belmont Road	MA2	01270030	Red	.47
Farragut North	MA1	01270023	Red	.72
Gallery Place	MB1	01270016	Red	.72
Union Station	MB2	01270008	Red	.57
New York Avenue	MB3	01270011	Red	.57
Rhode Island Avenue	MB4	01270013	Red	1.92
Brookland Avenue	MB5	01270005	Red	1.44
New Hampshire Avenue	MB6	01270004	Red	1.20
Takoma Park	MB7	01270002	Red	1.44
Potomac	MC4	01270029	Orange/Blue	.86
Farragut West	MC3	01270022	Orange/Blue	1.44
Metro Center	MC1	01270014	Orange/Blue	1.44
Smithsonian	MD2	01270033	Orange/Blue	1.44
Federal Center	MD4	01270032	Orange/Blue	1.20
Seward Square	MD6	01270042	Orange/Blue	1.44
Potomac Avenue	MD7	01270043	Orange/Blue	1.44
Stadium Armory	MD8	01270047	Orange/Blue	1.44
Minnesota Avenue	MD9	01270039	Orange	.47
Deanwood	MD10	01270040	Orange	.47
Fort Mahan	MG1	01270050	Blue	.47
Benning Road	MG01	01270054	Blue	.47
		Support Power*		
Dupont Circle	MSA3	01270027	Red	.50
Farragut North	MSA2	01270024	Red	.28
Metro Center	MSA1	01270017	Red	.23
Gallery Place	MSB1	01270019	Red	.23
Judiciary Square	MSB2	01270018	Red	.23
Union Station	MSB3	01270010	Red	.47
Rhode Island Avenue	MSB4	01270012	Red	.23
Brookland Avenue	MSB5	01270006	Red	.14
Fort Totten	MSB6	01270007	Red	.14
Takoma	MSB7	01270003	Red	.14
Foggy Bottom	MSC4	01270028	Orange/Blue	.18
Farragut West	MSC3	01270025	Orange/Blue	.23
McPherson Square	MSC2	01270026	Orange/Blue	.22
Metro Center	MSC1	01270015	Orange/Blue	.28
Federal Triangle	MSD1	01270021	Orange/Blue	.19
Smithsonian	MSD2	01270036	Orange/Blue	.18
L'Enfant Plaza	MSD3	01270034	Orange/Blue	.23
Federal Center	MSD4	01270031	Orange/Blue	.21
Capitol South	MSD5	01270046	Orange/Blue	.23
Eastern Market	MSD6	01270045	Orange/Blue	.23
Potomac Avenue	MSD7	01270044	Orange/Blue	.23
Stadium Armory	MSD8	01270041	Orange/Blue	.29
Minnesota Avenue	MSD9	01270037	Orange	.21
Deanwood	MS10	01270038	Orange	.21
L'Enfant Plaza	MSE1	01270035	Yellow/Green	.23
Archives	MSE2	01270049	Yellow/Green	.14
Gallery Place	MSE3	01270048	Yellow/Green	.17
Benning Road	MSG1	01270053	Blue	.08
Office Building**	MOB	01270020	-	.67
T-St. Repair Shop (Brentwood)	MRS	01270009	-	.72

*Passenger Stations

**Includes chiller plant power for Gallery Place & Judiciary Square.

TABLE 4-8

PEPCO METER CONSOLIDATION - MD JURISDICTION

METER LOCATION	METER DESIGNATION	METER ACCOUNT #	NEW ACCOUNT #	LINE	CONVERSION FACTOR PULSE TO KWH
		Traction Power			
Silver Spring	MB8	20023217	(20074812)	Red	1.80
Cheverly	MD11	41010600	(31014640)	Orange	.47
Landover Road	MD12	41010598	(31014639)	Orange	.47
Beaver Dam Creek	MD13	31012973	(31014638)	Orange	.53
New Carrollton Yard	MDY	41011140	(31014641)	Orange	.72
Capitol Heights	MG2	41220702	(31014648)	Blue	.47
Addison Road	MG3	41220701	(31014647)	Blue	.47
Grossvenor	MA10	22320240	(20074814)	Red	.10
		Support Power			
New Carrollton Yard	MS13	41021123	(31014645)	Orange	.10
Landover	MS12	41011181	(31014642)	Orange	.08
Cheverly	MS11	41011182	(31014643)	Orange	.14
Silver Spring	MSB8	20030850	(20074813)	Red	.16
Capitol Heights	MSG2	41220703	(31014649)	Blue	.08
Addison Road	MSG3	41021121	(31014644)	Blue	.10
Garden City Shop	MSCS	41120621	(31014646)	Orange	.47

TABLE 4-9 PEPCO METER CONSOLIDATION - VA JURISDICTION

METER LOCATION	METER DESIGNATION	METER ACCOUNT #	LINE	CONVERSION FACTOR PULSE TO KWH
		Traction Power		
Rosslyn	MC5	80010007	Orange/Blue	1.44
Washington Boulevard	MC6	80010004	Blue	.96
Shirley Highway	MC8	80010005	Blue	1.20
		Support Power		
Rosslyn*	MSC5	80010006	Orange/Blue	.23
Arlington Cemetery	MSC6	80010002	Blue	.29
Pentagon	MSC7	80010003	Blue	.35

*Includes chiller plant for Rosslyn Station.

5. TRACTION ENERGY

In Metrorail operation, traction energy is the time integrated power registered by the electric meters in the traction substations. It includes energy to operate the trains during revenue service, testing and yard movement. It also includes energy for other functions which are powered through these substations, such as auxiliaries aboard the cars during layup, heating and ventilation, some air conditioning, tunnel lighting and switchpoint heating. In order to determine what fraction of the energy was used for traction, it was necessary to undertake an audit of the energy end uses.

5.1. AUDIT

The traction energy audit was conducted by analyzing metering information supplied by PEPCO for nine months of the year 1980. This method was chosen because PEPCO supplied 86% of the energy for Metrorail operations during this time period. The VEPCO supplied the remaining 14%. Table 5-1[2] provides a summary of energy used in 1980 by utility and jurisdiction. A second reason for this course of action was that PEPCO had detailed metering information available while VEPCO did not.

5.1.1. Description of PEPCO Metering Data

The interval selected for the traction energy audit was a compromise based on the time span of the metering information provided by PEPCO and the period during which the 1980 Metrorail operating timetable remained relatively constant.

The PEPCO provided a magnetic tape which contained energy usage (pulses) for each fifteen minute interval for the twenty-six traction energy meters which were in operation during 1980. The time span was January 20, 1980, to January 19, 1981. Each meter was analyzed, and Appendix 9.3 contains the description of the system flow chart for the analysis of PEPCO tape.

Of the twenty-six traction meters considered in the analysis, eighteen, five and three were in the DC, MD and VA jurisdictions, respectively. During the analysis, it was found that pulses were not provided by PEPCO for the meters at Cheverly, Landover, Beaver Dam Creek, New Carrollton Yard and Silver Spring substations, all

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[2] Testimony of Richard T. Labonski of Washington Metro before the D.C. Public Service Commission, Formal Case #748, April 1981.

TABLE 5-1 ENERGY CONSUMED BY METRO OPERATIONS DURING 1980

(X1000 KWH)(% of TOTAL)

	PEPCO		VEPCO
ENERGY CONSUMED BY	DC	MD & VA	
All Passenger Stations	47,721 (66%)	12,541 (17%)	12,184 (17%)
All Rail Traction Operations	107,635 (62%)	43,371 (25%)	21,819 (13%)
TOTAL	155,356 (63%)	55,912 (23%)	34,453 (14%)

Source: Testimony of Richard T. Labonski of Washington Metro before the DC Public Service Commission, Formal Case #748, April 1981.

of which were in the MD jurisdiction. Thus, precautions were taken during the audit to discount the effect of these meters.

The 1980 Metrorail operating timetable showed the same weekly pattern of train operation from February 1, 1980, to November 1, 1980, at which time service on the Blue Line was extended from the Stadium Armory station to the Addison Road station.

Because of more missing metering information from October 15, 1980, to November 1, 1980, the time span for the audit was selected from February 1, 1980, to October 15, 1980, a total of 257 days.

5.1.2. Regression Analyses: Daily Car-Miles and Temperature

In order to determine the dependence of traction energy usage on car-miles and daily temperature, regression analyses were conducted using the traction meter data. Each day was divided into two periods: revenue service time and non-revenue 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. Non-revenue service time was all other time.

5.1.2.1. 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 is the average power over the revenue operating time as obtained from the meter data, P_0 is the background power in units of KW, CM/H is the average car-miles per hour over revenue service time on a daily basis, ADD is the average degree-day defined as the average temperature less 70°F. The coefficient E_1 represents the energy per car-mile (KWHPCM) and P_2 represents the average power per average degree day (KWPADD).

In order to conduct the regressions, the actual car-miles accumulated each day were obtained from Metrorail[3] over the interval of the audit. A statistical summary of the actual car-miles on the Red, Blue and Orange Lines are shown in Figures 5-1 to 5-3. The three peaks visible in the figures are attributed to weekday, Saturday, and Sunday operation. Table 5-2 presents a summary of the average, actual, and

[3] Obtained from Richard T. Labonski, Energy Management Officer.

scheduled car-miles per day for the Red Line, and Blue/Orange Line combination.

An increase in actual car-miles on the Red Line was observed to occur on May 1, 1980. Table 5-2 shows the average car-miles broken down into two periods: February 1-April 30, 1980, and May 1-October 15, 1980. The weekday and Saturday averages were significantly different for the two cases. Metro[4] reports that four-, together with six-car trains were used during weekday evenings, Saturdays, and Sundays during the spring of 1980.

The second independent variable of the revenue service time regression was the average degree day (ADD), defined as the average daily temperature less 70°F. A statistical summary of ADD over the audit period is shown in Figure 5-4. The average value is -3.7°, which represents an average daily temperature of 66.3°F.

5.1.2.2. Non-Revenue Service Time Regression

During non-revenue service time, the regression formula was assumed to have the form:

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

where all of the variables are the same as in the revenue service time regression, and MDD is the minimum degree day, the minimum temperature less 70°F. The average value of the minimum degree day is -13°, which represents a temperature of 57°F. The minimum temperature was selected as the independent variable because non-revenue service time generally had the minimum temperature.

5.1.2.3. Regression Analyses Results

The results of the regression analyses for the traction energy meters are shown in Table 5-3. In addition to those completed on the individual meters, regressions were also conducted on 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%, even for the smallest value of the coefficient (E_1) of 0.24 at the New Carrollton Yard substation meter.

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[4] Obtained from George Care, WMATA.

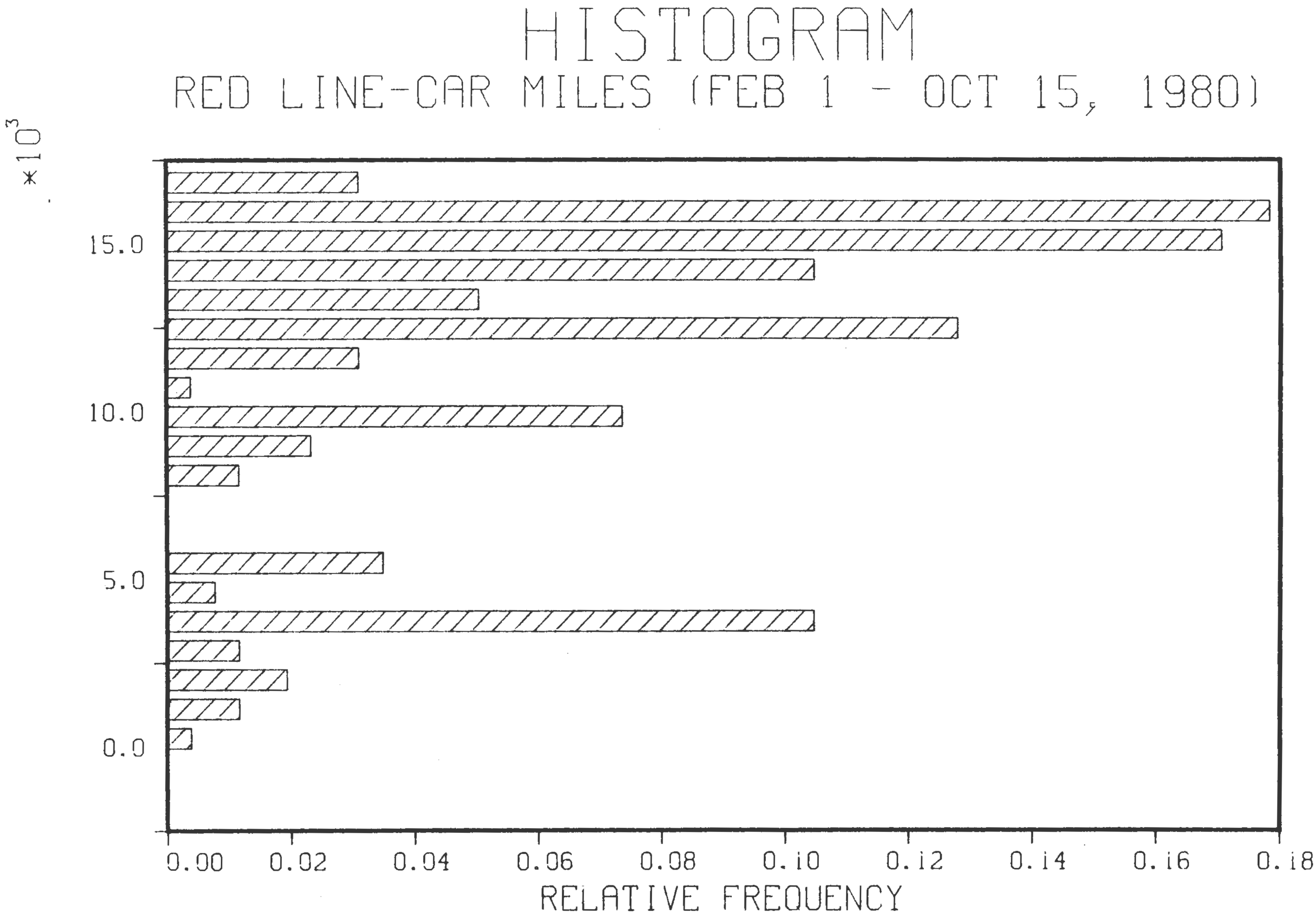
HISTOGRAM
RED LINE-CAR MILES (FEB 1 - OCT 15, 1980)
*10^3
15.0
10.0
5.0
0.0
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
RELATIVE FREQUENCY

FIGURE 5-1

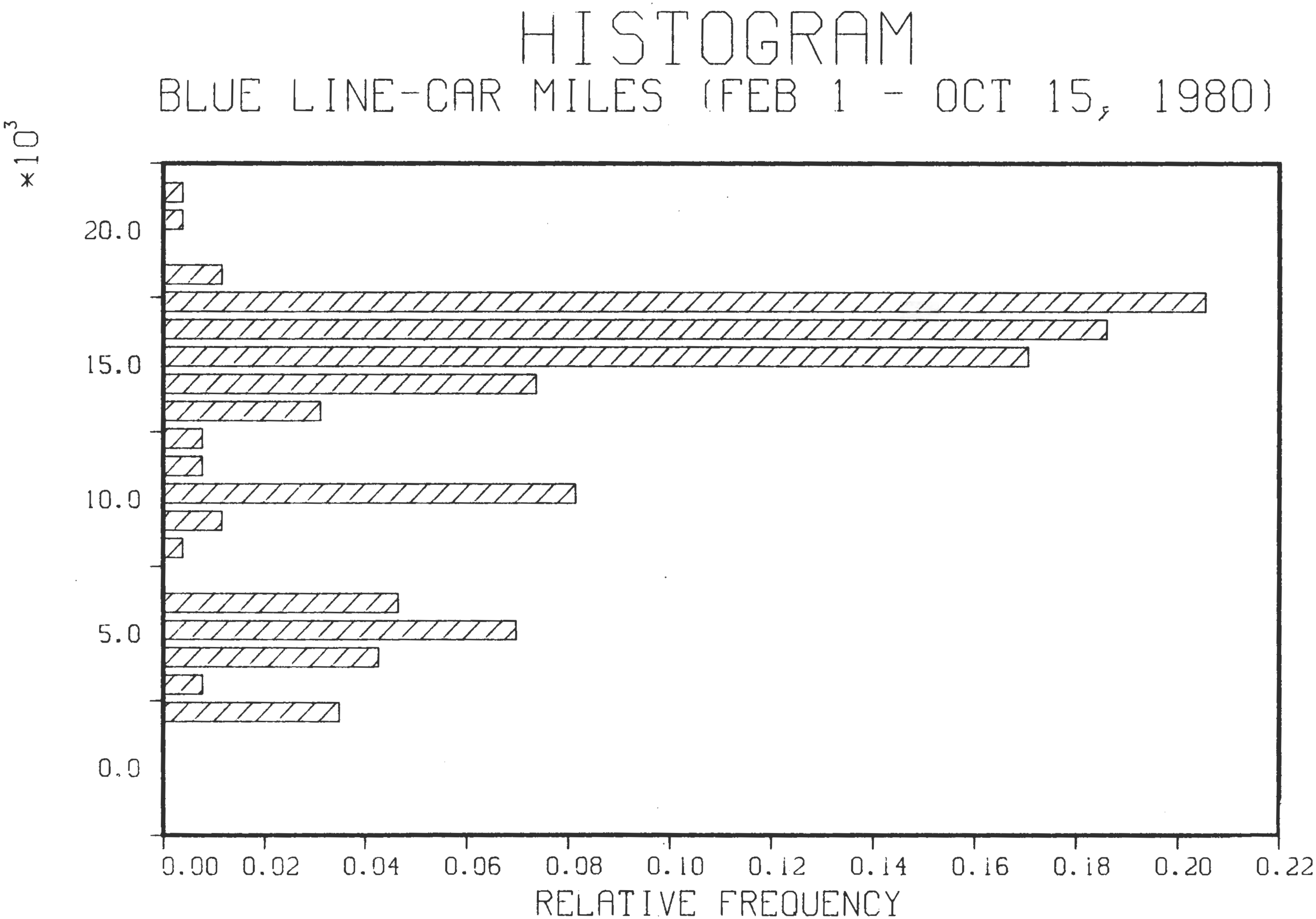
HISTOGRAM
BLUE LINE-CAR MILES (FEB 1 - OCT 15, 1980)
*10^3
20.0
15.0
10.0
5.0
0.0
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22
RELATIVE FREQUENCY

FIGURE 5-2

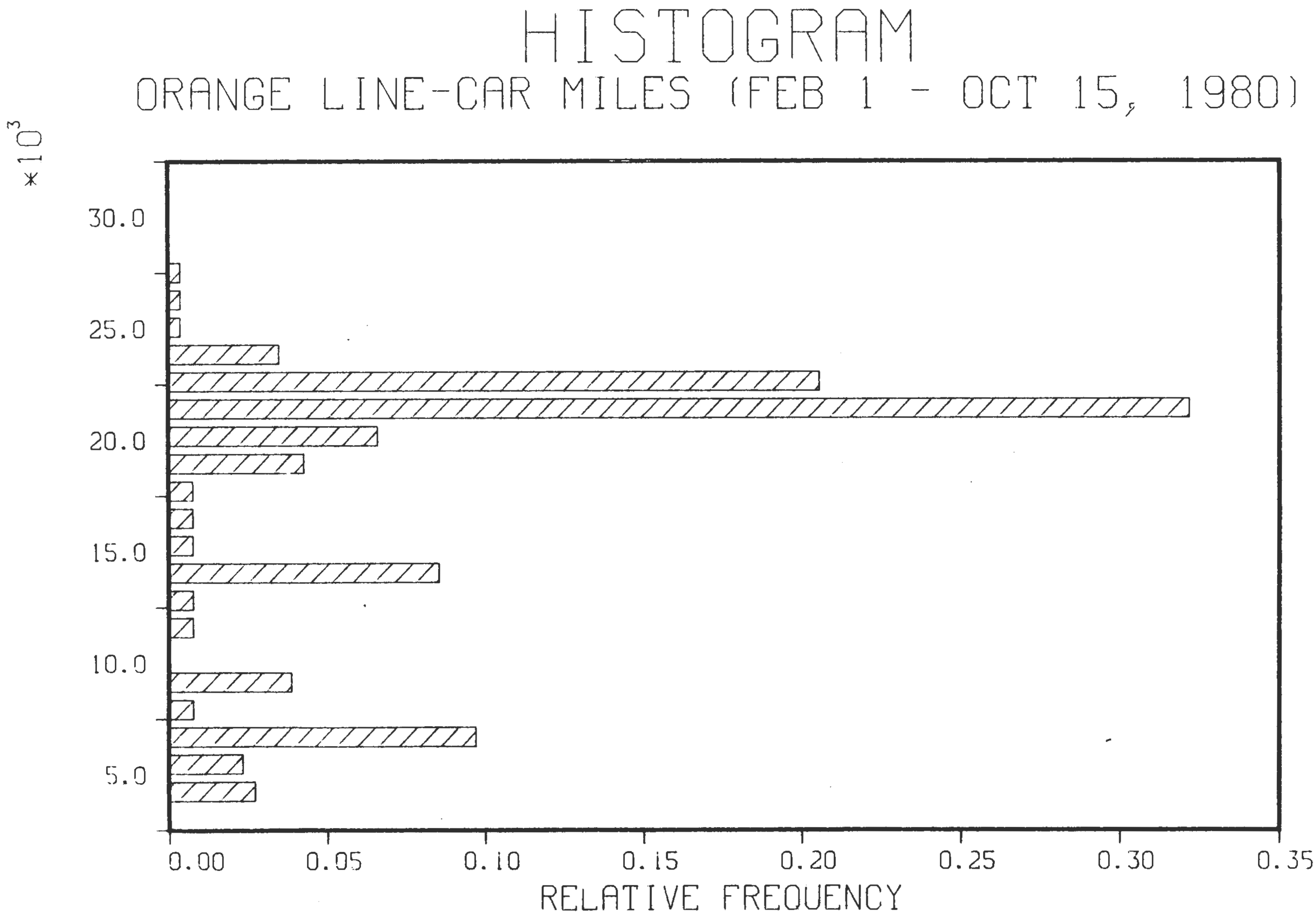
HISTOGRAM
ORANGE LINE-CAR MILES (FEB 1 - OCT 15, 1980)
*10^3
30.0
25.0
20.0
15.0
10.0
5.0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
RELATIVE FREQUENCY

FIGURE 5-3

TABLE 5-2 SUMMARY OF AVERAGE ACTUAL VS. SCHEDULED CAR-MILES FOR METRO (FEBRUARY 1, 1980 - OCTOBER 15, 1980)

RED LINE	Average Actual Car-Miles	Scheduled Car-Miles
Weekdays	16,470	18,018
Saturdays	10,489	11,571
Sundays	5,487	5,964
BLUE/ORANGE LINE		
Weekdays	41,338	41,855
Saturdays	25,186	26,779
Sundays	13,977	14,053

	Average Actual Car-Miles	
RED LINE	February 1-April 30, 1980	May 1-October 15, 1980
Weekdays	14,876	17,372
Saturday	8,712	11,419
Sunday	5,203	5,618

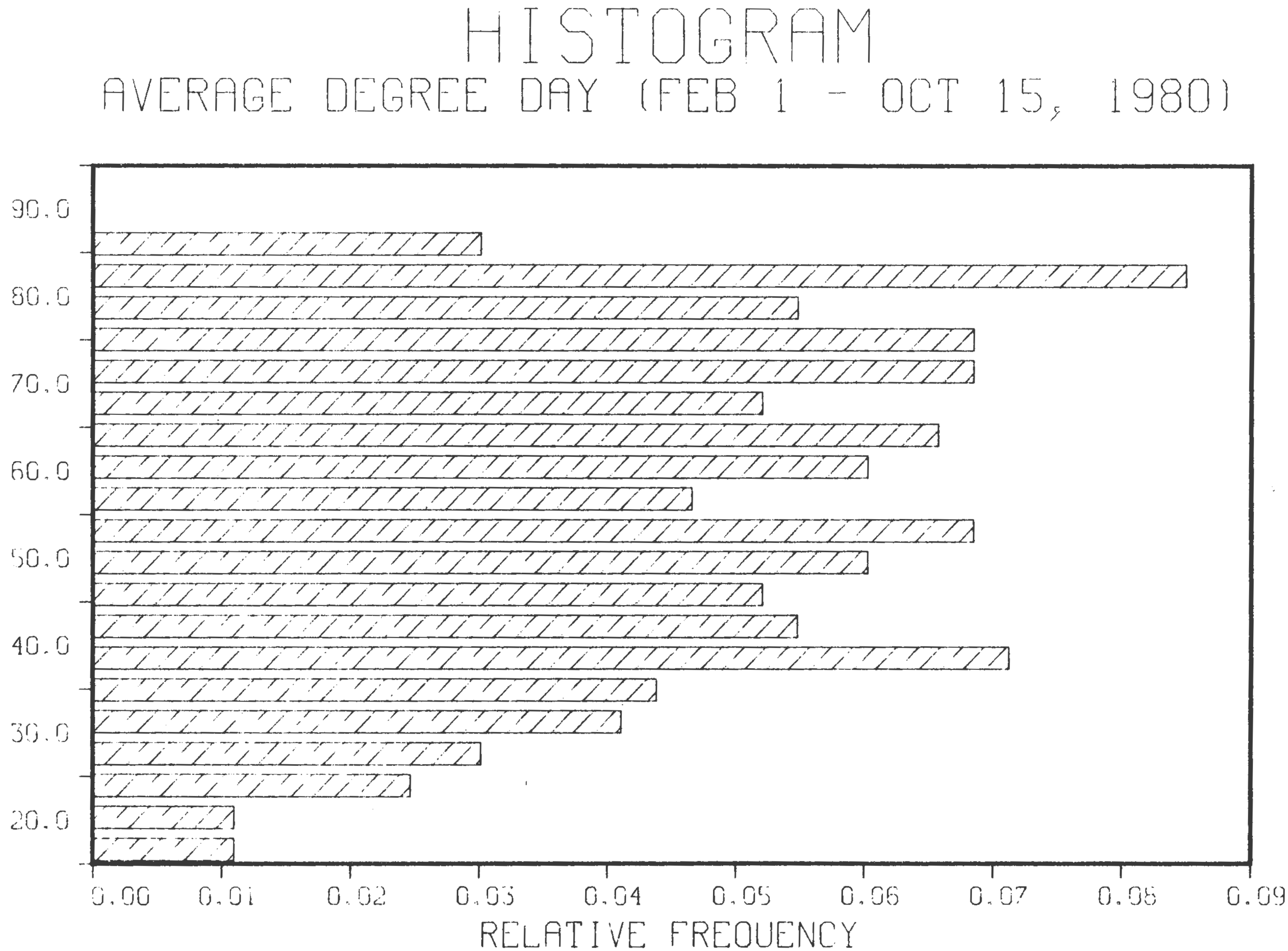
HISTOGRAM
AVERAGE DEGREE DAY (FEB 1 - OCT 15, 1980)
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
RELATIVE FREQUENCY

FIGURE 5-4

TABLE 5-3 RESULTS OF REGRESSION ANALYSES 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	333	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

Table 5-4, which is based on the results of Table 5-3, shows the degree-day coefficients (P_2) for five meter consolidations separated by heating and cooling effects. Load differences between winter (20-30°F) and summer (80-90°F) are also tabulated. For example, for non-revenue service time the summer-winter power differential is (235 KW-67 KW) 168 KW.

Car storage during revenue service time at midday and evenings on weekdays, 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% dependence on car-miles with the background accounting nearly for the remaining amount. The background is attributed to yard car movement and car storage.

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

During non-revenue service time, the temperature component is much higher because there is no car-mile component.

Several of the meters 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 result of chiller plant power being metered through the traction substation, and the effect at New Carrollton is due to air conditioning of the yard office building and tower. At the present time, there is no explanation for the effects at New Hampshire Avenue on the Red Line, and Potomac Avenue on the Blue/Orange Line.

Table 5-5 lists the average powers for the traction meters at different operating times from May 1, 1980, to October 15, 1980. This time interval was selected for the averages because six car trains were generally used on Saturdays, Sundays and weekday evenings rather than mixtures of four and six car trains as were used in the Spring of 1980. Ratios of average power of AM peak to midday, AM peak to PM peak, midday to evening, and midday to Sunday are listed.

TABLE 5-4 TEMPERATURE DEPENDENT COEFFICIENT OF REGRESSION ANALYSES AND LOAD DIFFERENCES FOR TRACTION METER CONSOLIDATION

	P_2(KWPADD) Revenue Service Time		P_2(KWPMDD) 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

TABLE 5-5 AVERAGE POWERS (KW) FOR TRACTION METERS AT DIFFERENT OPERATING TIMES (MAY 1, 1980 - OCTOBER 15, 1980)

RED LINE METER NAME (SYMBOL)	WEEKDAY AM PEAK 8:00-9:00	WEEKDAY MIDDAY 12:00-13:00	WEEKDAY PM PEAK 17:00-18:00	WEEKDAY EVENING 20:00-21:00	SATURDAY 12:00-13:00	SUNDAY 12:00-13:00	AM PEAK / MIDDAY	AM PEAK / PM PEAK	MIDDAY / EVENING	MIDDAY / SUNDAY
Farragut North (MA1)	1759	832	1836	819	813	796	2.11	.96	1.02	1.05
Gallery Place (MB1)	1585	757	1663	713	717	671	2.09	.95	1.06	1.13
Union Station (MB2)	1116	590	1283	557	526	484	1.89	.87	1.06	1.22
New York Avenue (MB3)	1149	735	1338	784	655	622	1.56	.86	.94	1.18
Rhode Island Avenue (MB4)	1160	534	1259	505	500	437	2.17	.92	1.06	1.22
Brookland Avenue (MB5)	1764	922	1827	926	889	846	1.91	.97	1.00	1.09
New Hampshire Avenue (M86)	970	639	1086	568	619	611	1.52	.89	1.13	1.05
Takoma Park (MB7)	1267	614	1277	593	626	606	2.06	.99	1.04	1.01
Silver Spring (MB8)	1241	854	1278	854	794	860	1.45	.97	1.00	.99
Coincident Red	12011	6476	12847	6318	6140	5933	1.85	.93	1.03	1.09

BLUE/ORANGE LINE METER NAME (SYMBOL)	WEEKDAY AM PEAK 8:00-9:00	WEEKDAY MIDDAY 12:00-13:00	WEEKDAY PM PEAK 17:00-18:00	WEEKDAY EVENING 20:00-21:00	SATURDAY 12:00-13:00	SUNDAY 12:00-13:00	AM PEAK / MIDDAY	AM PEAK / PM PEAK	MIDDAY / EVENING	MIDDAY / SUNDAY
Shirley Highway (MC8)	563	379	615	461	500	496	1.49	.92	.82	.76
Washington Boulevard (MC6)	1009	565	1055	572	523	499	1.79	.96	.99	1.13
Rosslyn (MC5)	1739	912	1841	887	832	853	1.91	.94	1.03	1.07
Potomac (MC4)	1705	918	1741	949	866	813	1.86	.98	.97	1.13
Farragut West (MC3)	1986	1017	2123	967	929	902	1.95	.94	1.05	1.13
Metro Center (MC1)	1962	1030	2016	992	986	963	1.90	.97	1.04	1.07
Smithsonian (MD2)	1800	972	1832	946	875	900	1.85	.98	1.03	1.08
Federal Center (MD4)	1248	640	1449	657	593	547	1.95	.86	.97	1.17
Seward Square (MD6)	2143	1177	2179	1144	1074	1103	1.82	.98	1.03	1.07
Potomac Avenue (MD7)	1006	537	1138	537	501	503	1.87	.88	1.00	1.07
Stadium Armory (MD8)	2031	1147	2079	1142	1100	1110	1.77	.98	1.00	1.03
Minnesota Avenue (MD9)	1036	615	1162	609	571	558	1.68	.89	1.01	1.10
Deanwood (MD10)	1023	591	1076	609	567	562	1.73	.95	.97	1.05
Cheverly (MD11)	978	625	1044	610	551	537	1.48	.94	1.02	1.16
Landover (MD12)	734	569	869	592	484	463	1.29	.85	.96	1.23
Beaver Dam Creek (MD13)	737	537	745	559	461	479	1.37	.99	.96	1.12
New Carrollton Yard (MDY)	635	747	638	1084	564	605	.85	1.00	.69	1.23
Coincident Blue/Orange	22332	12979	23600	13315	11975	11893	1.72	.95	.97	1.09
Coincident Blue/Orange (Less MD11, MD12, MD13, MDY)	19248	10501	20304	10470	9915	9809	1.83	.95	1.00	1.07

If there were no background, the ratio of AM peak to midday peak would be 2.3 on the Red Line, and 2.0 on the Blue/Orange Line.

The ratio of AM to PM peak power is 0.93 on the Red Line, and 0.95 on the Blue/Orange Line.

The ratio of midday to evening power is 1.03 on the Red Line, and 0.97 on the Blue/Orange Line. The ratio of midday to Sunday is 1.09 on all lines, so that 9% more power is used during midday operation than on Sunday.

5.1.3. Selection of Metered Background Power

It is clear from the regression analyses carried out on the traction energy meter that a background of power is registered even when no trains are operated. This background exists 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 substations and other structures, chiller plants metered through the traction meters, tunnel ventilation, lighting and switchpoint heating, and testing of trains.

This background is not simply the background of the regression analysis carried out during revenue service time, because of the intercept error discussed in Appendix 9.4. It is more appropriate to consider the non-revenue service time as the basis for the background estimate (Table 5-3).

Table 5-6 contains a summary of the background values for all the traction meters used in all of the subsequent analyses using the EMM. These backgrounds were derived using the following rules:

1. The minimum power through any traction meter is the no-load losses of the transformer-rectifier units in the substation.These are estimated at 8 KW per unit.[5] 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.[6]

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[5] Data on number of units and no-load losses per unit obtained from George Care in letters dated 11/13/81 and 12/18/81.

[6] Edgar Green, Office of Equipment Design, WMATA.

TABLE 5-6 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	9.984	MB8	-	3	24	388	180	208	328
									1412	1652
Shirley Highway	Blue	1.676	MC8	1500	2	16	163		163	163
Washington Boulevard	Blue	2.795	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	7.035	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

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

Since it was not possible to obtain a detailed analysis of the background associated with the VEPCO meter, this estimate was made by taking each VEPCO substation background the same as the average of all of PEPCO substations. Thus, the background value for the VEPCO meter was 686 KW.

5.1.4. Consolidation Histogram Analysis

Figures 5-5, 5-6, 5-7, 5-8 and 5-9 show statistical summaries of traction power metered by PEPCO for the AM peak for the Red Line, Blue/Orange Line, DC, MD and VA jurisdictions of PEPCO, respectively. Figures 5-10, 5-11, 5-12, 5-13 and 5-14 show statistical summaries for the PM peak for the same PEPCO traction meter consolidations. The time interval selected for these summaries was May 1-October 15, 1980, for which the timetable was relatively stable.

The statistical summaries show the average, standard deviation, and the maximum of the traction power over one-half hour intervals beginning each quarter hour. These values are the measured power demands.

Table 5-7 presents a comparison of the maximum power demand to the average power demand for the AM and PM peak operating periods, for four meter consolidations: Red Line, Blue/Orange Lines, DC and VA jurisdiction of PEPCO. Because of missing meter data on the MD jurisdiction meters, this consolidation was not considered. In the case of the Red and Blue/Orange Line traction meter consolidation, the percent increase of the maximum demand over the average demand is 25-31%. In the case of the DC jurisdiction, the percent increase of the maximum over the average demand was 18-19%. However, in the case of the PEPCO VA jurisdiction, the percent increase is 67-86%.

The large difference in the case of the VA jurisdiction can be attributed to the small number of meters in the consolidation (3 meters), and as a result, any variation in operating conditions over the portion of the rail network serviced through these three meters tend to be coincidental, whereas, in the case of the DC jurisdiction serviced by a large number of meters serving different portions of different lines, the operating difference effects tend to be non-coincidental.

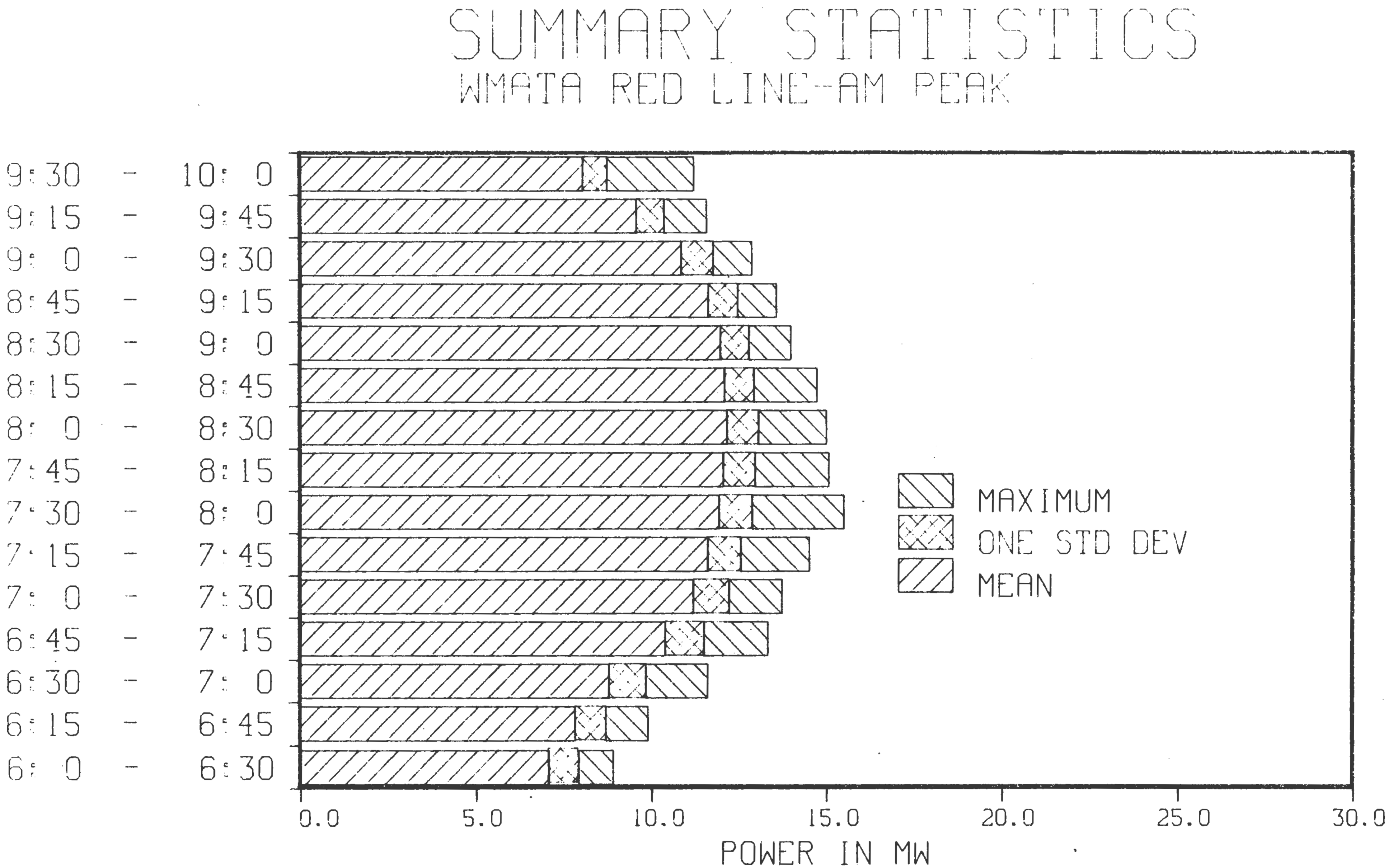

SUMMARY STATISTICS
WMATA RED LINE-AM PEAK
9:30 - 10: 0
9:15 - 9:45
9: 0 - 9:30
8:45 - 9:15
8:30 - 9: 0
8:15 - 8:45
8: 0 - 8:30
7:45 - 8:15
7:30 - 8: 0
7:15 - 7:45
7: 0 - 7:30
6:45 - 7:15
6:30 - 7: 0
6:15 - 6:45
6: 0 - 6:30
MAXIMUM
ONE STD DEV
MEAN
0.0
5.0
10.0
15.0
20.0
25.0
30.0
POWER IN MW

FIGURE 5-5

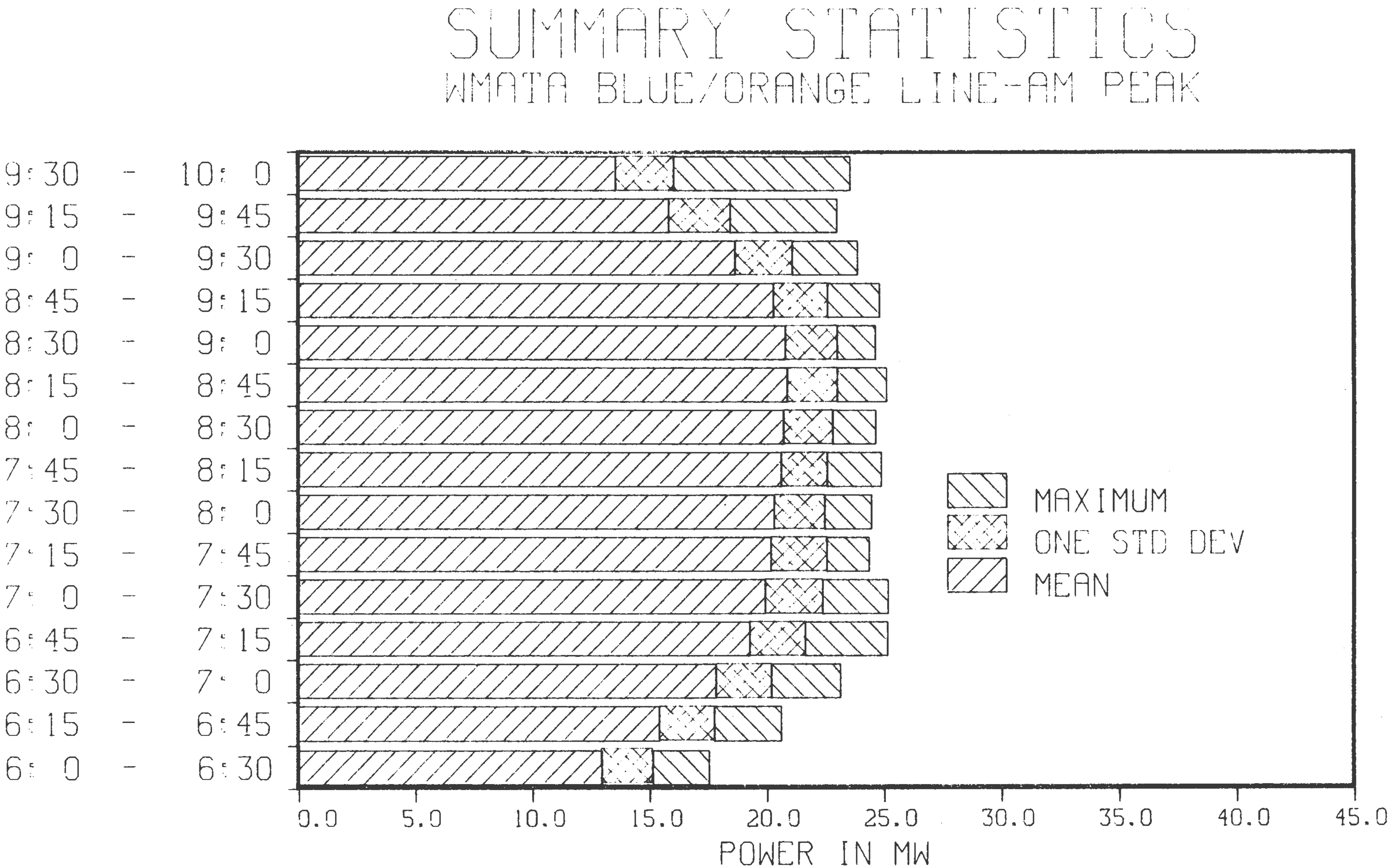

SUMMARY STATISTICS
WMATA BLUE/ORANGE LINE-AM PEAK
9:30 - 10: 0
9:15 - 9:45
9: 0 - 9:30
8:45 - 9:15
8:30 - 9: 0
8:15 - 8:45
8: 0 - 8:30
7:45 - 8:15
7:30 - 8: 0
7:15 - 7:45
7: 0 - 7:30
6:45 - 7:15
6:30 - 7: 0
6:15 - 6:45
6: 0 - 6:30
MAXIMUM
ONE STD DEV
MEAN
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
POWER IN MW

FIGURE 5-6

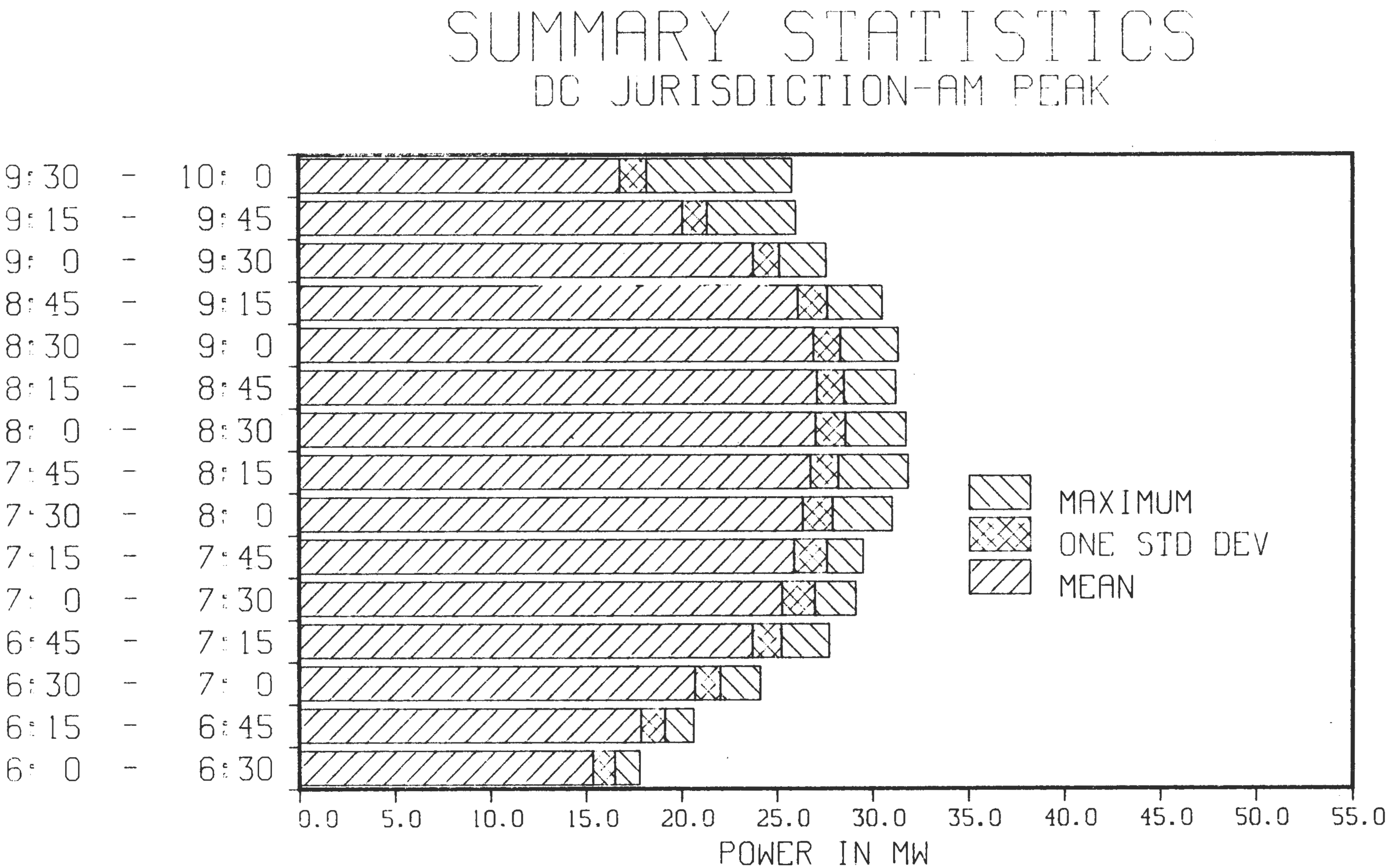

SUMMARY STATISTICS
DC JURISDICTION-AM PEAK
9:30 - 10: 0
9:15 - 9:45
9: 0 - 9:30
8:45 - 9:15
8:30 - 9: 0
8:15 - 8:45
8: 0 - 8:30
7:45 - 8:15
7:30 - 8: 0
7:15 - 7:45
7: 0 - 7:30
6:45 - 7:15
6:30 - 7: 0
6:15 - 6:45
6: 0 - 6:30
MAXIMUM
ONE STD DEV
MEAN
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
POWER IN MW

FIGURE 5-7

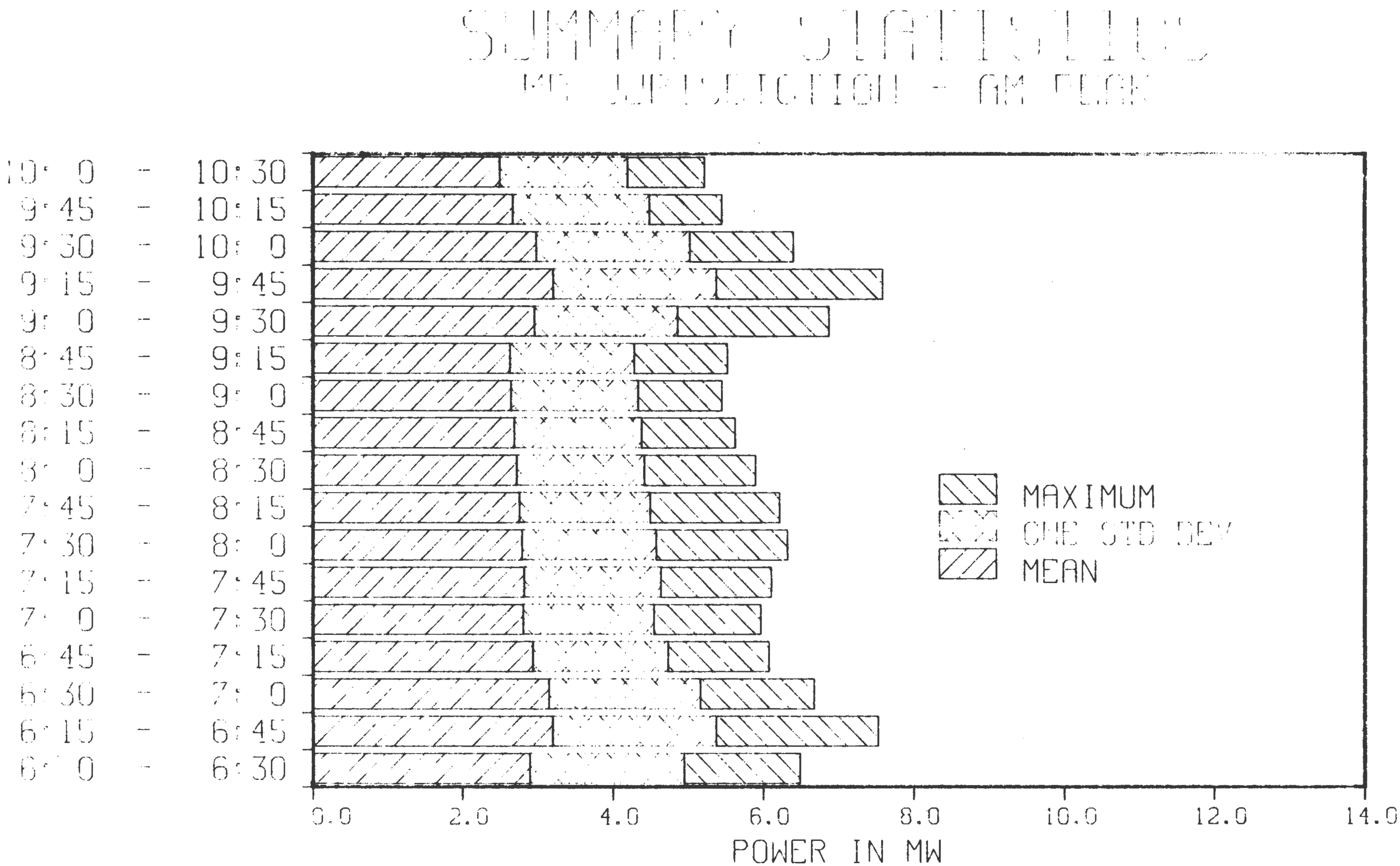

SUMMARY STATISTICS
MG JURISDICTION - AM PEAK
10:0 - 10:30
9:45 - 10:15
9:30 - 10:0
9:15 - 9:45
9:0 - 9:30
8:45 - 9:15
8:30 - 9:0
8:15 - 8:45
8:0 - 8:30
7:45 - 8:15
7:30 - 8:0
7:15 - 7:45
7:0 - 7:30
6:45 - 7:15
6:30 - 7:0
6:15 - 6:45
6:0 - 6:30
MAXIMUM
ONE STD DEV
MEAN
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
POWER IN MW

FIGURE 5-8

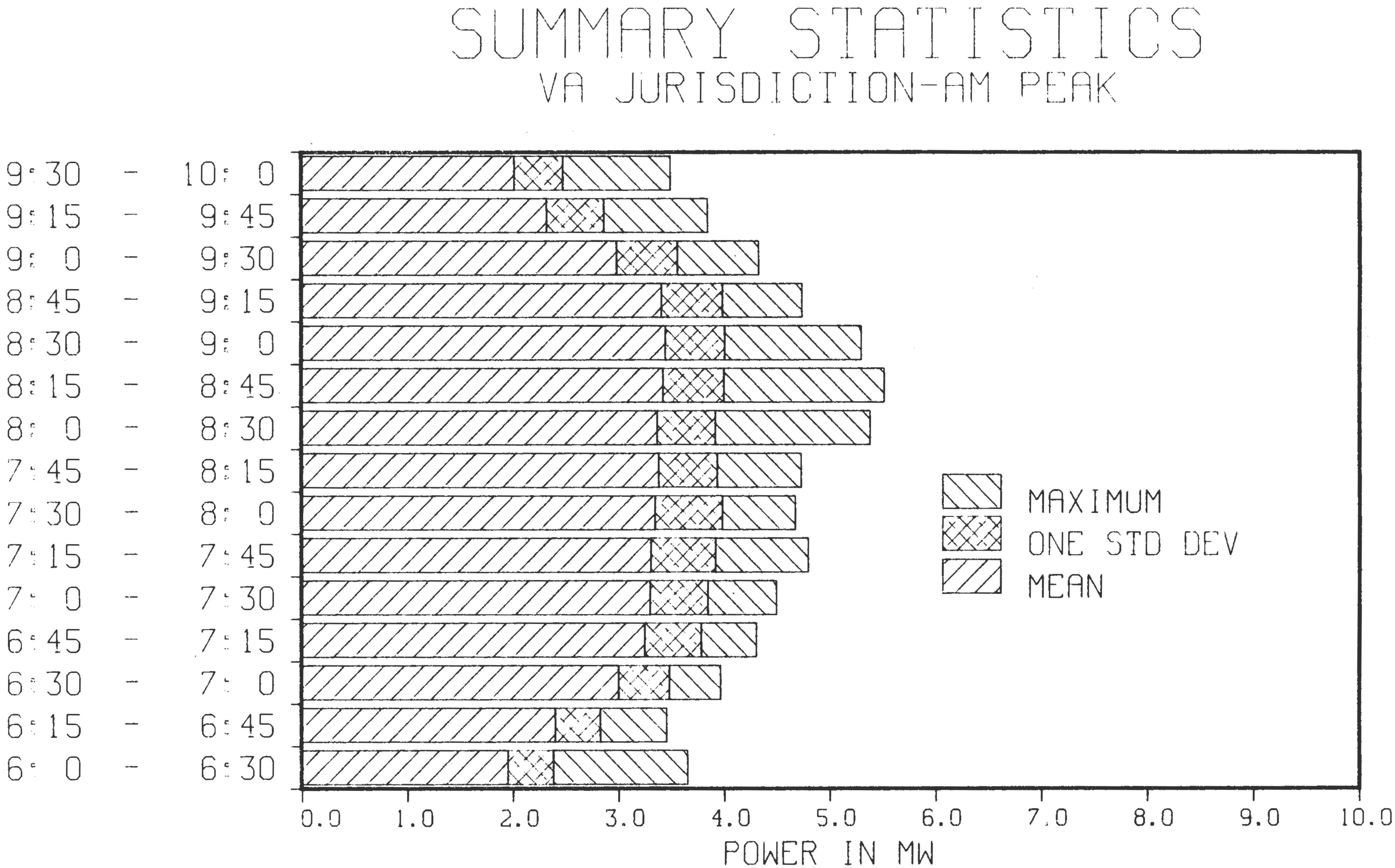

SUMMARY STATISTICS
VA JURISDICTION-AM PEAK
9:30 - 10: 0
9:15 - 9:45
9: 0 - 9:30
8:45 - 9:15
8:30 - 9: 0
8:15 - 8:45
8: 0 - 8:30
7:45 - 8:15
7:30 - 8: 0
7:15 - 7:45
7: 0 - 7:30
6:45 - 7:15
6:30 - 7: 0
6:15 - 6:45
6: 0 - 6:30
MAXIMUM
ONE STD DEV
MEAN
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
POWER IN MW

FIGURE 5-9

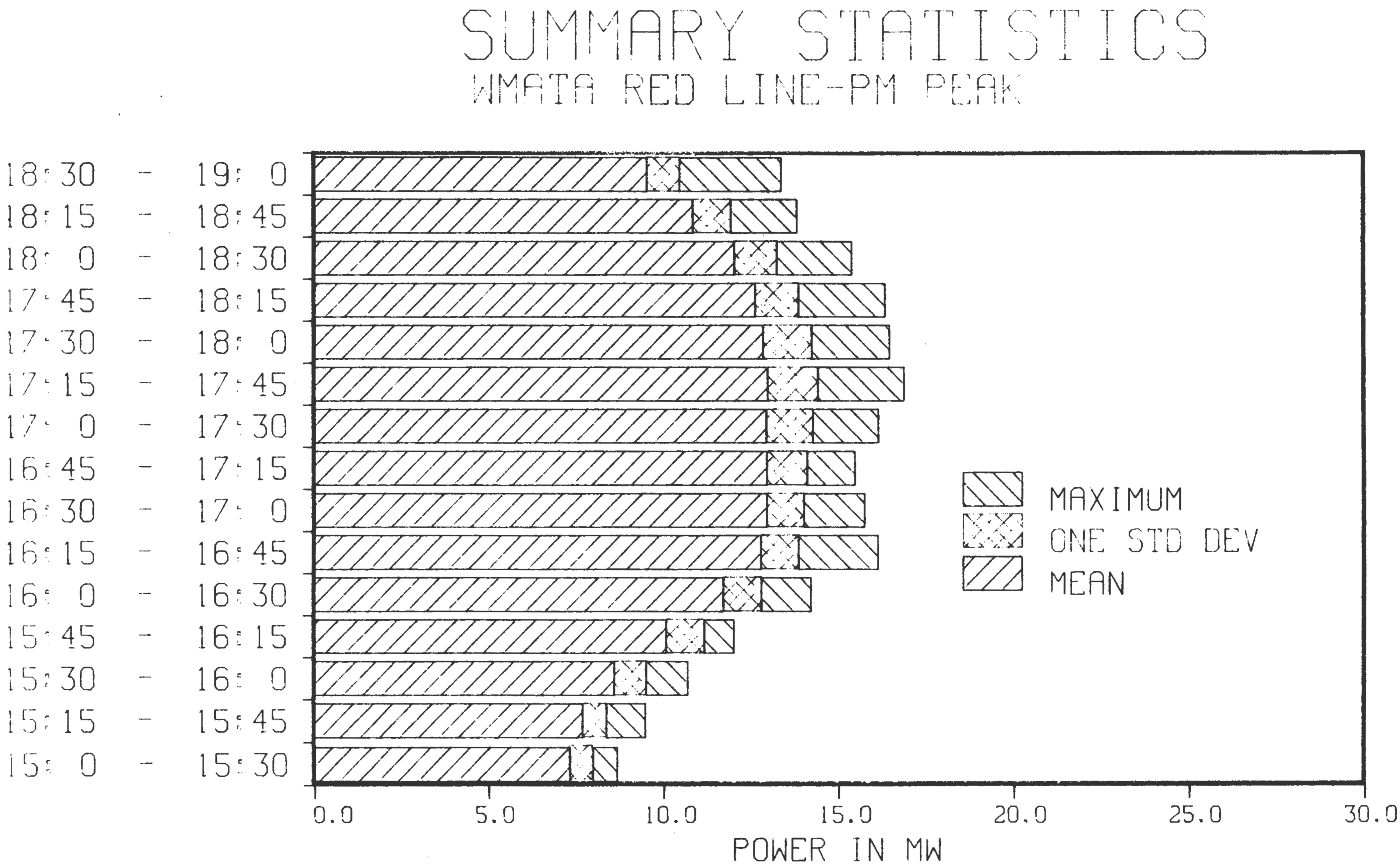

SUMMARY STATISTICS
WMATA RED LINE-PM PEAK
18:30 - 19: 0
18:15 - 18:45
18: 0 - 18:30
17:45 - 18:15
17:30 - 18: 0
17:15 - 17:45
17: 0 - 17:30
16:45 - 17:15
16:30 - 17: 0
16:15 - 16:45
16: 0 - 16:30
15:45 - 16:15
15:30 - 16: 0
15:15 - 15:45
15: 0 - 15:30
MAXIMUM
ONE STD DEV
MEAN
0.0
5.0
10.0
15.0
20.0
25.0
30.0
POWER IN MW

FIGURE 5-10

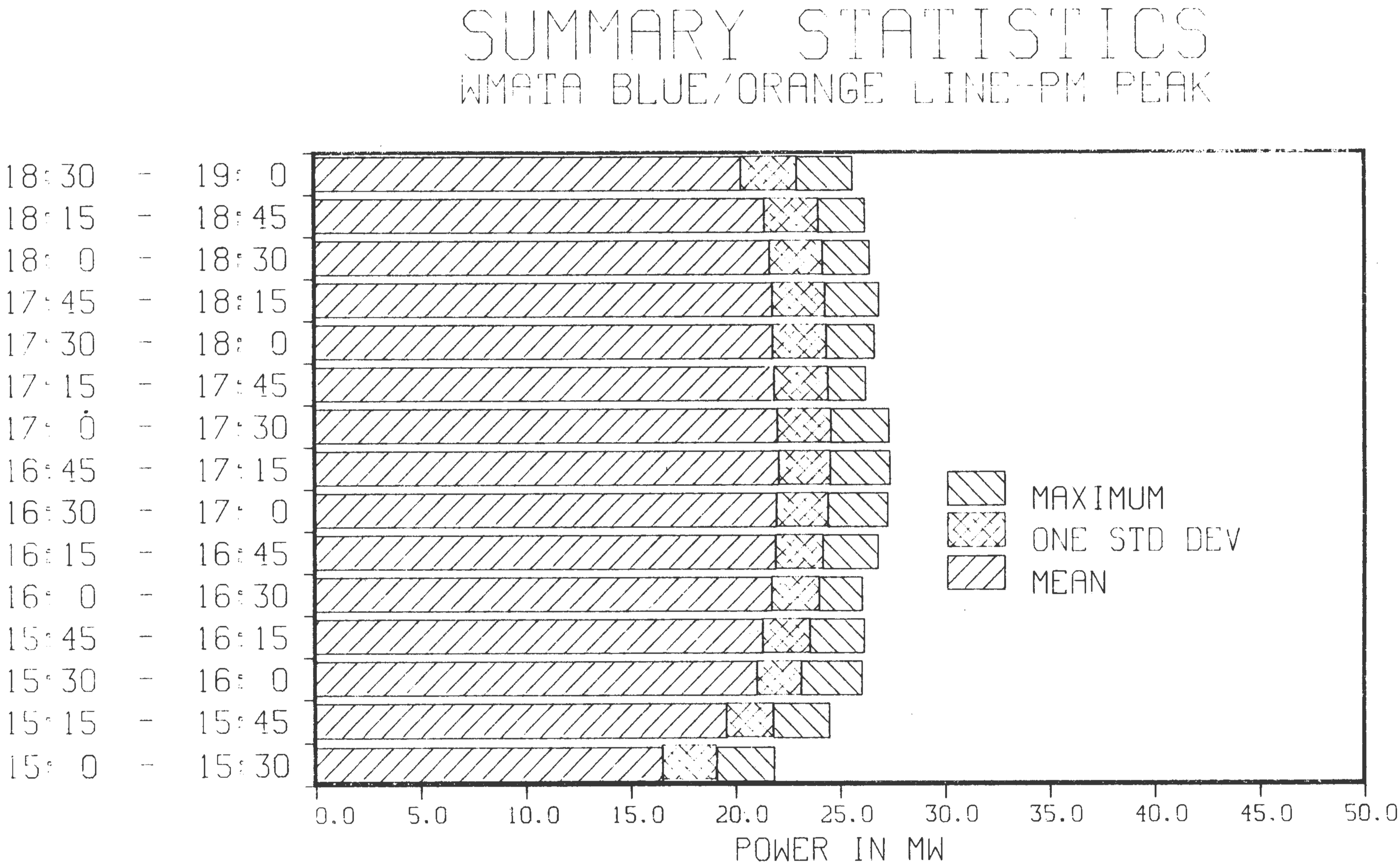

SUMMARY STATISTICS
WMATA BLUE/ORANGE LINE-PM PEAK
18:30 - 19: 0
18:15 - 18:45
18: 0 - 18:30
17:45 - 18:15
17:30 - 18: 0
17:15 - 17:45
17: 0 - 17:30
16:45 - 17:15
16:30 - 17: 0
16:15 - 16:45
16: 0 - 16:30
15:45 - 16:15
15:30 - 16: 0
15:15 - 15:45
15: 0 - 15:30
MAXIMUM
ONE STD DEV
MEAN
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
POWER IN MW

FIGURE 5-11

SUMMARY STATISTICS

DC JURISDICTION-PM PEAK

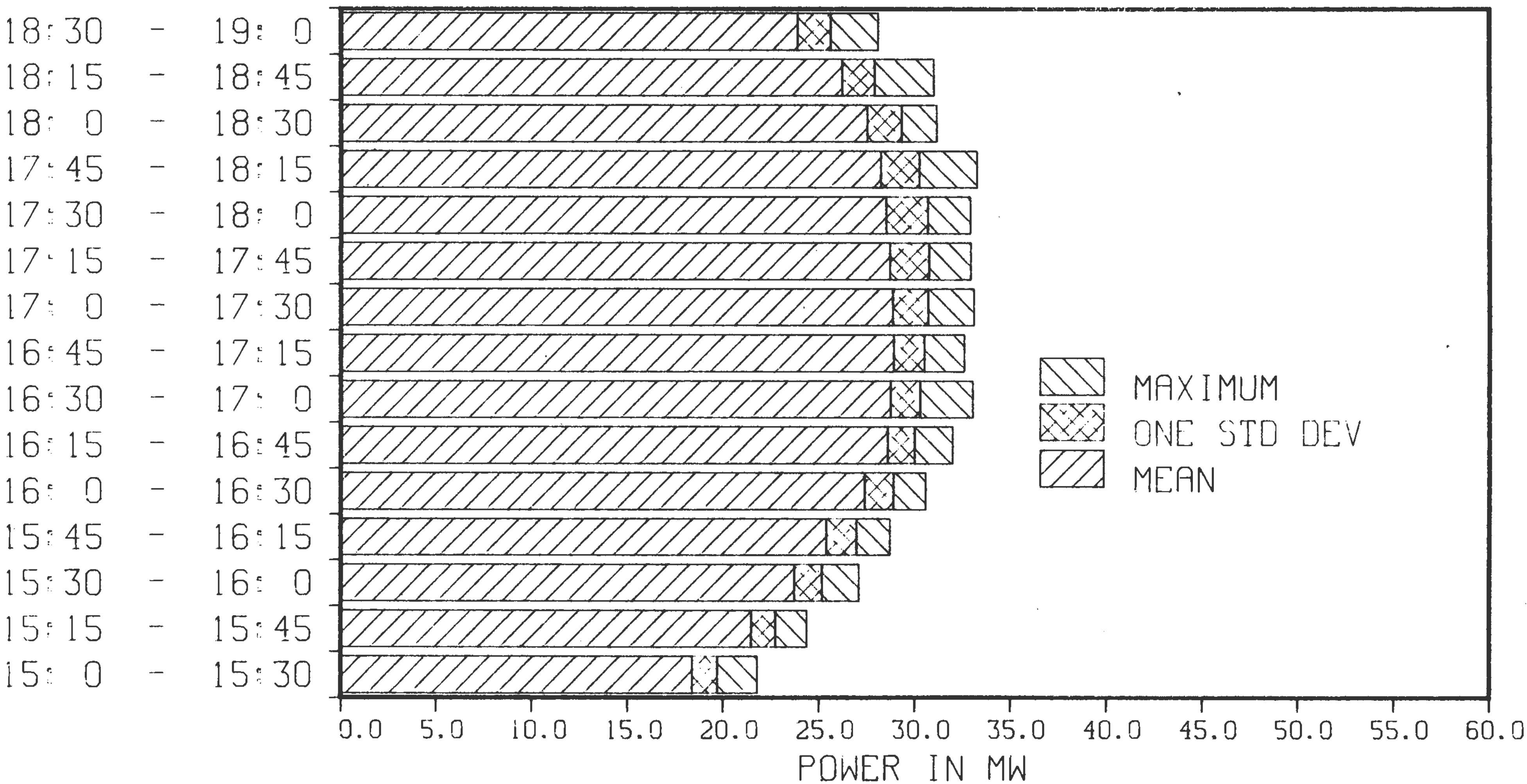
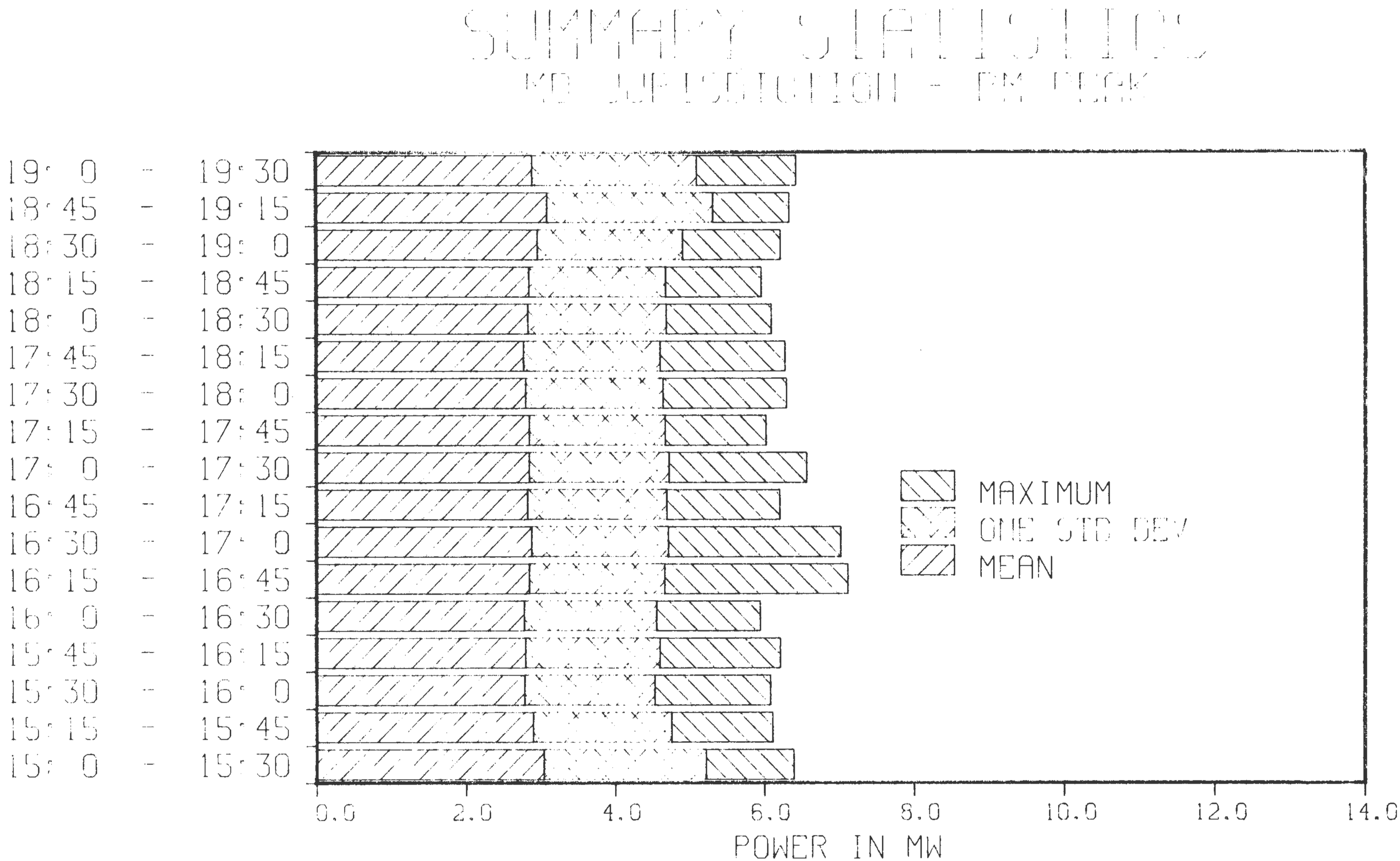


FIGURE 5-12



SUMMARY STATISTICS
MD JURISDICTION - PM PEAK
19: 0 - 19:30
18:45 - 19:15
18:30 - 19: 0
18:15 - 18:45
18: 0 - 18:30
17:45 - 18:15
17:30 - 18: 0
17:15 - 17:45
17: 0 - 17:30
16:45 - 17:15
16:30 - 17: 0
16:15 - 16:45
16: 0 - 16:30
15:45 - 16:15
15:30 - 16: 0
15:15 - 15:45
15: 0 - 15:30
MAXIMUM
ONE STD DEV
MEAN
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
POWER IN MW

FIGURE 5-13

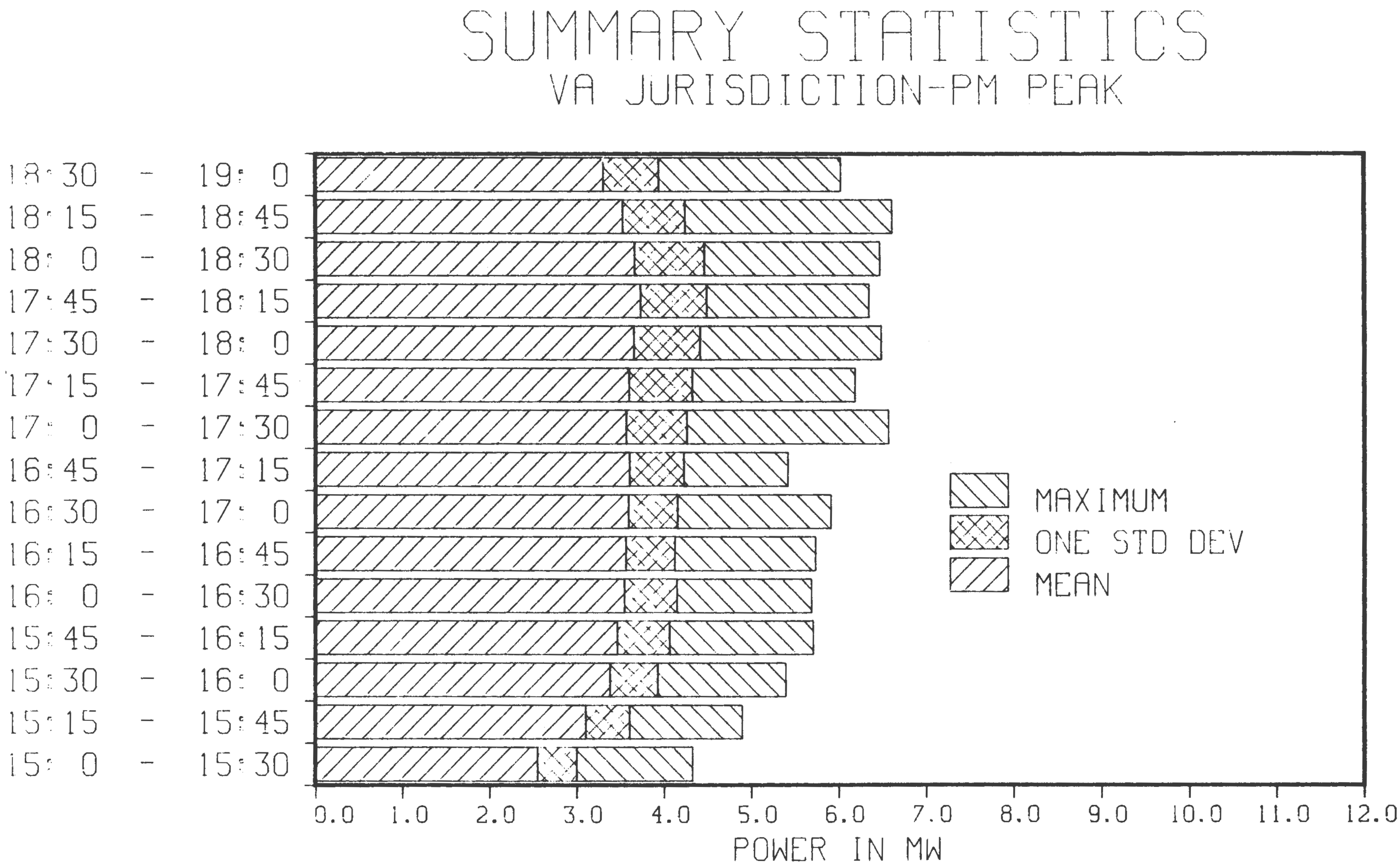

SUMMARY STATISTICS
VA JURISDICTION-PM PEAK
18:30 - 19: 0
18:15 - 18:45
18: 0 - 18:30
17:45 - 18:15
17:30 - 18: 0
17:15 - 17:45
17: 0 - 17:30
16:45 - 17:15
16:30 - 17: 0
16:15 - 16:45
16: 0 - 16:30
15:45 - 16:15
15:30 - 16: 0
15:15 - 15:45
15: 0 - 15:30
MAXIMUM
ONE STD DEV
MEAN
0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0
POWER IN MW

FIGURE 5-14

TABLE 5-7 COMPARISON OF MAXIMUM POWER DEMAND TO AVERAGE FOR SEVERAL TRACTION ENERGY METER CONSOLIDATIONS

	AM PEAK		PM PEAK	
METER CONSOLIDATION	MAXIMUM DEMAND INTERVAL	$\frac{MAX-AVG}{AVG}$ (%)	MAXIMUM DEMAND INTERVAL	$\frac{MAX-AVG}{AVG}$ (%)
Red Line	7:30-8:00	29	17:15-17:45	31
Blue/Orange Line	7:00-7:30	31	16:45-17:15	25
DC Jurisdiction	7:45-8:15	19	17:45-18:15	18
VA Jurisdiction	8:15-8:45	67	18:15-18:45	86

Note: The MD consolidation was not considered because of missing data from several of the MD meters.

It will be shown in Section 5.3.4 that the difference between maximum to average power demand can be attributed to catch-up operation.

5.2. SIMULATION FOR 1980 OPERATION

5.2.1. TPS Runs for Normal Operation

Using the 1980 timetable, the passenger load factors which were 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 AM peak, midday, PM peak, and evening periods on the Red, Blue and Orange Lines. The energy and running times are summarized in Table 5-8. The energy represents energy consumed at the line.

The principal variation among the energy consumption numbers of Table 5-8 can be explained as follows:

1. 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.

2. The average station spacing on the Blue/Orange Line is 0.7 miles, whereas the average spacing on the Red Line is 0.9 miles. Thus, the average energy consumption on the Red Line is less than that on the Blue/Orange Line on a car-mile basis.

3. 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 KWHPCM.) This difference does not exist on the Blue/Orange Line.

Appendix 9.5 contains the details of the TPS summaries of the runs which are summarized in Table 5-8.

Figures 5-15 through 5-20 show the power profiles for an empty six-car train running on the Red, Blue and Orange Lines in both directions. These power profiles were generated so that a profile of peak power regions could be identified.

5.2.2. ENS for Normal Operation

Using the electric distribution networks for the Red Line (Figure 4-21) and Blue/Orange Line (Figure 4-22) which were modified for 1980 operation (i.e., the section from D/G Junction to Addison Road was not included), and using Metro's 1980

TABLE 5-8 SUMMARY OF SIMULATED RUNNING TIME AND ENERGY CONSUMPTION FOR 1980 NORMAL OPERATION

	Red Line		Blue Line		Orange Line	
	Inbound	Outbound	Northbound	Southbound	Eastbound	Westbound
ENERGY CONSUMPTION (KWHPCM)						
AM Peak						
Six Car Train	5.48	6.60	7.17	7.08	6.63	6.80
Eight Car Train	5.48	6.58				
Midday						
Six Car Train	5.23	6.76	7.11	7.07	6.61	6.71
PM Peak						
Six Car Train	5.16	7.13	7.18	7.22	6.78	6.81
Eight Car Train	5.15	7.11				
Evening						
Six Car Train	5.10	6.73	6.94	6.93	6.51	6.60
Empty Six Car Train (No Dwell)	4.83	6.31	6.67	6.53	6.20	6.28
Crush Loaded Six Car Train (No Dwell)	6.37	8.54	8.59	8.53	7.95	8.22
RUNNING TIME (MINUTES)						
AM Peak						
Six Car Train	18.66	19.13	28.61	28.59	36.01	35.82
Eight Car Train	18.66	19.12				
Midday						
Six Car Train	18.63	19.13	28.61	28.59	36.01	35.81
PM Peak						
Six Car Train	18.65	19.15	28.61	28.59	36.02	35.81
Eight Car Train	18.65	19.14				
Evening						
Six Car Train	18.65	19.13	28.61	28.59	36.01	35.81
Empty Six Car Train (No Dwell)	14.39	14.87	21.44	21.42	27.71	27.51
Crush Loaded Six Car Train (No Dwell)	14.52	14.52	21.29	21.51	27.84	27.63

POWER PROFILE

RED-EMPTY 6 CAR TRAIN-INBOUND-PL2

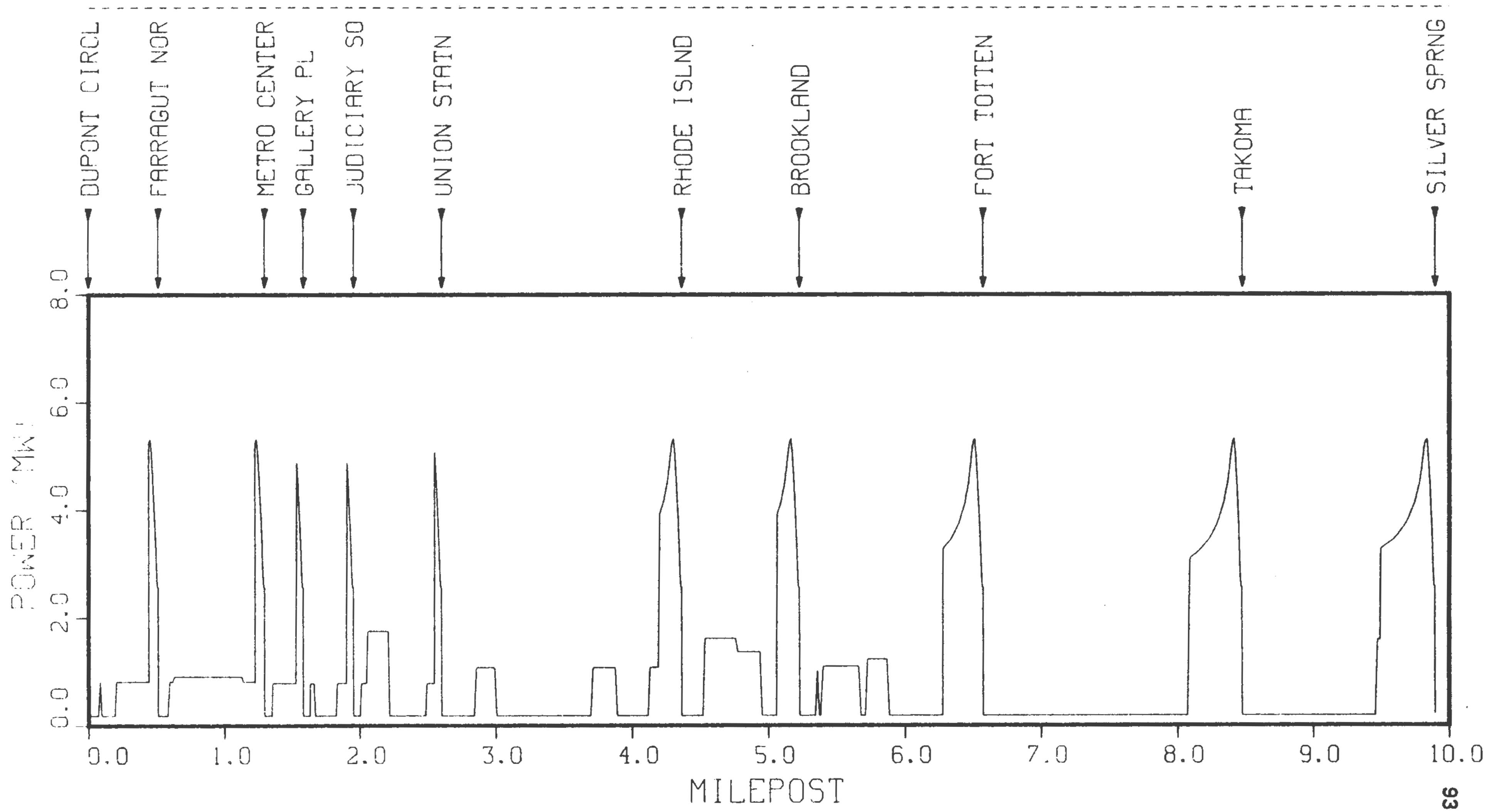


FIGURE 5-15

POWER PROFILE
RED-EMPTY 6 CAR TRAIN-OUTBOUND-PL2

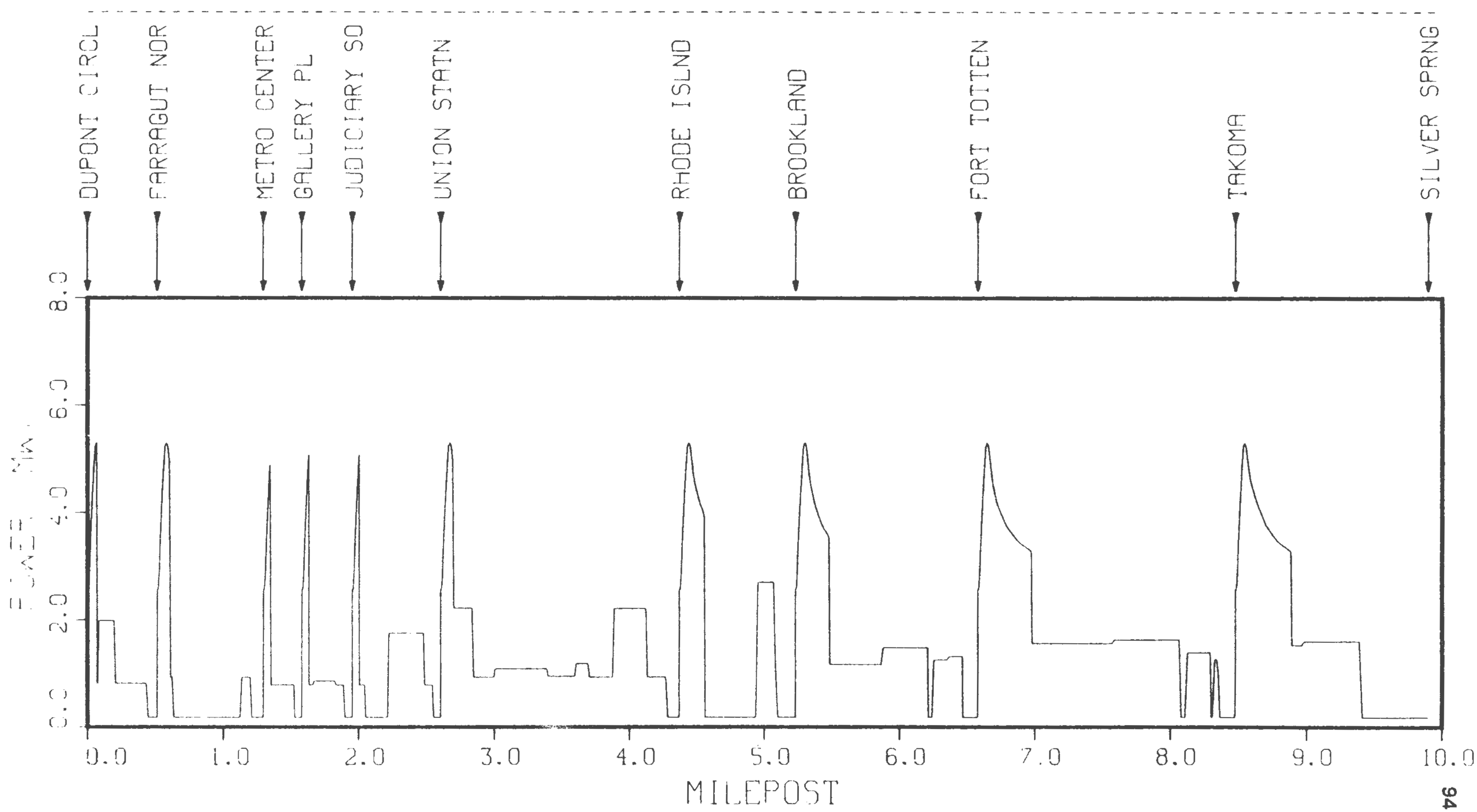


FIGURE 5-16

POWER PROFILE
ORANGE-EMPTY 6 CAR TRAIN-EASTBOUND-PL2

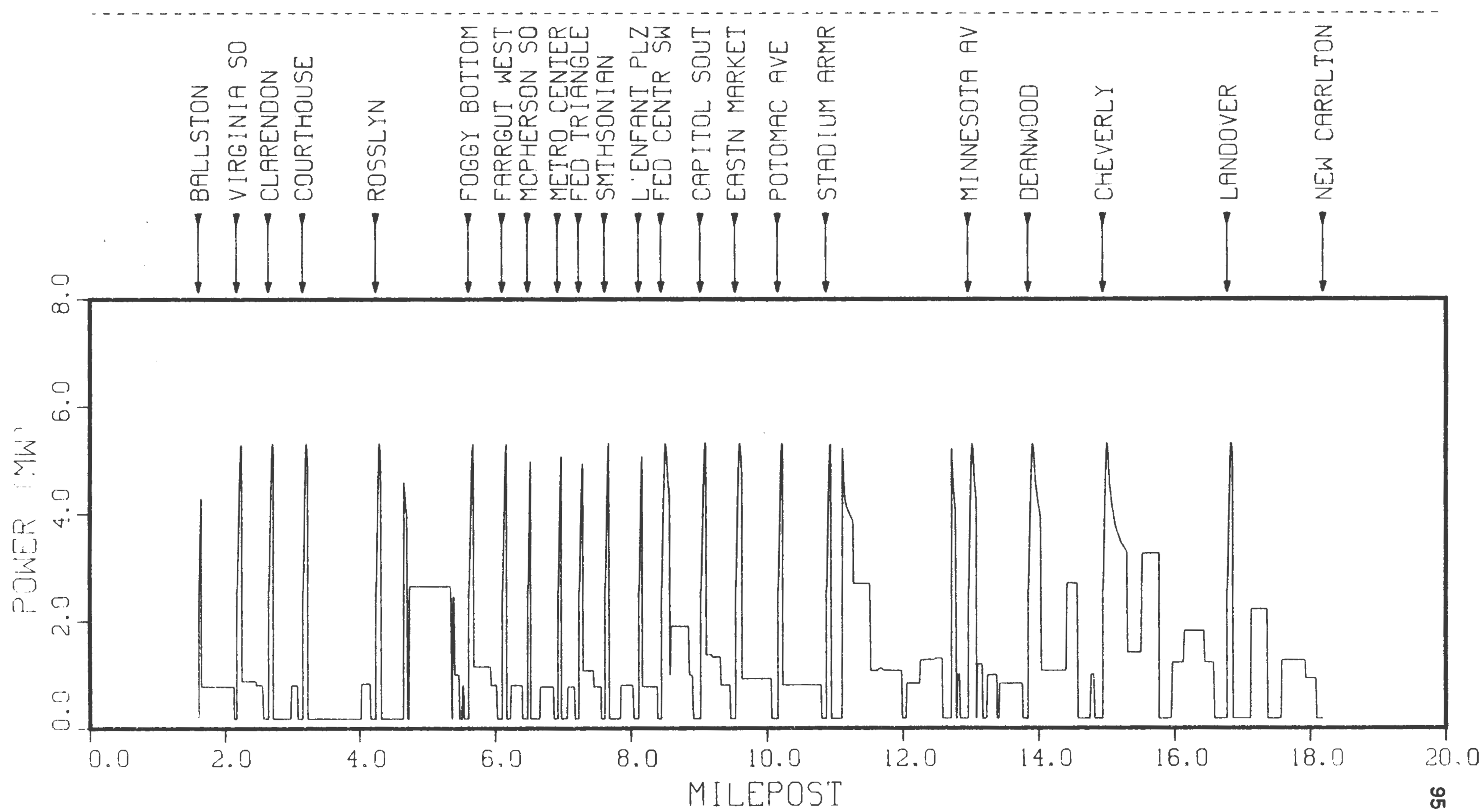


FIGURE 5-17

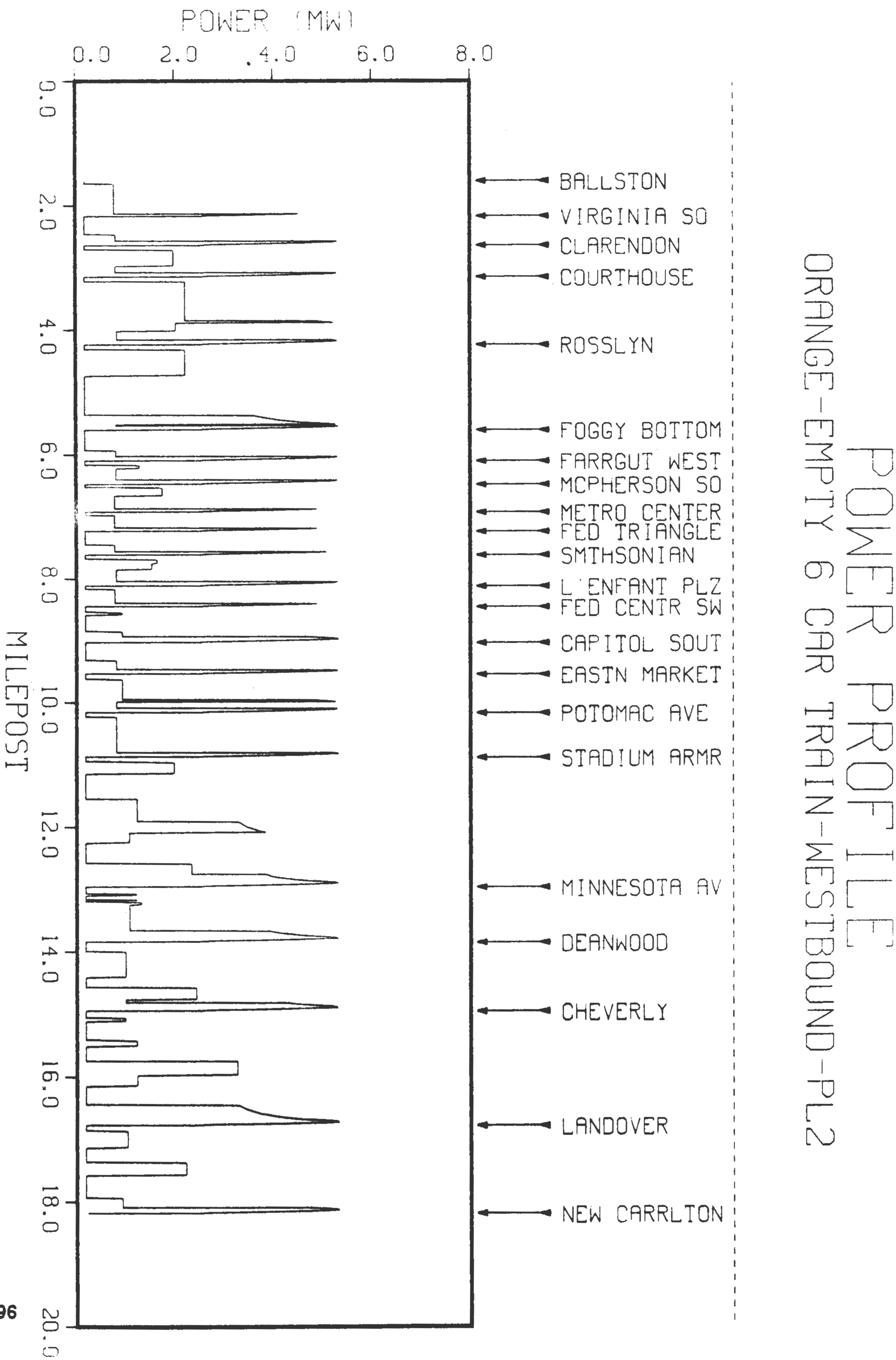
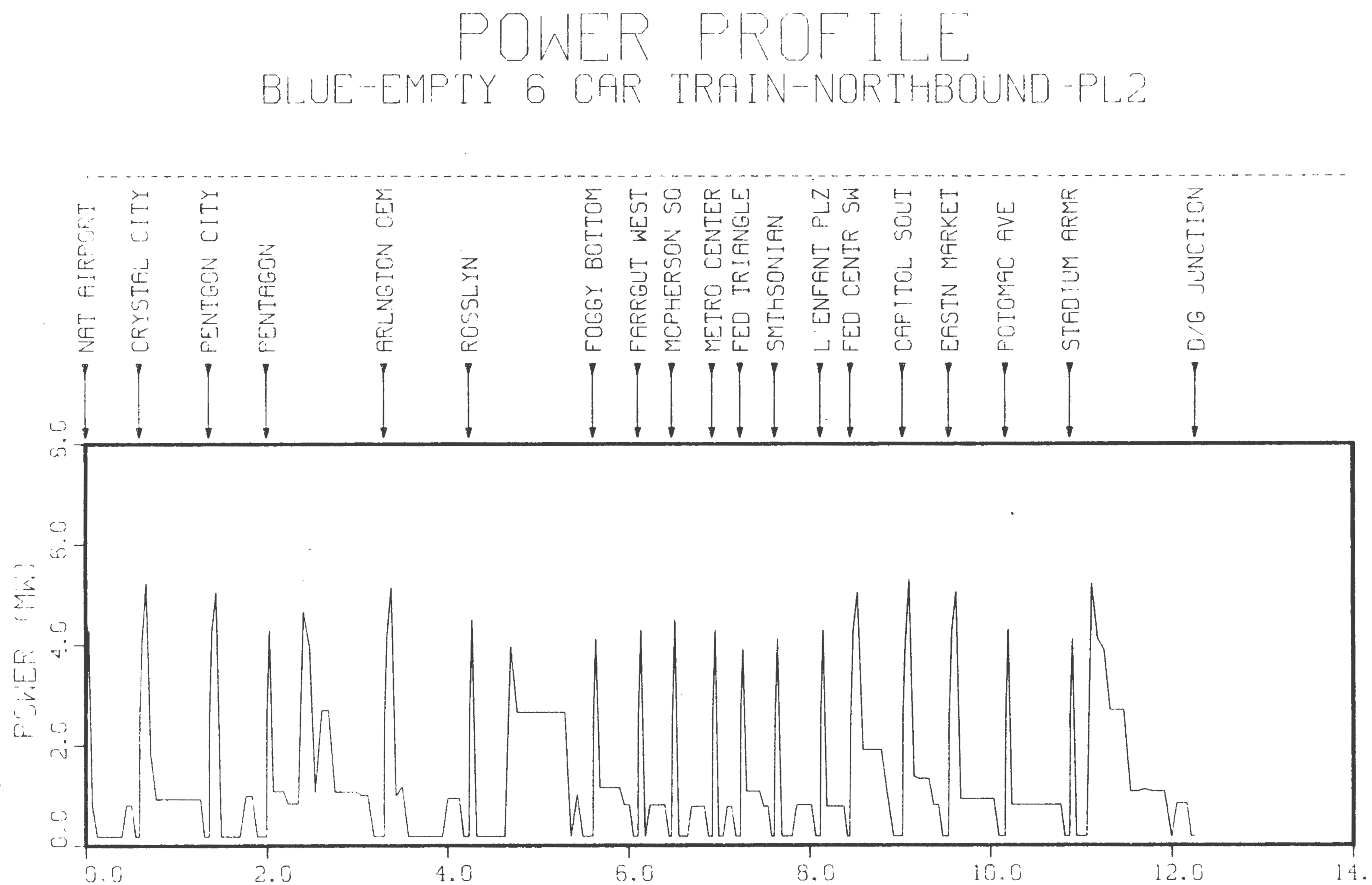

POWER PROFILE
ORANGE-EMPTY 6 CAR TRAIN-WESTBOUND-PL2
POWER (MW)
0.0
2.0
4.0
6.0
8.0
MILEPOST
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
BALLSTON
VIRGINIA SQ
CLARENDON
COURTHOUSE
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMTHSONIAN
L'ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
MINNESOTA AV
DEANWOOD
CHEVERLY
LANDOVER
NEW CARRLTON

FIGURE 5-18


POWER PROFILE
BLUE-EMPTY 6 CAR TRAIN-NORTHBOUND-PL2
NAT AIRPORT
CRYSTAL CITY
PENTGON CITY
PENTAGON
ARLNGTON CEM
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMITHSONIAN
L'ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
D/G JUNCTION
POWER (MW)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
MILEPOST
FIGURE 5-19

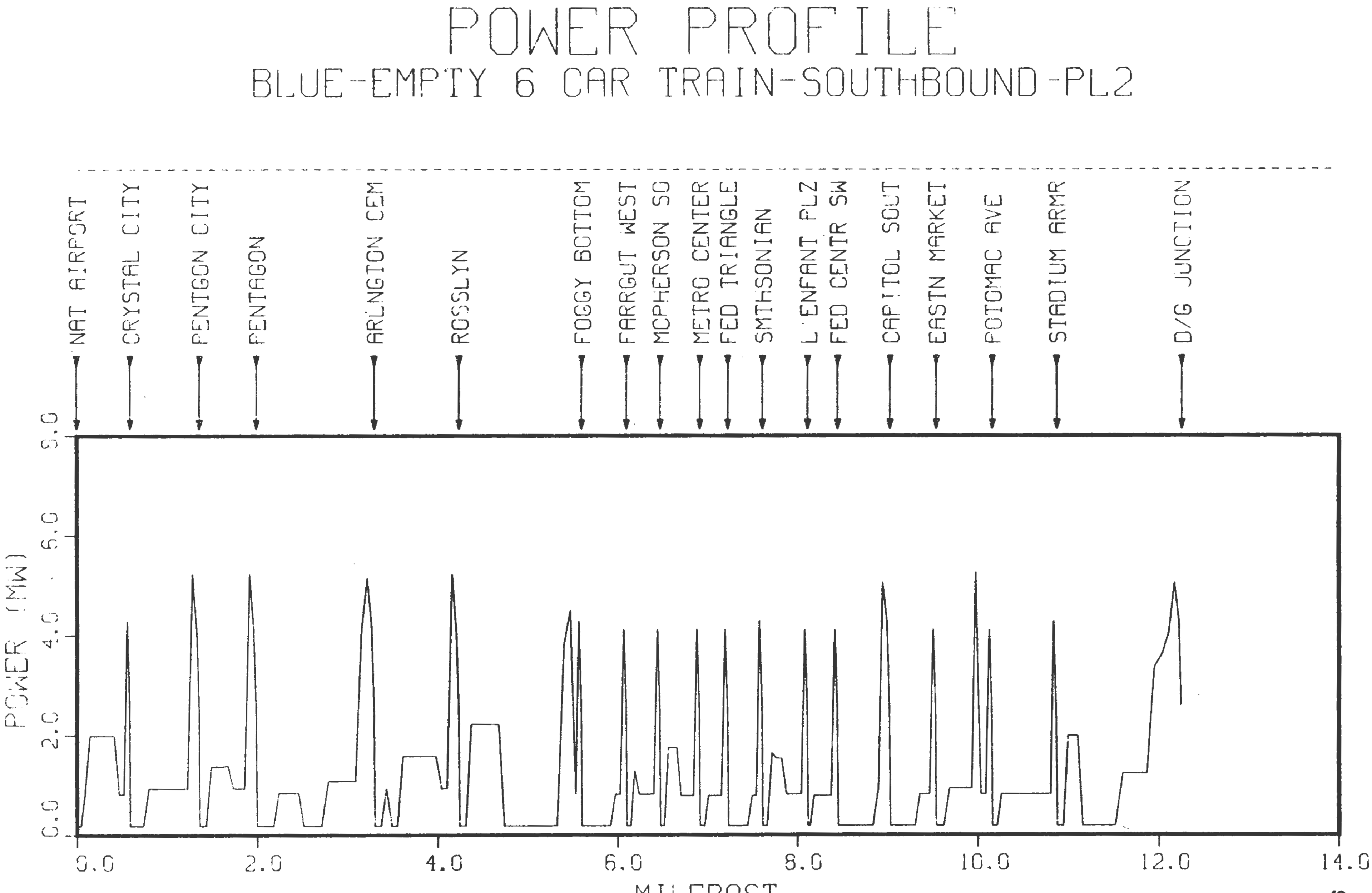

POWER PROFILE
BLUE-EMPTY 6 CAR TRAIN-SOUTHBOUND-PL2
NAT AIRPORT
CRYSTAL CITY
PENTGON CITY
PENTAGON
ARLNGTON CEM
ROSSLYN
FOGGY BOTTOM
FARRGUT WEST
MCPHERSON SQ
METRO CENTER
FED TRIANGLE
SMTHSONIAN
L'ENFANT PLZ
FED CENTR SW
CAPITOL SOUT
EASTN MARKET
POTOMAC AVE
STADIUM ARMR
D/G JUNCTION
POWER (MW)
0.0
2.0
4.0
6.0
8.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
MILEPOST

FIGURE 5-20

operational timetable, a summary of which is shown in Table 4-1, normal (average) operation was simulated using the ENS for four time periods on a weekday:

Simulation Time	To Represent
8:00 - 9:00A	AM Peak
10:00 -11:00A	Midday (Off-peak)
4:30 - 5:30P	PM Peak
8:00 - 9:00P	Evening (Off-peak)

Tables 5-9 and 5-10 contain the results of the ENS for the Red Line and Blue/Orange Line, respectively. These results do not include the background nor the effect of turnaround time at the terminals.

Table 5-11 presents the results of the ENS for PEPCO jurisdictions of DC, MD and VA. Again, these represent a consolidation of the traction energy meters without background and the power developed during turnaround time for the trains.

5.2.3. TPS Runs for Catch-up Operation

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

The energy and running times are summarized in Table 5-12. The energy represents energy consumed at the line. Appendix 9.5 contains the TPS summaries of the runs which are summarized in the table.

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 5-8, in order to ascertain the differences between PL1 and PL2 operation.

5.2.4. ENS Runs for Catch-up Operation

Tables 5-13 and 5-14 show the results of the ENS for catch-up (PL1) operation during the peak operating period for the Red Line, and Blue/Orange Line, respectively. Table 5-15 presents the results of the ENS for the PEPCO jurisdictions of DC, MD and VA for catch-up operation.

TABLE 5-9 RESULTS OF THE ENS FOR NORMAL OPERATION DURING 1980 FOR THE RED LINE*

METER NAME	AM PEAK	MIDDAY	PM PEAK	EVENING
	POWER (KW)			
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.

TABLE 5-10 RESULTS OF ENS FOR NORMAL OPERATION DURING 1980 FOR THE BLUE/ORANGE LINES*

	POWER (KW)			
METER NAME	AM PEAK	MIDDAY	PM PEAK	EVENING
VEPCO Traction Meter (MVP)	2787	1351	2836	1337
Shirley Highway (MC8)	635	316	646	310
Washington Boulevard (MC6)	870	422	865	420
Rosslyn (MC5)	1906	910	1952	924
Potomac (MC4)	1611	781	1586	768
Farragut North (MC3)	1721	850	1739	813
Metro Center (MC1)	1649	818	1672	778
Smithsonian (MD2)	1448	708	1460	684
Federal Center (MD4)	1578	772	1562	758
Seward Square (MD6)	1811	886	1838	881
Potomac Avenue (MD7)	1681	828	1692	825
Stadium Armory (MD8)	1479	733	1515	731
Minnesota Avenue (MD9)	1375	691	1394	687
Deanwood (MD10)	905	456	914	456
Cheverly (MD11)	979	494	1041	487
Landover (MD12)	838	419	849	415
Beaver Dam Creek (MD13)	617	309	606	309
New Carrollton Yard (MDY)	200	100	197	100
Coincident Blue/Orange	24089	11843	24364	11680
KWHPCM	6.97	6.85	7.05	6.75
Coincident Blue/Orange (Except MVP, MD11, MD12, MD13, MDY)	18668	9170	18835	9032
KWHPCM	5.40	5.31	5.45	5.23
Car - Miles	3458	1728	3457	1729

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

TABLE 5-11 RESULTS OF ENS FOR NORMAL OPERATION
DURING 1980 FOR
CONSOLIDATED TRACTION METER ENERGY UNDER THE PEPCO JURISDICTIONS*

	POWER (KW)			
PEPCO JURISDICTION	AM PEAK	MIDDAY	PM PEAK	EVENING
DC	25323	11695	25383	11488
MD	3108	1551	3237	1541
VA	3411	1647	3463	1654
TOTAL	31843	14893	32083	14683

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

TABLE 5-12 SUMMARY OF SIMULATED RUNNING TIME AND ENERGY CONSUMPTION FOR 1980 CATCH-UP OPERATION

	RED LINE		BLUE LINE		ORANGE LINE	
Energy Consumption (KWHPCM)	Inbound	Outbound	Northbound	Southbound	East	West
AM Peak						
Six Car Train	7.00	8.20	8.57	8.56	8.23	8.46
Eight Car Train	6.92	8.18				
PM Peak						
Six Car Train	6.61	8.84	8.63	8.69	8.40	8.44
Eight Car Train	6.53	8.81				
Empty Six Car Train (No Dwell)	6.25	7.85	7.95	7.94	7.77	7.87
Crush Loaded Six Car Train (No Dwell)	8.14	10.31	10.14	10.26	9.87	10.17
Running Time (Minutes)						
AM Peak						
Six Car Train	17.16	17.53	27.30	26.95	33.20	33.17
Eight Car Train	17.16	17.53				
PM Peak						
Six Car Train	17.14	17.61	27.29	26.97	33.23	33.17
Eight Car Train	17.14	17.61				
Empty Six Car Train (No Dwell)	12.88	13.27	19.86	19.76	24.88	24.83
Crush Loaded Six Car Train (No Dwell)	13.14	13.69	20.21	20.01	25.36	25.26

TABLE 5-13 RESULTS OF THE ENS FOR CATCH-UP OPERATION DURING 1980 FOR THE RED LINE*

METER NAME (SYMBOL)	POWER (KW) 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.

TABLE 5-14 RESULTS OF ENS FOR CATCH-UP OPERATION DURING 1980 FOR THE BLUE/ORANGE LINE*

METER NAME (SYMBOL)	POWER (KW) AM PEAK	PM PEAK
VEPCO Traction Meter (MVP)	3791	3792
Shirley Highway (MC8)	863	877
Washington Boulevard (MC6)	1251	1232
Rosslyn (MC5)	2224	2260
Potomac (MC4)	2015	2014
Farragut North (MC3)	2100	2113
Metro Center (MC1)	1905	1948
Smithsonian (MD2)	1837	1820
Federal Center (MD4)	2177	2219
Seward Square (MD6)	2517	2532
Potomac Avenue (MD7)	2165	2095
Stadium Armory (MD8)	1751	1714
Minnesota Avenue (MD9)	1600	1590
Deanwood (MD10)	1103	1135
Cheverly (MD11)	1129	1134
Landover (MD12)	961	989
Beaver Dam Creek (MD13)	837	829
New Carrollton Yard (MDY)	247	243
Coincident Blue/Orange	30472	30534
Car-Miles	3455	3456
KWHPCM	8.82	8.84

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

TABLE 5-15 RESULTS OF ENS FOR CATCH-UP DURING 1980 FOR CONSOLIDATED TRACTION METER ENERGY UNDER THE PEPCO JURISDICTION*

PEPCO JURISDICTION	POWER (KW) AM PEAK	POWER (KW) PM PEAK
DC	32048	32053
MD	3787	3877
VA	4338	4369
TOTAL	40173	40299

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

The results should be compared with normal operation shown in Tables 5-9 and 5-10.

5.3. VERIFICATION OF SIMULATION

The two areas in which the results of the EMM for normal operation can be compared to actual operation are running time and energy consumption.

5.3.1. 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.

Figures 5-21 through 5-23 show a comparison between simulated and actual running times between stations for the Red and Blue/Orange Lines, for both directions. The small dots indicate the results of observation. Both normal (PL2) and catch-up (PL1) operation simulation 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.

5.3.2. Verification of Energy Consumption

The EMM can only simulate the energy consumption which 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 5-16 lists the results of the estimate expressed in both KWHPCM and KW.

The results of the energy consumption for the Red Line are shown in Table 5-17. The average power (May 1-October 15, 1980) as metered by PEPCO, 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

RUNNING TIME COMPARISON
RED LINE

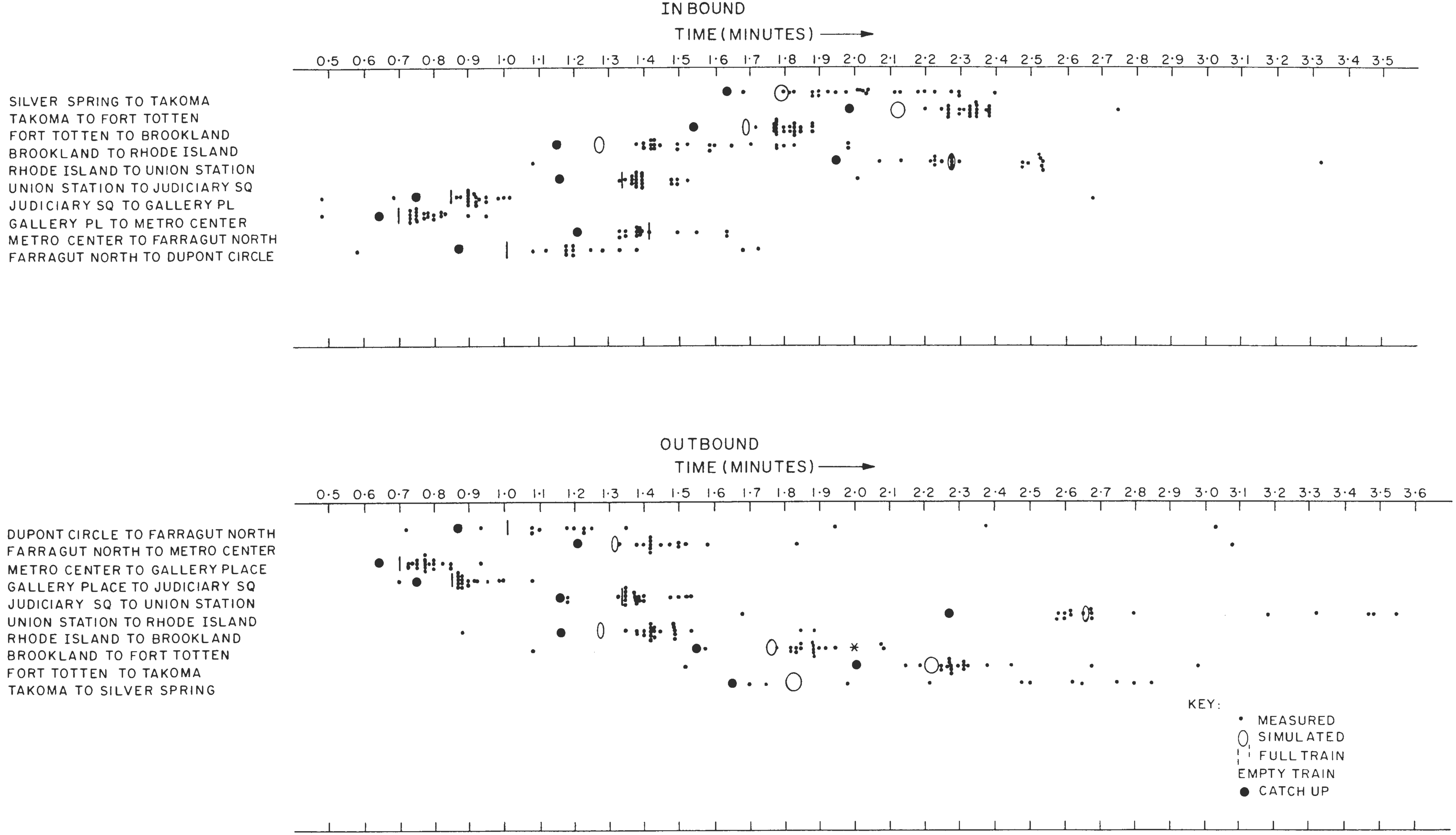


FIGURE 5-21

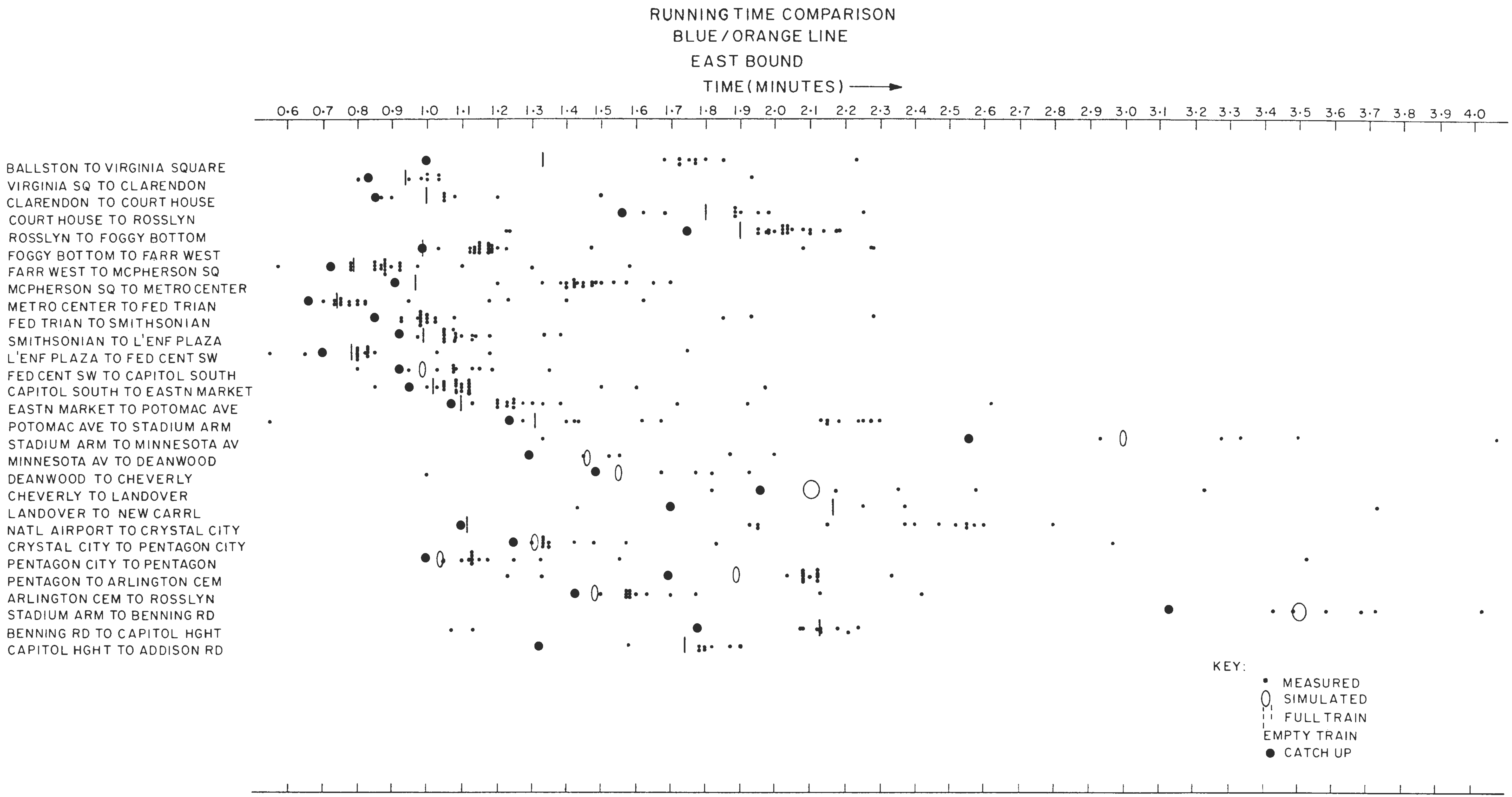

RUNNING TIME COMPARISON
BLUE / ORANGE LINE
EAST BOUND
TIME (MINUTES)
0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2 2.3 2.4 2.5 2.6 2.7 2.8 2.9 3.0 3.1 3.2 3.3 3.4 3.5 3.6 3.7 3.8 3.9 4.0
BALLSTON TO VIRGINIA SQUARE
VIRGINIA SQ TO CLARENDON
CLARENDON TO COURT HOUSE
COURT HOUSE TO ROSSLYN
ROSSLYN TO FOGGY BOTTOM
FOGGY BOTTOM TO FARR WEST
FARR WEST TO MCPHERSON SQ
MCPHERSON SQ TO METRO CENTER
METRO CENTER TO FED TRIAN
FED TRIAN TO SMITHSONIAN
SMITHSONIAN TO L'ENF PLAZA
L'ENF PLAZA TO FED CENT SW
FED CENT SW TO CAPITOL SOUTH
CAPITOL SOUTH TO EASTN MARKET
EASTN MARKET TO POTOMAC AVE
POTOMAC AVE TO STADIUM ARM
STADIUM ARM TO MINNESOTA AV
MINNESOTA AV TO DEANWOOD
DEANWOOD TO CHEVERLY
CHEVERLY TO LANDOVER
LANDOVER TO NEW CARRL
NATL AIRPORT TO CRYSTAL CITY
CRYSTAL CITY TO PENTAGON CITY
PENTAGON CITY TO PENTAGON
PENTAGON TO ARLINGTON CEM
ARLINGTON CEM TO ROSSLYN
STADIUM ARM TO BENNING RD
BENNING RD TO CAPITOL HGHT
CAPITOL HGHT TO ADDISON RD
KEY:
MEASURED
SIMULATED
FULL TRAIN
EMPTY TRAIN
CATCH UP

FIGURE 5-22

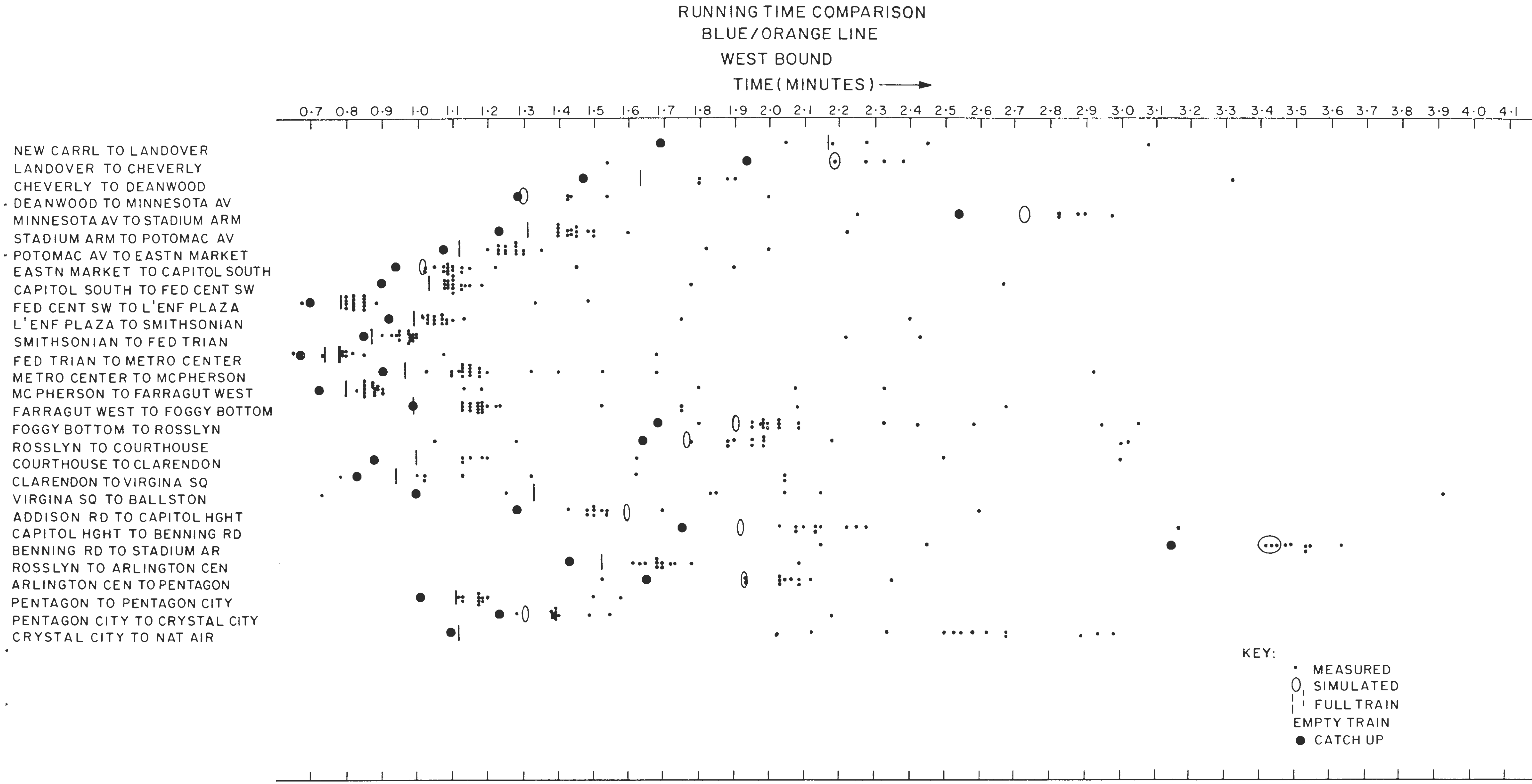

RUNNING TIME COMPARISON
BLUE/ORANGE LINE
WEST BOUND
TIME (MINUTES)
0·7 0·8 0·9 1·0 1·1 1·2 1·3 1·4 1·5 1·6 1·7 1·8 1·9 2·0 2·1 2·2 2·3 2·4 2·5 2·6 2·7 2·8 2·9 3·0 3·1 3·2 3·3 3·4 3·5 3·6 3·7 3·8 3·9 4·0 4·1
NEW CARRL TO LANDOVER
LANDOVER TO CHEVERLY
CHEVERLY TO DEANWOOD
DEANWOOD TO MINNESOTA AV
MINNESOTA AV TO STADIUM ARM
STADIUM ARM TO POTOMAC AV
POTOMAC AV TO EASTN MARKET
EASTN MARKET TO CAPITOL SOUTH
CAPITOL SOUTH TO FED CENT SW
FED CENT SW TO L'ENF PLAZA
L'ENF PLAZA TO SMITHSONIAN
SMITHSONIAN TO FED TRIAN
FED TRIAN TO METRO CENTER
METRO CENTER TO MCPHERSON
MC PHERSON TO FARRAGUT WEST
FARRAGUT WEST TO FOGGY BOTTOM
FOGGY BOTTOM TO ROSSLYN
ROSSLYN TO COURTHOUSE
COURTHOUSE TO CLARENDON
CLARENDON TO VIRGINA SQ
VIRGINA SQ TO BALLSTON
ADDISON RD TO CAPITOL HGHT
CAPITOL HGHT TO BENNING RD
BENNING RD TO STADIUM AR
ROSSLYN TO ARLINGTON CEN
ARLINGTON CEN TO PENTAGON
PENTAGON TO PENTAGON CITY
PENTAGON CITY TO CRYSTAL CITY
CRYSTAL CITY TO NAT AIR
KEY:
MEASURED
SIMULATED
FULL TRAIN
EMPTY TRAIN
CATCH UP

FIGURE 5-23

TABLE 5-16 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: $\frac{30\text{ KW} \times (\text{turnaround time})}{60 \times (\text{car-miles/hr})} \times (\text{trains/hr}) \times (\text{cars/train})$

coincident basis are within 3% of the observed average power for all four operating periods. The power through the individual meters is very sensitive to the voltage at the individual meter and adjacent meters. Since no measurements of these voltages were available, this dependence could not be tested.

The results of the energy consumption for part of the Blue/Orange Line are shown in Table 5-18. Because of the problems with missing data on PEPCO meters at Cheverly (MD10), Landover (MD11), Beaver Dam Creek (MD12), and at New Carrollton (MDY) Substation meters, these were not included in this table. Again, the average power, as metered by PEPCO, is shown for comparison. The same conclusion is valid for this portion of the results of the Blue/Orange Line as is for those of the Red Line. On an individual meter basis, agreement is not good, but on a consolidated basis, agreement with observed average power is within 3%. It is suspected that line voltage differences at the meters are responsible for the lack of agreement on an individual meter basis. No data were available from Metro to verify this hypothesis, however, ENS sums show that the power delivered through a given meter is extremely sensitive to the line voltage at the meter.

5.3.3. Power Estimation for Present Operation

Table 5-19 presents a breakdown of background power and the KWHPCM associated with each PEPCO traction energy meter based on the simulated results. The meters are shown by line and by jurisdiction. The background was estimated at the average temperature of 67.3°F over the period analyzed.

A formula can be developed for traction meter consolidations for both power demand and energy estimates. It has the form:

$$P = P_0 + E_R(RCM/T) + E_B(BCM/T) + E_0(OCM/T)$$

where P_0 is the consolidated background power (different for peak, off-peak and non-revenue operation). The quantities RCM, BCM, and OCM represent Red, Blue and Orange Line car-miles, respectively. The quantity T is the time interval, and the coefficients E_R , E_B , and E_0 are the KWHPRCM, KWHPBCM, and KWHPOCM, respectively. These latter coefficients will vary according to performance level. There is also a slight variation due to passenger load factor differences. These variations were found to be so small that they can be discounted.

TABLE 5-17 VERIFICATION OF TRACTION METER POWER (KW) DURING NORMAL OPERATION ON RED LINE

METER NAME (SYMBOL)	AM PEAK		MIDDAY	
	PEPCO	SIM*	PEPCO	SIM*
Farragut North (MA1)	1759	1438	832	659
Gallery Place (MB1)	1585	1470	757	681
Union Station (MB2)	1116	1397	590	663
New York Avenue (MB3)	1149	753	735	512
Rhode Island Avenue (MB4)	1160	1686	534	744
Brookland Avenue (MB5)	1764	1828	922	902
New Hampshire Avenue (MB6)	970	1425	639	730
Takoma Park (MB7)	1267	1552	614	726
Silver Spring (MB8)	1241	846	854	721
Coincident Red	12011	12395 (3%)	6476	6338 (2%)

	PM PEAK		EVENING	
	PEPCO	SIM*	PEPCO	SIM*
Farragut North (MA1)	1836	1414	819	647
Gallery Place (MB1)	1663	1388	713	656
Union Station (MB2)	1283	1394	557	650
New York Avenue (MB3)	1338	778	784	511
Rhode Island Avenue (MB4)	1259	1752	505	735
Brookland Avenue (MB5)	1827	1762	926	898
New Hampshire Avenue (MB6)	1086	1412	568	731
Takoma Park (MB7)	1277	1596	593	726
Silver Spring (MB8)	1278	916	854	722
Coincident Red	12847	12412 (3%)	6318	6276 (1%)

*Includes background, ENS result and turnaround of:

	AM PEAK	MIDDAY	PM PEAK	EVENING
Silver Spring	164	164	164	164
Farragut North	280	121	280	121

TABLE 5-18 VERIFICATION OF TRACTION METER POWER (KW) DURING NORMAL OPERATION ON BLUE/ORANGE LINES

METER NAME (SYMBOL)	AM PEAK		MIDDAY	
	PEPCO	SIM*	PEPCO	SIM*
Shirley Highway (MC8)	563	798	379	479
Washington Boulevard (MC6)	1009	960	565	512
Rosslyn (MC5)	1739	2090	912	1094
Potomac (MC4)	1705	1711	918	881
Farragut West (MC3)	1986	1775	1017	904
Metro Center (MC1)	1962	1680	1030	849
Smithsonian (MD2)	1800	1484	972	744
Federal Center (MD4)	1248	1600	640	794
Seward Square (MD6)	2143	1852	1177	927
Potomac Avenue (MD7)	1006	1733	537	880
Stadium Armory (MD8)	2031	1556	1147	810
Minnesota Avenue (MD9)	1036	1534	615	806
Deanwood (MD10)	1023	1118	591	669
Coincident	19248	19891 (3%)	10501	10349 (1%)

	PM PEAK		EVENING	
	PEPCO	SIM*	PEPCO	SIM*
Shirley Highway (MC8)	615	809	461	473
Washington Boulevard (MC6)	1055	955	572	510
Rosslyn (MC5)	1841	2136	887	1108
Potomac (MC4)	1741	1686	949	868
Farragut West (MC3)	2123	1793	967	867
Metro Center (MC1)	2016	1703	992	809
Smithsonian (MD2)	1832	1496	946	720
Federal Center (MD4)	1449	1584	657	780
Seward Square (MD6)	2179	1879	1144	922
Potomac Avenue (MD7)	1138	1744	537	877
Stadium Armory (MD8)	2079	1592	1142	808
Minnesota Avenue (MD9)	1162	1553	609	802
Deanwood (MD10)	1076	1127	609	669
Coincident	20304	20057 (1%)	10470	10213 (3%)

*Includes background, ENS result plus turnaround power of 88 and 44 KW at Minnesota Avenue for peak and off-peak operation, respectively.

TABLE 5-19 BACKGROUND POWER AND KWHPCM PREDICTED BY EMM FOR EACH TRACTION ENERGY METER FOR NORMAL OPERATION

				Background (KW) @Avg. Temp.*			KWHPCM**				KWHPCM**											
											AM PEAK			MIDDAY			PM PEAK			EVENING		
METER NAME	(SYMBOL)	LINE	JURIS-DICTION	PEAK	OFF-PEAK	NON-REVENUE	AM PEAK	MIDDAY	PM PEAK	EVENING	R	B	O	R	B	O	R	B	O	R	B	O
Farragut North	(MA1)	R	DC	88	88	88	0.82	0.80	0.81	0.79	0.82**	-	-	0.80**	-	-	0.81**	-	-	0.79**	-	-
Gallery Place	(MB1)	R	DC	98	98	98	0.83	0.82	0.78	0.78	0.83	-	-	0.82	-	-	0.78	-	-	0.78	-	-
Union Station	(MB2)	R	DC	133	133	133	0.77	0.75	0.77	0.73	0.77	-	-	0.75	-	-	0.77	-	-	0.73	-	-
New York Avenue	(MB3)	R	DC	121	201	321	0.38	0.38	0.40	0.38	0.38	-	-	0.38	-	-	0.40	-	-	0.38	-	-
Rhode Island Avenue	(MB4)	R	DC	84	84	84	0.97	0.93	1.01	0.92	0.97	-	-	0.93	-	-	1.01	-	-	0.92	-	-
Brookland Avenue	(MB5)	R	DC	306	306	306	0.93	0.84	0.89	0.83	0.93	-	-	0.84	-	-	0.89	-	-	0.83	-	-
New Hampshire Avenue	(MB6)	R	DC	250	250	250	0.71	0.68	0.71	0.68	0.71	-	-	0.68	-	-	0.71	-	-	0.68	-	-
Takoma Park	(MB7)	R	DC	124	124	124	0.87	0.85	0.90	0.85	0.87	-	-	0.85	-	-	0.90	-	-	0.85	-	-
Silver Spring	(MB8)	R	MD	208	328	388	0.39	0.55	0.43	0.55	0.39**	-	-	0.55**	-	-	0.43**	-	-	0.55**	-	-
Shirley Highway	(MC8)	B	VA	163	163	163	0.43	0.43	0.44	0.42	-	0.43	-	-	0.43	-	-	0.44	-	-	0.42	-
Washington Boulevard	(MC6)	B	VA	90	90	90	0.59	0.57	0.59	0.57	-	0.59	-	-	0.57	-	-	0.59	-	-	0.57	-
Rosslyn	(MC5)	BO	VA	184	184	184	0.55	0.53	0.56	0.53	-	0.69	0.44	-	0.67	0.43	-	0.71	0.45	-	0.67	0.43
Potomac	(MC4)	BO	DC	100	100	100	0.47	0.45	0.46	0.44	-	0.55	0.41	-	0.53	0.39	-	0.54	0.40	-	0.51	0.39
Farragut West	(MC3)	BO	DC	54	54	54	0.50	0.49	0.50	0.47	-	0.58	0.44	-	0.57	0.43	-	0.58	0.44	-	0.55	0.41
Metro Center	(MC1)	BO	DC	31	31	31	0.48	0.47	0.48	0.45	-	0.56	0.42	-	0.55	0.41	-	0.56	0.42	-	0.53	0.39
Smithsonian	(MD2)	BO	DC	36	36	36	0.42	0.41	0.42	0.40	-	0.49	0.37	-	0.48	0.36	-	0.49	0.37	-	0.47	0.35
Federal Center	(MD4)	BO	DC	22	22	22	0.46	0.45	0.45	0.44	-	0.54	0.40	-	0.53	0.39	-	0.53	0.39	-	0.51	0.39
Seward Square	(MD6)	BO	DC	41	41	41	0.52	0.51	0.53	0.51	-	0.61	0.46	-	0.60	0.45	-	0.62	0.46	-	0.60	0.45
Potomac Avenue	(MD7)	BO	DC	52	52	52	0.49	0.48	0.49	0.48	-	0.57	0.43	-	0.56	0.42	-	0.57	0.43	-	0.56	0.42
Stadium Armory	(MD8)	BO	DC	77	77	77	0.43	0.42	0.44	0.42	-	0.50	0.38	-	0.49	0.37	-	0.51	0.39	-	0.49	0.37
Minnesota Avenue	(MD9)	BO	DC	71	71	71	0.40	0.40	0.40	0.40**	-	0.26**	0.55	-	0.26**	0.55	-	0.26**	0.55	-	0.26**	0.55
Deanwood	(MD10)	O	DC	213	213	213	0.45	0.46	0.46	0.46	-	-	0.45	-	-	0.46	-	-	0.46	-	-	0.46
Cheverly	(MD11)	O	MD	140	140	140	0.49	0.50	0.52	0.49	-	-	0.49	-	-	0.50	-	-	0.52	-	-	0.49
Landover	(MD12)	O	MD	287	287	287	0.42	0.42	0.43	0.42	-	-	0.42	-	-	0.42	-	-	0.43	-	-	0.42
Beaver Dam Creek	(MD13)	O	MD	266	266	266	0.31	0.31	0.30	0.31	-	-	0.31	-	-	0.31	-	-	0.30	-	-	0.31
New Carrollton Yard	(MDY)	O	MD	329	599	929	0.14	0.15	0.15	0.15	-	-	0.14**	-	-	0.15**	-	-	0.15**	-	-	0.15**

*Includes Car Layup Power (KW):
@5KW/car

Meter Name (Symbol)	Off-Peak	Non-Revenue
New York Avenue (MB3)	80	200
Silver Spring (MB8)	120	180
New Carrollton (MDY)	270	600

**Includes On-board Auxiliaries During Turnaround:

	KWHPCM	
Meter Name (Symbol)	Peak	Off-Peak
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Ave. (MD9)	0.06	0.06
New Carrollton (MDY)	0.04	0.04

Table 5-20 lists the values of the background, and the KWHPCM coefficients for normal operation (PL2) for six different traction energy meter consolidations. These consolidations are all Red Line meters, all PEPCO Blue/Orange Line meters, PEPCO jurisdictions of DC, MD and VA, and the VEPCO meter. The background of the VEPCO meter is increased during non-peak periods because of the storage of twenty-four cars at National Airport and Ballston, and during non-revenue periods by the berthing of sixty cars at the same locations.

Table 5-21 shows a comparison of the results obtained for PEPCO metering consolidations using the average power formula whose coefficients are given in Table 5-20.

With the exception of the MD and VA jurisdictions, the simulated average power is within 6% of the observed values. In the case of the VA and MD jurisdictions, the number of meters is small (three for VA and five for MD). Thus, the previously mentioned line voltage variation between meters can easily be responsible for the large deviation of the coincident meters from the measured values.

Table 5-22 presents a breakdown of the KWHPCM associated with each PEPCO traction energy meter based on the simulated results using catch-up operation (PL1) for the peak operating periods. Table 5-23 lists the values of the KWHPCM coefficients for catch-up operation for the six different traction energy meter consolidations, including the VEPCO meter.

Table 5-24 shows a comparison of the ratio of peak demand, calculated using catch-up (PL1), to that of normal (PL2) operation with the ratio of actual maximum to average peak demand for the various meter consolidations.

Catch-up operation (PL1) results in a 10% 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-mile/hour results in an increase of 34-36% in power over normal operation. If catch-up 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% increase in power demand over the normal power demand. Normally, catch-up would not take as long on the Red Line as the Blue/Orange Line since the running times from end to end are shorter. Also, catch-up on the Red and Blue/Orange Lines simultaneously are not likely, thus, the maximum/average peak demand on the DC

TABLE 5-20 VALUES OF THE COEFFICIENTS OF THE AVERAGE POWER FORMULA FOR NORMAL OPERATION (PL2) DURING THE FIVE OPERATING PERIODS

METER CONSOLIDATION	P_0	E_R	E_B	E_0
AM PEAK				
PEPCO				
Coincident Red	1412	6.67	-	-
Coincident Blue/Orange	2156	-	6.37	6.11
DC Jurisdiction	1901	6.28	4.66	4.31
MD Jurisdiction	1230	0.39	-	1.36
VA Jurisdiction	437	-	1.71	0.44
VEPCO	686	-	0.87	0.85
MIDDAY				
PEPCO				
Coincident Red	1612	6.60	-	-
Coincident Blue/Orange	2426	-	6.24	6.04
DC Jurisdiction	1981	6.05	4.57	4.23
MD Jurisdiction	1620	0.55	-	1.33
VA Jurisdiction	437	-	1.67	0.43
VEPCO	806	-	0.84	0.90
PM PEAK				
PEPCO				
Coincident Red	1412	6.70	-	-
Coincident Blue/Orange	2156	-	6.40	6.16
DC Jurisdiction	1901	6.27	4.66	4.31
MD Jurisdiction	1230	0.43	-	1.40
VA Jurisdiction	437	-	1.74	0.45
VEPCO	686	-	0.88	0.86
EVENING				
PEPCO				
Coincident Red	1612	6.51	-	-
Coincident Blue/Orange	2426	-	6.14	5.98
DC Jurisdiction	1981	5.96	4.48	4.18
MD Jurisdiction	1620	0.55	-	1.37
VA Jurisdiction	437	-	1.66	0.43
VEPCO	806	-	0.83	0.89
NON-REVENUE				
PEPCO				
Coincident Red	1792			
Coincident Blue/Orange	2756			
DC Jurisdiction	2101			
MD Jurisdiction	2010			
VA Jurisdiction	437			
VEPCO	986			

TABLE 5-21 COMPARISON OF AVERAGE POWER FORMULA RESULTS TO THE PEPCO METERING RESULTS FOR A ONE HOUR INTERVAL DURING EACH OPERATING PERIOD FOR NORMAL OPERATION

	POWER (KW)											
	AM PEAK			MIDDAY			PM PEAK			EVENING		
	PEPCO	SIM*	Δ%	PEPCO	SIM*	Δ%	PEPCO	SIM*	Δ%	PEPCO	SIM*	Δ%
Red	12011	12377	+3	6476	6305	-3	12847	12427	-3	6318	6241	-1
Blue/Orange	22322	23667	+6	12979	13004	+0	23600	23810	-1	13315	12866	-3
B/O (Except MD11-Y)	19248	19941	+4	10501	10341	-2	20304	20004	-1	10470	10213	-2
DC Jurisdiction	26707	27644	+4	14267	13838	-3	28362	27627	-3	14014	13554	-3
MD Jurisdiction	4325	4575	+6	3332	3383	+2	4574	4720	+3	3699	3403	-8
VA Jurisdiction	3311	3826	+16	1856	2092	+13	3511	3889	+9	1920	2085	+8

*Car-Miles/Hr Used in Simulation Estimate:

	Red Line	Blue Line	Orange Line
Peak	1644	1470	1988
Off-Peak	711	735	994

The simulation includes background plus on-board auxiliaries during turnaround.

$$\Delta\% = \frac{\text{Simulated} - \text{PEPCO}}{\text{PEPCO}} \times 100\%$$

TABLE 5-22 KWHPCM PREDICTED BY EMM FOR EACH TRACTION METER FOR CATCH-UP OPERATION

METER NAME	(SYMBOL)	LINE	JURISDICTION	AM PEAK R	AM PEAK B	AM PEAK O	PM PEAK R	PM PEAK B	PM PEAK O
RED LINE									
Farragut North	(MA1)	R	DC	1.18*	-	-	1.13*	-	-
Gallery Place	(MB1)	R	DC	1.16	-	-	1.09	-	-
Union Station	(MB2)	R	DC	0.99	-	-	1.02	-	-
New York Avenue	(MB3)	R	DC	0.52	-	-	0.57	-	-
Rhode Island Avenue	(MB4)	R	DC	1.19	-	-	1.20	-	-
Brookland Avenue	(MB5)	R	DC	1.09	-	-	1.11	-	-
New Hampshire Avenue	(MB6)	R	DC	0.82	-	-	0.85	-	-
Takoma Park	(MB7)	R	DC	1.05	-	-	1.07	-	-
Silver Spring	(MB8)	R	MD	0.47*	-	-	0.52*	-	-
BLUE/ORANGE LINE									
Shirley Highway	(MC8)	B	VA	-	0.58	-	-	0.58	-
Washington Boulevard	(MC6)	B	VA	-	0.84	-	-	0.84	-
Rosslyn	(MC5)	BO	VA	-	0.81	0.52	-	0.82	0.52
Potomac	(MC4)	BO	DC	-	0.68	0.51	-	0.68	0.51
Farragut West	(MC3)	BO	DC	-	0.71	0.53	-	0.71	0.53
Metro Center	(MC1)	BO	DC	-	0.64	0.48	-	0.65	0.49
Smithsonian	(MD2)	BO	DC	-	0.62	0.46	-	0.62	0.46
Federal Center	(MD4)	BO	DC	-	0.74	0.55	-	0.75	0.56
Seward Square	(MD6)	BO	DC	-	0.85	0.64	-	0.85	0.64
Potomac Avenue	(MD7)	BO	DC	-	0.74	0.55	-	0.71	0.53
Stadium Armory	(MD8)	BO	DC	-	0.60	0.45	-	0.58	0.44
Minnesota Avenue	(MD9)	BO	DC	-	0.29*	0.64	-	0.29*	0.64
Deanwood	(MD10)	O	DC	-	-	0.56	-	-	0.58
Cheverly	(MD11)	O	MD	-	-	0.58	-	-	0.58
Landover	(MD12)	O	MD	-	-	0.49	-	-	0.51
Beaver Dam Creek	(MD13)	O	MD	-	-	0.42	-	-	0.42
New Carrollton Yard	(MDY)	O	MD	-	-	0.16*	-	-	0.16*

*Includes on-board auxiliaries during turnaround.

METER NAME (SYMBOL)	KWHPCM PEAK	KWHPCM OFF-PEAK
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Avenue (MD9)	0.06	0.06
New Carrollton Yard (MDY)	0.04	0.04

TABLE 5-23 VALUES OF THE COEFFICIENTS OF THE AVERAGE POWER FORMULA FOR CATCH-UP OPERATION (PL1) DURING THE PEAK OPERATING PERIODS

METER CONSOLIDATION	P_0	E_R	E_B	E_O
AM PEAK				
PEPCO				
Coincident Red	1412	8.47	-	-
Coincident Blue/Orange	2156	-	8.10	7.54
DC Jurisdiction	1901	8.00	5.87	5.37
MD Jurisdiction	1230	0.47	-	1.65
VA Jurisdiction	437	-	2.23	0.52
VEPCO (MVP)	686	-	1.20	1.20
PM PEAK				
PEPCO				
Coincident Red	1412	8.56	-	-
Coincident Blue/Orange	2156	-	8.08	7.57
DC Jurisdiction	1901	8.04	5.84	5.38
MD Jurisdiction	1230	0.52	-	1.67
VA Jurisdiction	437	-	2.24	0.52
VEPCO (MVP)	686	-	1.20	1.20

TABLE 5-24 COMPARISON OF RATIO OF SIMULATED CATCH-UP TO NORMAL OPERATION POWER AND RATIO OF MAXIMUM TO AVERAGE PEAK DEMAND

METER CONSOLIDATION	SIMULATED CATCH-UP POWER / SIMULATED NORMAL POWER	MAXIMUM PEAK DEMAND / AVERAGE PEAK DEMAND
Red Line	1.35	1.29
Blue/Orange Line	1.34	1.31
DC Jurisdiction	1.36	1.19
VA Jurisdiction	1.35	1.67

Note: The MD Jurisdiction consolidation was not considered because of missing data from several of the MD meters.

jurisdiction is expected to be smaller.

It is clear from the above analysis that a case to be avoided is one-half hour or greater catch-up operations on both Red and Blue/Orange Lines, simultaneously, which entirely coincide with the demand interval.

5.4. 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. Passenger Load Factor Improvement.

3. Regeneration.

Strategies from the first two categories could be implemented in a relatively short period of time (three months to one year) while regeneration strategies would take substantially longer.

In order to assess the benefits of these strategies using the EMM, the linear power formula described in the previous section was used. It has the form:

$$P = P_0 + E_R(RCM/H) + E_B(BCM/H) + E_0(OCM/H)$$

where P_0 is the background power on the day with the average annual temperature, the quantities RCM/H, BCM/H, and OCM/H are the Red, Blue and Orange Line car-miles/hour, and E_R , E_B , and E_0 are the KWHPCM for the Red, Blue and Orange Lines, respectively.

The base operation selected was the 1980 timetable, and for the purpose of the strategy benefit estimates, it was divided into normal peak and off-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, and for off-peak operation were the averages of weekday midday and evening operation. These coefficients, together with the traction power background, are shown in Table 5-25. Using the 1980 operating timetable, and considering peak operation for seven hours on weekdays, and off-peak operation for eleven hours on weekdays, sixteen hours on Saturdays, and eight 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 5-25. The results are shown in Table 5-26. If catch-up operation were used for one-half hour during the peak operating period on all three lines, a peak demand associated with the catch-up entry would result.

5.4.1. Performance Modification Strategies

Two performance modification strategies were seriously considered in the study: Top Speed Reduction and Coasting.

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

A top speed reduction which results in a ten percent increase in average schedule time can be implemented immediately by using Performance Level Three (PL3) operation. However, this strategy could seriously effect system capacity and is not recommended.

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 which controls the power and brake mode, and inhibit the brake from being applied until the lower value of the speed band is reached.

The implementation of performance modification strategies which result in running time increases from 0-3% in schedule time could probably be accommodated. These strategies would require equipment modification whose cost aspect is covered in Section 7.2.

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

TABLE 5-25 VALUES OF THE COEFFICIENTS OF THE AVERAGE POWER FORMULA FOR OPERATION DURING NORMAL PEAK AND OFF-PEAK AND CATCH-UP PEAK PERIODS AS BASE FOR ENERGY CONSERVATION STRATEGIES APPLIED TO 1980 TIMETABLE

METER CONSOLIDATION NORMAL PEAK (PL2)	P_0	E_R	E_B	E_0
PEPCO				
Coincident Red	1412	6.69	-	-
Coincident Blue/Orange	2156	-	6.39	6.14
DC Jurisdiction	1901	6.28	4.66	4.31
MD Jurisdiction	1230	0.41	-	1.38
VA Jurisdiction	437	-	1.73	0.45
VEPCO	686	-	0.88	0.86
NORMAL OFF-PEAK (PL2)				
PEPCO				
Coincident Red	1612	6.56	-	-
Coincident Blue/Orange	2426	-	6.19	6.01
DC Jurisdiction	1981	6.01	4.53	4.21
MD Jurisdiction	1620	0.55	-	1.38
VA Jurisdiction	437	-	1.67	0.43
VEPCO	806	-	0.84	0.90
CATCH-UP PEAK (PL1)				
PEPCO				
Coincident Red	1412	8.52	-	-
Coincident Blue/Orange	2156	-	8.09	7.56
DC Jurisdiction	1901	8.02	5.86	5.38
MD Jurisdiction	1230	0.50	-	1.66
VA Jurisdiction	437	-	2.24	0.52
VEPCO	686	-	1.16	1.14
NON-REVENUE				
PEPCO				
Coincident Red	1792			
Coincident Blue/Orange	2756			
DC Jurisdiction	2101			
MD Jurisdiction	2010			
VA Jurisdiction	437			
VEPCO	986			

TABLE 5-26 TRACTION POWER DEMAND AND ANNUAL ENERGY USE FOR NORMAL OPERATION WITH 1980 TIMETABLE

METER CONSOLIDATION	POWER DEMAND (KW) AND ANNUAL ENERGY USE (MWH)*			
	Power Demand			Energy Use**
	Catch-Up	Normal	Δ	
PEPCO				
Coincident Red	15420	12410	3010	50800
Coincident Blue/Orange	29075	23755	5320	101500
DC Jurisdiction	34395	27645	6750	108400
MD Jurisdiction	5350	4645	705	27400
VA Jurisdiction	4760	3875	885	16500
VEPCO	4660	3690	970	18600

	**Annual Background Energy (MWH)
PEPCO	
Coincident Red	14200
Coincident Blue/Orange	21600
DC Jurisdiction	17500
MD Jurisdiction	14500
VA Jurisdiction	3800
VEPCO	7300

*Based on 1980 operating timetable with peak period operation of 1644, 1470 and 1988 CM/H for the Red, Blue and Orange Lines, respectively, and peak(off-peak) annual car-miles of 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

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.

Figures 5-24 and 5-25 show plots of percent traction energy decrease as functions of percent schedule time increase on the Red, Blue and Orange Lines for coasting and top speed reduction for two operating periods (peak and off-peak). In terms of energy reduction for minimum schedule time increase, coasting is a better strategy. At schedule time increases of 2-3% which can be achieved by coasting from maximum permitted speed to 50MPH (usually referred as coasting speed = 50MPH), traction energy decreases of 12-16% are attainable.

The Figures were constructed using the EMM, and the summaries of the TPS are contained in Appendix 9.6.

Reduction of initial accelerating rate was briefly considered as another performance modification strategy. Table 5-27 presents the results of TPS runs on the Red, Blue and Orange Lines comparing a reduced accelerating rate (1.5MPHPS) with the normal rate (3.0MPHPS). It is clear from the table that the energy consumption increases rather than decreases, but at a rate of 0.2-0.3% per percent increase in schedule time. This strategy was not considered further.

5.4.1.1. Coasting

A detailed analysis using the ENS was conducted using the coasting strategy with coasting (speed = 50MPH). The results of this analysis are presented in Table 5-28. The background power for each of the traction meters would be no different than the base operation.

The actual increase in running times for this coasting strategy is 3% on the Red Line and 1/2% on the Blue/Orange Line.

The power savings by applying coasting (speed = 50MPH), 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

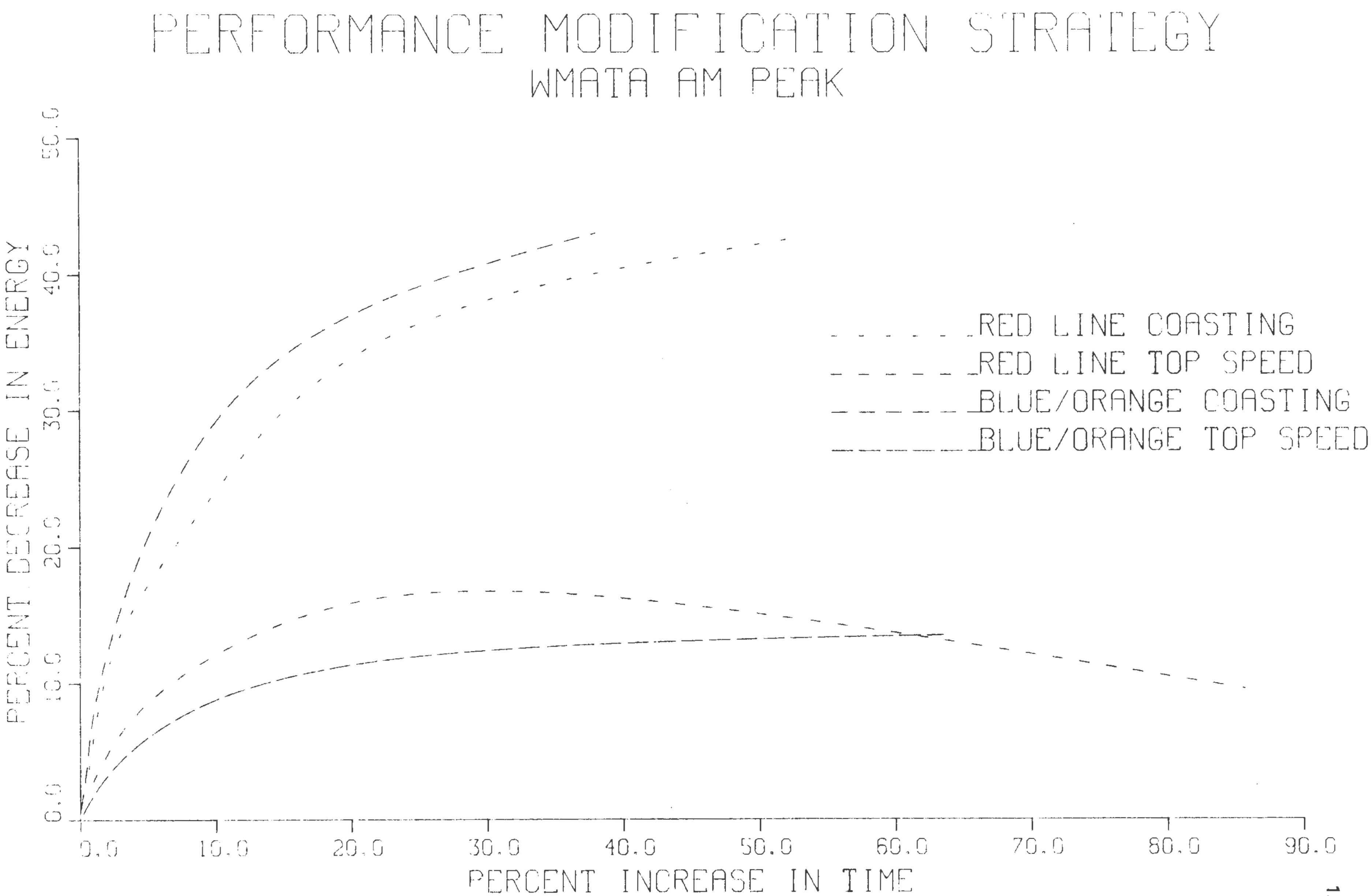

PERFORMANCE MODIFICATION STRATEGY
WMATA AM PEAK
PERCENT DECREASE IN ENERGY
0.0
10.0
20.0
30.0
40.0
50.0
RED LINE COASTING
RED LINE TOP SPEED
BLUE/ORANGE COASTING
BLUE/ORANGE TOP SPEED
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
PERCENT INCREASE IN TIME

FIGURE 5-24

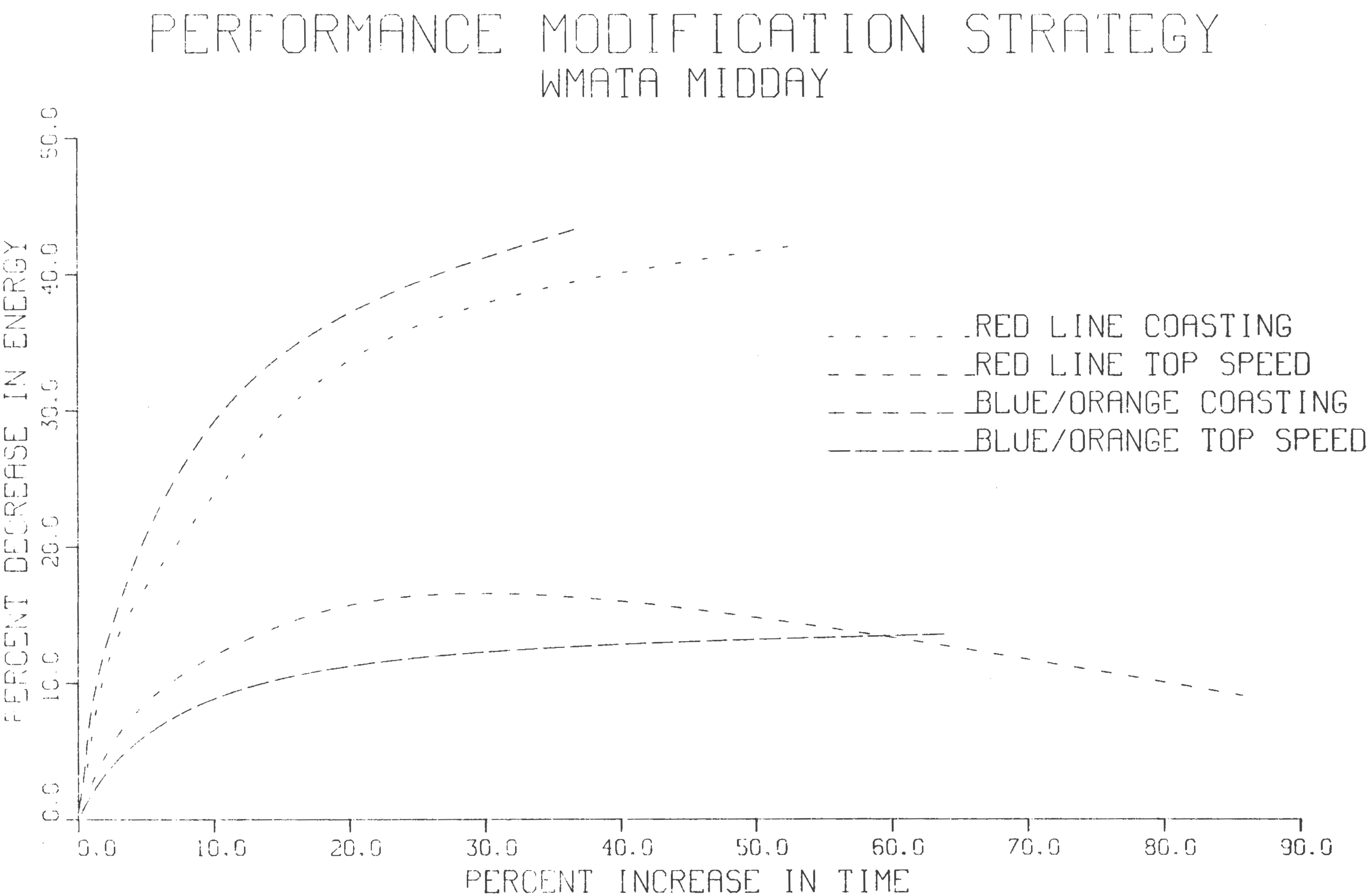

PERFORMANCE MODIFICATION STRATEGY
WMATA MIDDAY
PERCENT DECREASE IN ENERGY
0.0
10.0
20.0
30.0
40.0
50.0
RED LINE COASTING
RED LINE TOP SPEED
BLUE/ORANGE COASTING
BLUE/ORANGE TOP SPEED
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
PERCENT INCREASE IN TIME

FIGURE 5-25

TABLE 5-27 ENERGY CONSUMPTION WITH REDUCED ACCELERATING RATE (1.5 MPHPS) AS COMPARED TO NORMAL (3.0 MPHPS)

LINE	1.5 MPHPS E_1	1.5 MPHPS T_1	3.0 MPHPS E_0	3.0 MPHPS T_0	$\Delta E=(E_1-E_0)$	$\Delta T=(T_1-T_0)$	$\frac{\Delta E}{E_0}$(%)	$\frac{\Delta T}{T_0}$(%)	$\frac{\Delta E/E_0}{\Delta T/T_0}$
Red Inbound	4.94	15.71	4.83	14.39	0.11	1.32	2.3	9.2	0.25
Red Outbound	6.50	16.36	6.31	14.87	0.19	1.49	3.0	10.0	0.30
Blue Northbound	6.74	23.35	6.56	21.20	0.18	2.15	2.7	10.1	0.27
Blue Southbound	6.72	23.67	6.53	21.42	0.19	2.25	2.9	10.5	0.28
Orange Eastbound	6.32	30.19	6.20	27.71	0.12	2.48	1.9	8.9	0.21
Orange Westbound	6.43	30.17	6.28	27.51	0.15	2.66	2.4	9.7	0.25

TABLE 5-28 VALUES OF KWHPCM COEFFICIENTS IN THE AVERAGE POWER FORMULA FOR COASTING (SPEED = 50MPH)

				NORMAL (PL2)						CATCH-UP (PL1)		
				PEAK			OFF-PEAK			PEAK		
METER NAME	(SYMBOL)	LINE	JURIS-DICTION	R	B	O	R	B	O	R	B	O
RED LINE												
Farragut North	(MA1)*	R	DC	0.83	-	-	0.81	-	-	0.99	-	-
Gallery Place	(MB1)	R	DC	0.82	-	-	0.79	-	-	1.07	-	-
Union Station	(MB2)	R	DC	0.74	-	-	0.72	-	-	0.87	-	-
New York Avenue	(MB3)	R	DC	0.34	-	-	0.33	-	-	0.30	-	-
Rhode Island Avenue	(MB4)	R	DC	0.86	-	-	0.79	-	-	0.84	-	-
Brookland Avenue	(MB5)	R	DC	0.67	-	-	0.64	-	-	0.66	-	-
New Hampshire Avenue	(MB6)	R	DC	0.57	-	-	0.54	-	-	0.54	-	-
Takoma Park	(MB7)	R	DC	0.60	-	-	0.59	-	-	0.57	-	-
Silver Spring	(MB8)*	R	DC	0.30	-	-	0.43	-	-	0.28	-	-
BLUE/ORANGE LINE												
Shirley Highway	(MC8)	B	VA	-	0.42	-	-	0.42	-	-	0.44	-
Washington Boulevard	(MC6)	B	VA	-	0.51	-	-	0.50	-	-	0.49	-
Rosslyn	(MC5)	BO	VA	-	0.69	0.45	-	0.66	0.42	-	0.72	0.46
Potomac	(MC4)	BO	DC	-	0.51	0.39	-	0.49	0.37	-	0.48	0.36
Farragut West	(MC3)	BO	DC	-	0.58	0.44	-	0.56	0.42	-	0.63	0.47
Metro Center	(MC1)	BO	DC	-	0.56	0.42	-	0.54	0.40	-	0.64	0.48
Smithsonian	(MD2)	BO	DC	-	0.49	0.37	-	0.47	0.35	-	0.61	0.46
Federal Center	(MD4)	BO	DC	-	0.53	0.39	-	0.51	0.39	-	0.62	0.46
Seward Square	(MD6)	BO	DC	-	0.62	0.46	-	0.59	0.45	-	0.67	0.50
Potomac Avenue	(MD7)	BO	DC	-	0.57	0.43	-	0.56	0.41	-	0.62	0.46
Stadium Armory	(MD8)	BO	DC	-	0.40	0.30	-	0.39	0.29	-	0.33	0.25
Minnesota Avenue	(MD9)*	BO	DC	-	0.20	0.40	-	0.21	0.40	-	0.20	0.40
Deanwood	(MD10)	O	DC	-	-	0.42	-	-	0.42	-	-	0.37
Cheverly	(MD11)	O	MD	-	-	0.40	-	-	0.40	-	-	0.40
Landover	(MD12)	O	MD	-	-	0.28	-	-	0.28	-	-	0.26
Beaver Dam Creek	(MD13)	O	MD	-	-	0.31	-	-	0.32	-	-	0.21
New Carrollton Yard	(MDY)*	O	MD	-	-	0.15	-	-	0.15	-	-	0.15
METER CONSOLIDATIONS*												
PEPCO												
Coincident Red				5.72	-	-	5.63	-	-	6.12	-	-
Coincident Blue/Orange				-	6.08	5.59	-	5.89	5.46	-	6.45	5.69
DC Jurisdiction				5.42	4.45	4.01	5.21	4.31	3.90	5.48	4.80	4.21
MD Jurisdiction				0.30	-	1.14	0.43	-	1.14	0.28	-	1.02
VA Jurisdiction				-	1.63	0.45	-	1.58	0.42	-	1.65	0.46
VEPCO (MVP)				-	0.87	0.85	-	0.84	0.90	-	0.97	0.95

	KWHPCM	
METER NAME (SYMBOL)	PEAK	OFF-PEAK
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Avenue (MD9)	0.06	0.06
New Carrollton Yard (MDY)	0.04	0.04
Ballston (MVP)**	0.04	0.12
National Airport (MVP)***	0.06	0.06

*Includes on-board auxiliaries during turnaround.

**Orange Line only.

***Blue Line only.

listed in Table 5-29 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 5-30. The actual savings in dollars will be discussed in Section 7.1.

5.4.1.2. Top Speed Restriction

A detailed analysis using the ENS was conducted using a top speed reduction strategy which allowed the running times to be increased by the same amount as for the coasting strategy (coasting speed = 50MPH). This increase in schedule time was 3% on the Red Line, and 1/2 on the Blue/Orange Line. to achieve this effect, the top speed on the system was reduced to 55MPH.

The detailed results of this analysis are shown in Table 5-31. Again, the background power for each of the traction meters would be no different than the base 1980 operation.

The power savings, by reducing the top speed of the system to 55MPH, 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 listed in Table 5-32 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 5-33.

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 Figures 5-24 and 5-25.

5.4.2. Passenger Load Factor Improvement Strategies

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 of operation. Both of these strategies have the ultimate effect of reducing car-miles/hour. The KWHPCM coefficients will change slightly because of heavier cars, train resistance effects (aerodynamics) and, in the case of turning trains, because of a change in running profile. But these changes will be small compared to the car-mile

TABLE 5-29 VALUE OF THE KWHPCM COEFFICIENTS FOR THE AVERAGE POWER SAVINGS FOR COASTING (SPEED > 50 MPH) FOR PEAK AND NON-PEAK PL2 AND PEAK PL1 OPERATION

METER CONSOLIDATION	ΔE_R	ΔE_B	ΔE_O
NORMAL PEAK (PL2)*			
PEPCO			
Coincident Red	0.97	-	-
Coincident Blue/Orange	-	0.31	0.55
DC Jurisdiction	0.86	0.21	0.30
MD Jurisdiction	0.11	-	0.24
VA Jurisdiction	-	0.10	0.00
VEPCO	-	0.01	0.01
NORMAL OFF-PEAK (PL2)**			
PEPCO			
Coincident Red	0.93	-	-
Coincident Blue/Orange	-	0.30	0.55
DC Jurisdiction	0.80	0.22	0.31
MD Jurisdiction	0.12	-	0.24
VA Jurisdiction	-	0.09	0.01
VEPCO	-	0.00	0.00
CATCH-UP PEAK (PL1)			
PEPCO			
Coincident Red	2.40	-	-
Coincident Blue/Orange	-	1.64	1.87
DC Jurisdiction	2.18	1.06	1.17
MD Jurisdiction	0.22	-	0.64
VA Jurisdiction	-	0.59	0.06
VEPCO	-	0.19	0.19

*Average of AM and PM Peak

**Average of Midday and Evening

TABLE 5-30 TRACTION POWER DEMAND AND ANNUAL ENERGY USE SAVINGS OVER 1980 TIMETABLE OPERATION BY APPLYING COASTING (>50 MPH) STRATEGIES DURING REVENUE OPERATION

METER CONSOLIDATION	PEAK POWER DEMAND		ENERGY USE
	Catch-Up (PL1)	Normal (PL2)	
TRACTION POWER DEMAND (KW) AND ANNUAL ENERGY SAVINGS (MWH)*			
PEPCO			
Coincident Red	3945	1595	5200
Coincident Blue/Orange	6130	1550	5700
DC Jurisdiction	7470	2320	8000
MD Jurisdiction	1635	670	2400
VA Jurisdiction	990	145	600
VEPCO	660	35	<100
TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)			
PEPCO			
Coincident Red	26	13	10
Coincident Blue/Orange	21	6	6
DC Jurisdiction	22	8	7
MD Jurisdiction	31	14	9
VA Jurisdiction	21	4	4
VEPCO	14	1	<1

*Based on 1980 operating timetable of 1644, 1470 and 1988 CM/H for Red, Blue and Orange Lines, respectively, during peak periods and peak (off-peak) annual car-miles 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

TABLE 5-31 VALUES OF THE KWHPCM COEFFICIENTS IN THE AVERAGE POWER FORMULA FOR TOP SPEED REDUCTION TO 55 MPH

METER NAME	(SYMBOL)	LINE	JURIS-DICTION	NORMAL (PL2) PEAK R	PEAK B	PEAK O	OFF-PEAK R	OFF-PEAK B	OFF-PEAK O
RED LINE									
Farragut North	(MA1)*	R	DC	0.83	-	-	0.81	-	-
Gallery Place	(MB1)	R	DC	0.77	-	-	0.82	-	-
Union Station	(MB2)	R	DC	0.79	-	-	0.75	-	-
New York Avenue	(MB3)	R	DC	0.42	-	-	0.38	-	-
Rhode Island Avenue	(MB4)	R	DC	0.90	-	-	0.91	-	-
Brookland Avenue	(MB5)	R	DC	0.80	-	-	0.78	-	-
New Hampshire Avenue	(MB6)	R	DC	0.64	-	-	0.59	-	-
Takoma Park	(MB7)	R	DC	0.81	-	-	0.71	-	-
Silver Spring	(MB8)*	R	MD	0.42	-	-	0.50	-	-
BLUE/ORANGE LINE									
Shirley Highway	(MC8)	B	VA	-	0.42	-	-	0.42	-
Washington Boulevard	(MC6)	B	VA	-	0.58	-	-	0.56	-
Rosslyn	(MC5)	BO	VA	-	0.69	0.44	-	0.68	0.43
Potomac	(MC4)	BO	DC	-	0.55	0.41	-	0.54	0.40
Farragut West	(MC3)	BO	DC	-	0.58	0.44	-	0.57	0.43
Metro Center	(MC1)	BO	DC	-	0.56	0.42	-	0.55	0.41
Smithsonian	(MD2)	BO	DC	-	0.49	0.37	-	0.48	0.36
Federal Center	(MD4)	BO	DC	-	0.54	0.40	-	0.53	0.39
Seward Square	(MD6)	BO	DC	-	0.62	0.46	-	0.60	0.45
Potomac Avenue	(MD7)	BO	DC	-	0.57	0.43	-	0.56	0.42
Stadium Armory	(MD8)	BO	DC	-	0.49	0.37	-	0.48	0.36
Minnesota Avenue	(MD9)*	BO	DC	-	0.25	0.53	-	0.25	0.53
Deanwood	(MD10)	O	DC	-	-	0.46	-	-	0.46
Cheverly	(MD11)	O	MD	-	-	0.46	-	-	0.46
Landover	(MD12)	O	MD	-	-	0.37	-	-	0.37
Beaver Dam Creek	(MD13)	O	MD	-	-	0.30	-	-	0.30
New Carrollton Yard	(MDY)*	O	MD	-	-	0.15	-	-	0.15
METER CONSOLIDATIONS*									
PEPCO									
Coincident Red				6.38	-	-	6.25	-	-
Coincident Blue/Orange				-	6.34	6.01	-	6.22	5.92
DC Jurisdiction				5.96	4.65	4.29	5.75	4.56	4.21
MD Jurisdiction				0.42	-	1.28	0.50	-	1.28
VA Jurisdiction				-	1.69	0.44	-	1.66	0.43
VEPCO (MVP)				-	0.87	0.85	-	0.84	0.90

METER NAME (SYMBOL)	KWHPCM PEAK	KWHPCM OFF-PEAK
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Avenue (MD9)	0.06	0.06
New Carrollton Yard (MDY)	0.04	0.04
Ballston (MVP)**	0.04	0.12
National Airport (MVP)***	0.06	0.06

*Includes on-board auxiliaries during turnaround.

**Orange Line only.

***Blue Line only.

TABLE 5-32 VALUES OF THE KWHPCM COEFFICIENTS FOR THE AVERAGE POWER SAVINGS FOR TOP SPEED REDUCTION TO 55 MPH FOR PEAK AND NON-PEAK PL2 AND PEAK PL1 OPERATION

METER CONSOLIDATION	ΔE_R	ΔE_B	ΔE_O
NORMAL PEAK (PL2)			
PEPCO			
Coincident Red	0.31	-	-
Coincident Blue/Orange	-	0.05	0.13
DC Jurisdiction	0.32	0.01	0.02
MD Jurisdiction	0.00	-	0.10
VA Jurisdiction	-	0.04	0.01
VEPCO	-	0.01	0.01
NORMAL OFF-PEAK (PL2)			
PEPCO			
Coincident Red	0.31	-	-
Coindident Blue/Orange	-	0.00	0.09
DC Jurisdiction	0.26	0.00	0.00
MD Jurisdiction	0.05	-	0.10
VA Jurisdiction	-	0.01	0.00
VEPCO	-	0.00	0.00
CATCH-UP PEAK (PL1)			
PEPCO			
Coincident Red	1.83	-	-
Coincident Blue/Orange	-	1.70	1.42
DC Jurisdiction	1.74	1.20	1.07
MD Jurisdiction	0.09	-	0.28
VA Jurisdiction	-	0.51	0.07
VEPCO	-	0.28	0.28

TABLE 5-33 TRACTION POWER DEMAND AND ANNUAL ENERGY USE
SAVINGS OVER 1980 TIMETABLE OPERATION BY
REDUCING TOP SPEED TO 55 MPH DURING REVENUE OPERATION

METER CONSOLIDATION	PEAK POWER DEMAND		ENERGY USE
	Catch-Up (PL1)	Normal (PL2)	
TRACTION POWER DEMAND (KW) AND ANNUAL ENERGY SAVINGS (MWH)*			
PEPCO			
Coincident Red	3010	510	1700
Coincident Blue/Orange	5320	330	900
DC Jurisdiction	6750	580	1700
MD Jurisdiction	705	200	900
VA Jurisdiction	890	80	200
VEPCO	970	35	100
TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)			
PEPCO			
Coincident Red	20	4	3
Coindident Blue/Orange	18	1	1
DC Jurisdiction	20	2	2
MD Jurisdiction	13	4	3
VA Jurisdiction	19	2	1
VEPCO	21	1	1

*Based on 1980 operating timetable of 1644, 1470 and 1988 CM/H for Red, Blue and Orange Lines, respectively, during peak periods and peak (off-peak) annual car-miles 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

effect.

Passenger load factor improvement must be considered carefully because of complications introduced in scheduling. To be most effective, car-miles should be set to match passenger-miles in the best operational way practical. A cost will generally be involved in both turning trains and in coupling/uncoupling operations.

An example is worked out where alternate six-car and four-car trains are run during midday, and alternate two-car and four-car trains are run on evenings, Saturdays and Sundays. The results are shown in Table 5-34. Since no changes are made during the peak period, the peak power demand will not change.

5.4.3. Regeneration Strategies

The regeneration strategies are those which Metro would use if they had all regenerative braking cars which fed their braking power either to the line, or to storage devices aboard the car itself.

Three regeneration strategies were investigated as part of this study. All of them were based on 1980 timetable operation using chopper propulsion equipment which BREDA will deliver to Metro. The propulsion system is described in Section 4.0.

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

The second strategy was regeneration with assured receptivity in which all of the substations contain inverters which have the ability to feed power back to the utility whenever the substation voltage exceeds a predetermined value. The energy savings from this strategy is very close, but slightly better than that of substation storage devices (batteries or flywheels).

Finally, the third strategy is on-board storage, typically flywheels similar to the energy storage cars which were modified by Garrett Corporation for the New York City Transit Authority.

TABLE 5-34 ENERGY SAVINGS WHICH RESULTS FROM A PASSENGER LOAD FACTOR IMPROVEMENT DURING NON-PEAK OPERATION*

PEPCO	Traction Energy Savings(MWH)	% Traction Energy Savings
Coincident Red	7700	15
Coincident Blue/Orange	16100	16
DC Jurisdiction	18500	17
MD Jurisdiction	2800	10
VA Jurisdiction	2500	15
VEPCO	2100	12

*Instead of six car trains in off-peak periods, the following timetable is in effect:

Midday: Alternate 4 and 6 car trains
Evening: Alternate 2 and 4 car trains
Saturday and Sunday: Alternate 2 and 4 car trains

Time Period	Normal Car-Miles			Δ Car-Miles		
	R	B	O	R	B	O
Midday	4409	4201	5601	675	700	934
Evening	4291	4157	5543	2145	1663	2772
Saturday	11390	11477	15302	5695	5738	7651
Sunday	5700	6023	8030	2850	3012	4015
Annual Savings (MCM)				1.178	1.069	1.570

5.4.3.1. Regeneration with Natural Receptivity

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

Table 5-35 lists the results of the simulation for regeneration with the 1980 timetable operation. Although some of the background power which is obtained from the 750VDC 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 KWHPCM coefficients which are the differences between the regeneration and base operation cases. These coefficients are listed in Table 5-36.

A summary of the peak power demand and energy savings obtained by a completely regenerating fleet of cars is shown in Table 5-37. This savings is calculated with respect to the 1980 base operation. The benefit of these savings is quantified in Section 7.1.

5.4.3.2. Regeneration with Assured Receptivity - Regenerative Substations

Table 5-38 lists the detailed results of the ENS using regenerative substations. All of the substations on the Red and Blue/Orange Lines are made regenerative by using inverters which feed the power of the regeneration vehicles back through the utility meters to be used in the utility systems for other customers.

The full credit of the peak power demand and energy savings, which is expressed in the KWHPCM savings of Table 5-39, can only be realized if the meters are allowed to run backwards and negotiations with the utilities are such that full credit can be given.

Table 5-40 presents a summary of the peak power demand and energy savings using the 1980 timetable for system operation.

A second method to obtain nearly the same peak power demand and energy savings would be to incorporate off-board storage devices such as flywheels either in substations or other strategic locations. Energy savings are expected to be less than that of regenerative substations, but more than that which results from natural

TABLE 5-35 VALUES OF KWHPCM COEFFICIENTS IN THE AVERAGE POWER FORMULA FOR REGENERATION WITH NATURAL RECEPTIVITY

METER NAME	(SYMBOL)	LINE	JURIS-DICTION	NORMAL (PL2) PEAK R	B	O	NORMAL (PL2) OFF-PEAK R	B	O	CATCH-UP (PL1) PEAK R	B	O
RED LINE												
Farragut North	(MA1)*	R	DC	0.63	-	-	0.58	-	-	0.88	-	-
Gallery Place	(MB1)	R	DC	0.50	-	-	0.66	-		0.75	-	-
Union Station	(MB2)	R	DC	0.44	-	-	0.54	-	-	0.56	-	-
New York Avenue	(MB3)	R	DC	0.26	-	-	0.22	-	-	0.27	-	-
Rhode Island Avenue	(MB4)	R	DC	0.79	-	-	0.71	-	-	0.76	-	-
Brookland Avenue	(MB5)	R	DC	0.67	-	-	0.61	-	-	0.59	-	-
New Hampshire Avenue	(MB6)	R	DC	0.47	-	-	0.54	-	-	0.67	-	-
Takoma Park	(MB7)	R	DC	0.61	-	-	0.78	-	-	0.96	-	-
Silver Spring	(MB8)*	R	MD	0.31	-	-	0.53	-	-	0.46	-	-
BLUE/ORANGE LINE												
Shirley Highway	(MC8)	B	VA	-	0.26	-	-	0.30	-	-	0.51	-
Washington Boulevard	(MC6)	B	VA	-	0.26	-	-	0.47	-	-	0.61	-
Rosslyn	(MC5)	BO	VA	-	0.42	0.27	-	0.40	0.26	-	0.42	0.27
Potomac	(MC4)	BO	DC	-	0.34	0.25	-	0.34	0.25	-	0.40	0.30
Farragut West	(MC3)	BO	DC	-	0.35	0.26	-	0.33	0.25	-	0.40	0.30
Metro Center	(MC1)	BO	DC	-	0.26	0.19	-	0.32	0.24	-	0.28	0.21
Smithsonian	(MD2)	BO	DC	-	0.25	0.18	-	0.27	0.20	-	0.29	0.22
Federal Center	(MD4)	BO	DC	-	0.29	0.22	-	0.28	0.21	-	0.43	0.32
Seward Square	(MD6)	BO	DC	-	0.39	0.29	-	0.36	0.27	-	0.48	0.36
Potomac Avenue	(MD7)	BO	DC	-	0.36	0.27	-	0.34	0.25	-	0.41	0.31
Stadium Armory	(MD8)	BO	DC	-	0.28	0.21	-	0.36	0.27	-	0.33	0.25
Minnesota Avenue	(MD9)*	BO	DC	-	0.20	0.40	-	0.19	0.36	-	0.23	0.48
Deanwood	(MD10)	O	DC	-	-	0.37	-	-	0.40	-	-	0.40
Cheverly	(MD11)	O	MD	-	-	0.37	-	-	0.42	-	-	0.49
Landover	(MD12)	O	MD	-	-	0.35	-	-	0.33	-	-	0.46
Beaver Dam Creek	(MD13)	O	MD	-	-	0.21	-	-	0.23	-	-	0.35
New Carrollton Yard	(MDY)*	O	MD	-	-	0.11	-	-	0.11	-	-	0.13
METER CONSOLIDATIONS*												
PEPCO												
Coincident Red				4.68	-	-	5.17	-	-	5.90	-	-
Coincident Blue/Orange				-	3.66	3.95	-	3.96	4.05	-	4.79	4.85
DC Jurisdiction				4.37	2.72	2.64	4.64	2.79	2.70	5.44	3.25	3.15
MD Jurisdiction				0.31	-	1.04	0.53	-	1.09	0.46	-	1.43
VA Jurisdiction				-	0.94	0.27	-	1.17	0.26	-	1.54	0.27
VEPCO (MVP)				-	0.66	0.64	-	0.62	0.68	-	0.77	0.75

METER NAME (SYMBOL)	KWHPCM PEAK	KWHPCM OFF-PEAK
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Avenue (MD9)	0.06	0.06
New Carrollton Yard (MDY)	0.04	0.04
Ballston (MVP)**	0.04	0.12
National Airport (MVP)***	0.06	0.06

*Includes on-board auxiliaries during turnaround.
**Orange Line only.
***Blue Line only.

TABLE 5-36 VALUES OF THE KWHPCM COEFFICIENTS FOR THE AVERAGE POWER SAVINGS FOR REGENERATION WITH NATURAL RECEPTIVITY FOR PEAK AND NON-PEAK PL2 AND PEAK PL1 OPERATION

METER CONSOLIDATION	ΔE_R	ΔE_B	ΔE_O
NORMAL PEAK (PL2)			
PEPCO			
Coincident Red	2.01	-	-
Coincident Blue/Orange	-	2.73	2.19
DC Jurisdiction	1.91	1.94	1.67
MD Jurisdiction	0.10	-	0.34
VA Jurisdiction	-	0.79	0.18
VEPCO	-	0.22	0.22
NORMAL OFF-PEAK (PL2)			
PEPCO			
Coincident Red	1.39	-	-
Coincident Blue/Orange	-	2.23	1.96
DC Jurisdiction	1.37	1.74	1.51
MD Jurisdiction	0.02	-	0.29
VA Jurisdiction	-	0.50	0.17
VEPCO	-	0.22	0.22
CATCH-UP PEAK (PL1)			
PEPCO			
Coincident Red	2.62	-	-
Coincident Blue/Orange	-	3.30	2.71
DC Jurisdiction	2.58	2.61	2.23
MD Jurisdiction	0.04	-	0.23
VA Jurisdiction	-	0.70	0.25
VEPCO	-	0.39	0.39

TABLE 5-37 TRACTION POWER DEMAND AND ANNUAL ENERGY USE SAVINGS OVER 1980 TIMETABLE OPERATION BY APPLYING REGENERATION WITH NATURAL RECEPTIVITY

METER CONSOLIDATION	PEAK POWER DEMAND		ENERGY USE
	Catch-Up (PL1)	Normal (PL2)	
TRACTION POWER DEMAND (KW) AND ANNUAL ENERGY SAVINGS (MWH)*			
PEPCO			
Coincident Red	4305	3305	9200
Coincident Blue/Orange	10240	8365	28900
DC Jurisdiction	12510	9310	30800
MD Jurisdiction	525	840	2600
VA Jurisdiction	1525	1520	4800
VEPCO	1350	760	2900
TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)			
PEPCO			
Coincident Red	28	27	18
Coincident Blue/Orange	35	35	29
DC Jurisdiction	36	34	28
MD Jurisdiction	10	18	9
VA Jurisdiction	32	39	29
VEPCO	28	20	15

*Based on 1980 operating timetable of 1644, 1470 and 1988 CM/H for Red, Blue and Orange Lines, respectively, during peak periods and peak (off-peak) annual car-miles 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

TABLE 5-38 VALUES OF KWHPCM COEFFICIENTS IN THE AVERAGE POWER FORMULA FOR REGENERATION WITH ASSURED RECEPTIVITY

				NORMAL (PL2)						CATCH-UP (PL1)		
				PEAK			OFF-PEAK			PEAK		
METER NAME	(SYMBOL)	LINE	JURIS-DICTION	R	B	O	R	B	O	R	B	O
RED LINE												
Farragut North	(MA1)*	R	DC	0.52	-	-	0.51	-	-	0.69	-	-
Gallery Place	(MB1)	R	DC	0.53	-	-	0.56	-	-	0.53	-	-
Union Station	(MB2)	R	DC	0.46	-	-	0.46	-	-	0.47	-	-
New York Avenue	(MB3)	R	DC	0.31	-	-	0.31	-	-	0.37	-	-
Rhode Island Avenue	(MB4)	R	DC	0.58	-	-	0.56	-	-	0.73	-	-
Brookland Avenue	(MB5)	R	DC	0.58	-	-	0.65	-	-	0.74	-	-
New Hampshire Avenue	(MB6)	R	DC	0.43	-	-	0.48	-	-	0.58	-	-
Takoma Park	(MB7)	R	DC	0.54	-	-	0.53	-	-	0.72	-	-
Silver Spring	(MB8)*	R	MD	0.25	-	-	0.41	-	-	0.31	-	-
BLUE/ORANGE LINE												
Shirley Highway	(MC8)	B	VA	-	0.26	-	-	0.26	-	-	0.33	-
Washington Boulevard	(MC6)	B	VA	-	0.37	-	-	0.37	-	-	0.54	-
Rosslyn	(MC5)	BO	VA	-	0.43	0.27	-	0.34	0.22	-	0.45	0.29
Potomac	(MC4)	BO	DC	-	0.25	0.18	-	0.21	0.16	-	0.43	0.32
Farragut West	(MC3)	BO	DC	-	0.33	0.25	-	0.32	0.24	-	0.28	0.21
Metro Center	(MC1)	BO	DC	-	0.32	0.24	-	0.32	0.24	-	0.32	0.24
Smithsonian	(MD2)	BO	DC	-	0.29	0.22	-	0.29	0.22	-	0.37	0.28
Federal Center	(MD4)	BO	DC	-	0.29	0.22	-	0.27	0.20	-	0.37	0.28
Seward Square	(MD6)	BO	DC	-	0.33	0.25	-	0.33	0.25	-	0.41	0.31
Potomac Avenue	(MD7)	BO	DC	-	0.37	0.28	-	0.37	0.28	-	0.36	0.27
Stadium Armory	(MD8)	BO	DC	-	0.28	0.21	-	0.30	0.23	-	0.33	0.25
Minnesota Avenue	(MD9)*	BO	DC	-	0.19	0.36	-	0.19	0.37	-	0.19	0.36
Deanwood	(MD10)	O	DC	-	-	0.33	-	-	0.33	-	-	0.28
Cheverly	(MD11)	O	MD	-	-	0.32	-	-	0.33	-	-	0.35
Landover	(MD12)	O	MD	-	-	0.30	-	-	0.30	-	-	0.37
Beaver Dam Creek	(MD13)	O	MD	-	-	0.19	-	-	0.19	-	-	0.26
New Carrollton Yard	(MDY)*	O	MD	-	-	0.11	-	-	0.11	-	-	0.11
METER CONSOLIDATIONS*												
PEPCO												
Coincident Red				4.20	-	-	4.47	-	-	5.14	-	-
Coincident Blue/Orange				-	3.71	3.73	-	3.57	3.67	-	4.38	4.18
DC Jurisdiction				3.95	2.65	2.54	4.06	2.60	2.52	4.83	3.06	2.80
MD Jurisdiction				0.25	-	0.92	0.41	-	0.93	0.31	-	1.09
VA Jurisdiction				-	1.06	0.27	-	0.97	0.22	-	1.32	0.29
VEPCO (MVP)				-	0.53	0.51	-	0.53	0.59	-	0.54	0.52

*Includes on-board auxiliaries during turnaround.
**Orange Line only.
***Blue Line only.

METER NAME (SYMBOL)	KWHPCM PEAK	KWHPCM OFF-PEAK
Farragut North (MA1)	0.17	0.17
Silver Spring (MB8)	0.10	0.23
Minnesota Ave. (MD9)	0.06	0.06
New Carrollton (MDY)	0.04	0.04
Ballston (MVP)**	0.04	0.12
National Airport (MVP)***	0.06	0.06

TABLE 5-39 VALUES OF THE KWHPCM COEFFICIENTS FOR THE AVERAGE POWER SAVINGS FOR REGENERATION WITH ASSURED RECEPTIVITY FOR PEAK AND NON-PEAK PL2 AND PEAK PL1 OPERATION

METER CONSOLIDATION	ΔE_R	ΔE_B	ΔE_O
NORMAL PEAK (PL2)			
PEPCO			
Coincident Red	2.49	-	-
Coincident Blue/Orange	-	2.68	2.41
DC Jurisdiction	2.33	2.01	1.77
MD Jurisdiction	0.16	-	0.46
VA Jurisdiction	-	0.07	0.18
VEPCO	-	0.35	0.35
NORMAL OFF-PEAK (PL2)			
PEPCO			
Coincident Red	2.09	-	-
Coincident Blue/Orange	-	2.62	2.34
DC Jurisdiction	1.95	1.93	1.69
MD Jurisdiction	0.14	-	0.45
VA Jurisdiction	-	0.70	0.21
VEPCO	-	0.31	0.31
CATCH-UP PEAK (PL1)			
PEPCO			
Coincident Red	3.38	-	-
Coincident Blue/Orange	-	3.71	3.38
DC Jurisdiction	3.19	2.80	2.58
MD Jurisdiction	0.19	-	0.57
VA Jurisdiction	-	0.92	0.23
VEPCO	-	0.62	0.62

TABLE 5-40 TRACTION POWER DEMAND AND ANNUAL ENERGY USE SAVINGS OVER 1980 TIMETABLE OPERATION BY APPLYING REGENERATION WITH ASSURED RECEPTIVITY

METER CONSOLIDATION	PEAK POWER DEMAND		ENERGY USE
	Catch-Up (PL1)	Normal (PL2)	
TRACTION POWER DEMAND (KW) AND ANNUAL ENERGY SAVINGS (MWH)*			
PEPCO			
Coincident Red	5555	4095	12500
Coincident Blue/Orange	12175	8730	32300
DC Jurisdiction	14490	10305	35400
MD Jurisdiction	1445	1180	4200
VA Jurisdiction	1810	1345	5300
VEPCO	2145	1210	4300
TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)			
PEPCO			
Coincident Red	36	33	25
Coincident Blue/Orange	42	37	32
DC Jurisdiction	42	37	33
MD Jurisdiction	27	25	15
VA Jurisdiction	38	35	32
VEPCO	44	31	22

*Based on 1980 operating timetable of 1644, 1470 and 1988 CM/H for Red, Blue and Orange Lines, respectively, during peak periods and peak (off-peak) annual car-miles 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

receptivity. Savings using this method of assured receptivity does not require credit from the utility to be effective.

5.4.3.3. Regeneration with Assured Receptivity - On-board Storage

Table 5-41 lists the detailed results of the ENS using on-board storage devices such as flywheel systems to assure regeneration receptivity.

The empty weights of all of the cars were increased by 10% to accommodate the on-board storage system. The on-board storage flywheel system was sized to accommodate both the maximum power to be accepted in braking, and the maximum energy storage required. Both input and output efficiencies were set at 92%.

The chopper used for controlling regeneration to the flywheel could operate at higher voltage because the line voltage limit, using regeneration with natural receptivity, is no restriction with on-board storage. Thus, the requirement for a resistor in series with the line to limit the voltage rise is no longer necessary. With this condition, the chopper efficiency in regenerative braking is shown in Figure 5-26. This is to be compared with the chopper efficiency used for natural receptivity which is shown in Figure 4-9. Because the requirement for a resistor is no longer necessary, the high speed regeneration efficiency is improved substantially.

Table 5-42 shows the KWHPCM coefficients which can be used to calculate the peak power demand and energy use savings which are possible using on-board storage. The values of these coefficients were used to estimate the peak power demand and annual energy savings using the 1980 operational timetable in the simulation. These savings are shown in Table 5-43.

5.4.3.4. Discussion of Regeneration Results

Figure 5-27 summarizes the annual energy and peak power demand savings in percent for the Red and the Blue/Orange Line using 1980 operations. The Figures were constructed using the EMM, and the summaries of the TPS are contained in Appendix 9.7.

On a percentage basis, the regeneration savings on the Blue/Orange Line is larger than on the Red Line because the interstation spacing is smaller, and the headways are less on most of the Blue/Orange Line.

The percent savings in peak power for both normal and catch-up operation is

TABLE 5-41 VALUES OF THE KWHPCM COEFFICIENTS IN THE AVERAGE POWER FORMULA FOR REGENERATION WITH ON-BOARD STORAGE

METER NAME	(SYMBOL)	LINE	JURIS-DICTION	NORMAL (PL2) PEAK R	B	O	NORMAL (PL2) OFF-PEAK R	B	O	CATCH-UP (PL1) PEAK R	B	O
RED LINE												
Farragut North	(MA1)*	R	DC	0.63	-	-	0.62	-	-	0.88	-	-
Gallery Place	(MB1)	R	DC	0.54	-	-	0.52	-	-	0.56	-	-
Union Station	(MB2)	R	DC	0.46	-	-	0.45	-	-	0.55	-	-
New York Avenue	(MB3)	R	DC	0.30	-	-	0.30	-	-	0.41	-	-
Rhode Island Avenue	(MB4)	R	DC	0.64	-	-	0.64	-	-	0.70	-	-
Brookland Avenue	(MB5)	R	DC	0.55	-	-	0.57	-	-	0.66	-	-
New Hampshire Avenue	(MB6)	R	DC	0.50	-	-	0.50	-	-	0.57	-	-
Takoma Park	(MB7)	R	DC	0.62	-	-	0.62	-	-	0.67	-	-
Silver Spring	(MB8)*	R	MD	0.28	-	-	0.45	-	-	0.37	-	-
BLUE/ORANGE LINE												
Shirley Highway	(MC8)	B	VA	-	0.23	-	-	0.23	-	-	0.28	-
Washington Boulevard	(MC6)	B	VA	-	0.42	-	-	0.40	-	-	0.58	-
Rosslyn	(MC5)	BO	VA	-	0.42	0.27	-	0.39	0.25	-	0.37	0.23
Potomac	(MC4)	BO	DC	-	0.36	0.27	-	0.35	0.26	-	0.42	0.32
Farragut West	(MC3)	BO	DC	-	0.40	0.30	-	0.39	0.29	-	0.39	0.29
Metro Center	(MC1)	BO	DC	-	0.37	0.28	-	0.36	0.27	-	0.37	0.28
Smithsonian	(MD2)	BO	DC	-	0.32	0.24	-	0.32	0.24	-	0.33	0.25
Federal Center	(MD4)	BO	DC	-	0.33	0.25	-	0.33	0.25	-	0.37	0.28
Seward Square	(MD6)	BO	DC	-	0.37	0.28	-	0.39	0.29	-	0.51	0.39
Potomac Avenue	(MD7)	BO	DC	-	0.35	0.26	-	0.35	0.26	-	0.37	0.28
Stadium Armory	(MD8)	BO	DC	-	0.36	0.27	-	0.36	0.27	-	0.44	0.33
Minnesota Avenue	(MD9)*	BO	DC	-	0.14	0.40	-	0.14	0.40	-	0.16	0.44
Deanwood	(MD10)	O	DC	-	-	0.37	-	-	0.35	-	-	0.32
Cheverly	(MD11)	O	MD	-	-	0.35	-	-	0.33	-	-	0.35
Landover	(MD12)	O	MD	-	-	0.30	-	-	0.28	-	-	0.33
Beaver Dam Creek	(MD13)	O	MD	-	-	0.21	-	-	0.21	-	-	0.30
New Carrollton Yard	(MDY)*	O	MD	-	-	0.10	-	-	0.10	-	-	0.10
METER CONSOLIDATIONS*												
PEPCO												
Coincident Red				4.52	-	-	4.67	-	-	5.37	-	-
Coincident Blue/Orange				-	4.07	4.15	-	4.01	4.05	-	4.59	4.49
DC Jurisdiction				4.24	3.00	2.92	4.22	2.99	2.88	5.00	3.36	3.18
MD Jurisdiction				0.28	-	0.96	0.45	-	0.92	0.37	-	1.08
VA Jurisdiction				-	1.07	0.27	-	1.02	0.25	-	1.23	0.23
VEPCO (MVP)				-	0.58	0.58	-	0.57	0.65	-	0.72	0.72

METER NAME (SYMBOL)	KWHPCM PEAK	KWHPCM OFF-PEAK
Farragut North (MA1)	0.09	0.09
Silver Spring (MB8)	-0.02	0.11
Minnesota Avenue (MD9)	0.00	0.00
New Carrollton Yard (MDY)	-0.01	-0.01
Ballston (MVP)**	0.02	0.10
National Airport (MVP)***	0.02	0.02

*Includes on-board auxiliaries during tunraround & correction for storage at end of run.

**Orange Line only.

***Blue Line only.

PROPULSION SYSTEM EFFICIENCY

WMATA-CHOPPER-HIGHLY REGENERATIVE BRAKE

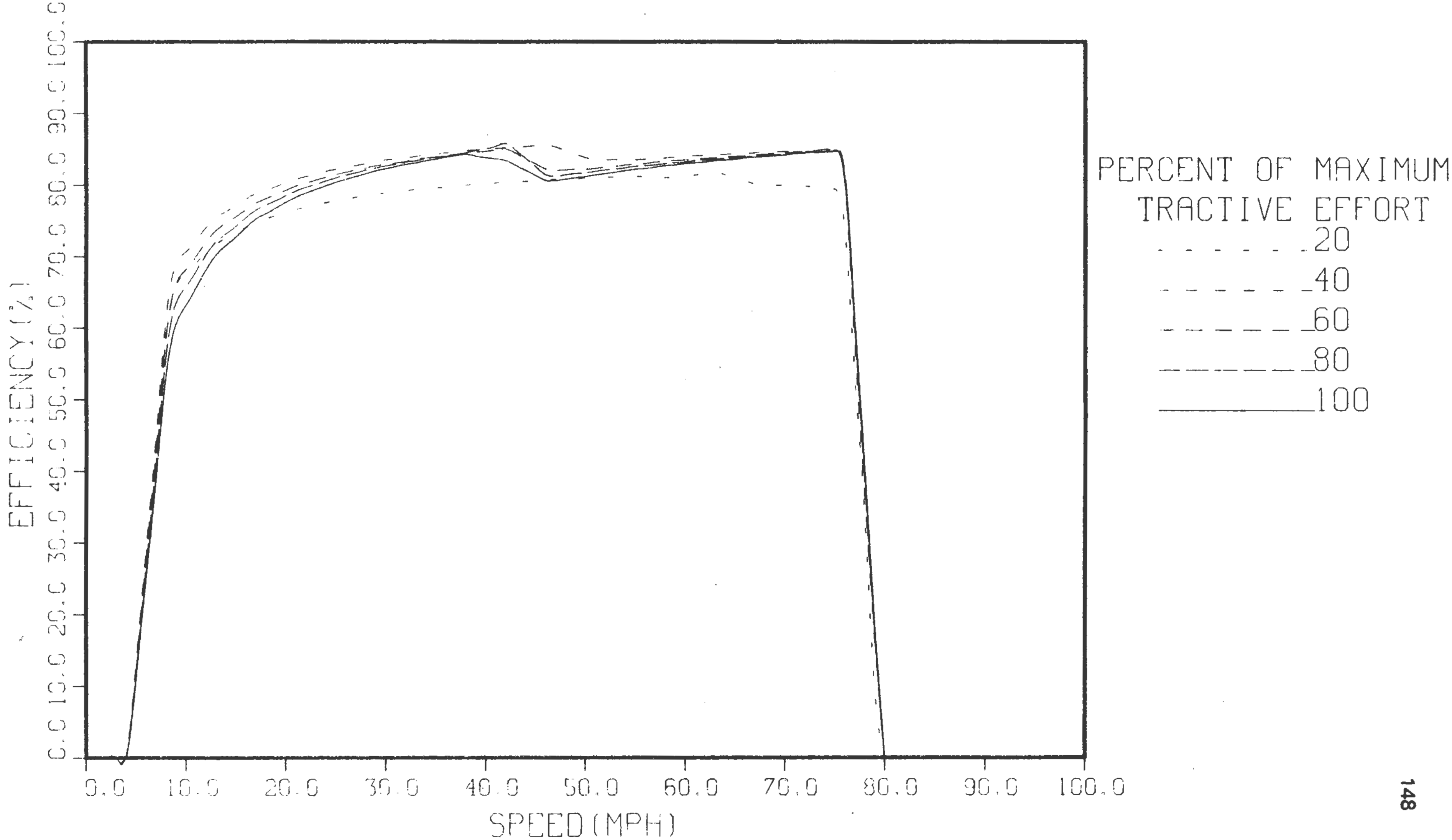


FIGURE 5-26

TABLE 5-42 VALUES OF THE KWHPCM COEFFICIENTS FOR THE AVERAGE POWER SAVINGS FOR REGENERATION WITH ON-BOARD STORAGE FOR PEAK AND NON-PEAK PL2 AND PEAK PL1 OPERATION

METER CONSOLIDATION	ΔE_R	ΔE_B	ΔE_O
NORMAL PEAK (PL2)			
PEPCO			
Coincident Red	2.17	-	-
Coincident Blue/Orange	-	2.32	1.99
DC Jurisdiction	2.04	1.66	1.39
MD Jurisdiction	0.13	-	0.42
VA Jurisdiction	-	0.66	0.18
VEPCO	-	0.30	0.28
NORMAL OFF-PEAK (PL2)			
PEPCO			
Coincident Red	1.89	-	-
Coincident Blue/Orange	-	2.18	1.96
DC Jurisdiction	1.79	1.54	1.33
MD Jurisdiction	0.10	-	0.46
VA Jurisdiction	-	0.65	0.18
VEPCO	-	0.27	0.25
CATCH-UP PEAK (PL1)			
PEPCO			
Coincident Red	3.15	-	-
Coincident Blue/Orange	-	3.50	3.07
DC Jurisdiction	3.02	2.50	2.20
MD Jurisdiction	0.13	-	0.58
VA Jurisdiction	-	1.01	0.29
VEPCO	-	0.44	0.42

TABLE 5-43 TRACTION POWER DEMAND AND ANNUAL ENERGY USE SAVINGS OVER 1980 TIMETABLE OPERATION BY APPLYING REGENERATION WITH ON-BOARD STORAGE

METER CONSOLIDATION	PEAK POWER DEMAND		ENERGY USE
	Catch-Up (PL1)	Normal (P12)	
TRACTION POWER DEMAND (KW) AND ANNUAL ENERGY SAVINGS (MWH)*			
PEPCO			
Coincident Red	5180	3565	11100
Coincident Blue/Orange	11250	7365	27100
DC Jurisdiction	13015	8555	29400
MD Jurisdiction	1365	1050	3900
VA Jurisdiction	2060	1330	5000
VEPCO	1480	1000	3500
TRACTION POWER DEMAND AND ANNUAL ENERGY SAVINGS (%)			
PEPCO			
Coincident Red	34	29	22
Coincident Blue/Orange	39	31	27
DC Jurisdiction	38	31	27
MD Jurisdiction	26	23	14
VA Jurisdiction	43	34	30
VEPCO	32	27	19

*Based on 1980 operating timetable of 1644, 1470 and 1988 CM/H for Red, Blue and Orange Lines, respectively, during peak periods and peak (off-peak) annual car-miles 2.467M (3.057M), 2.477M (3.083M) and 3.309M (4.111M) for the Red, Blue and Orange Lines, respectively.

SUMMARY
REGENERATIVE SAVINGS – WMATA

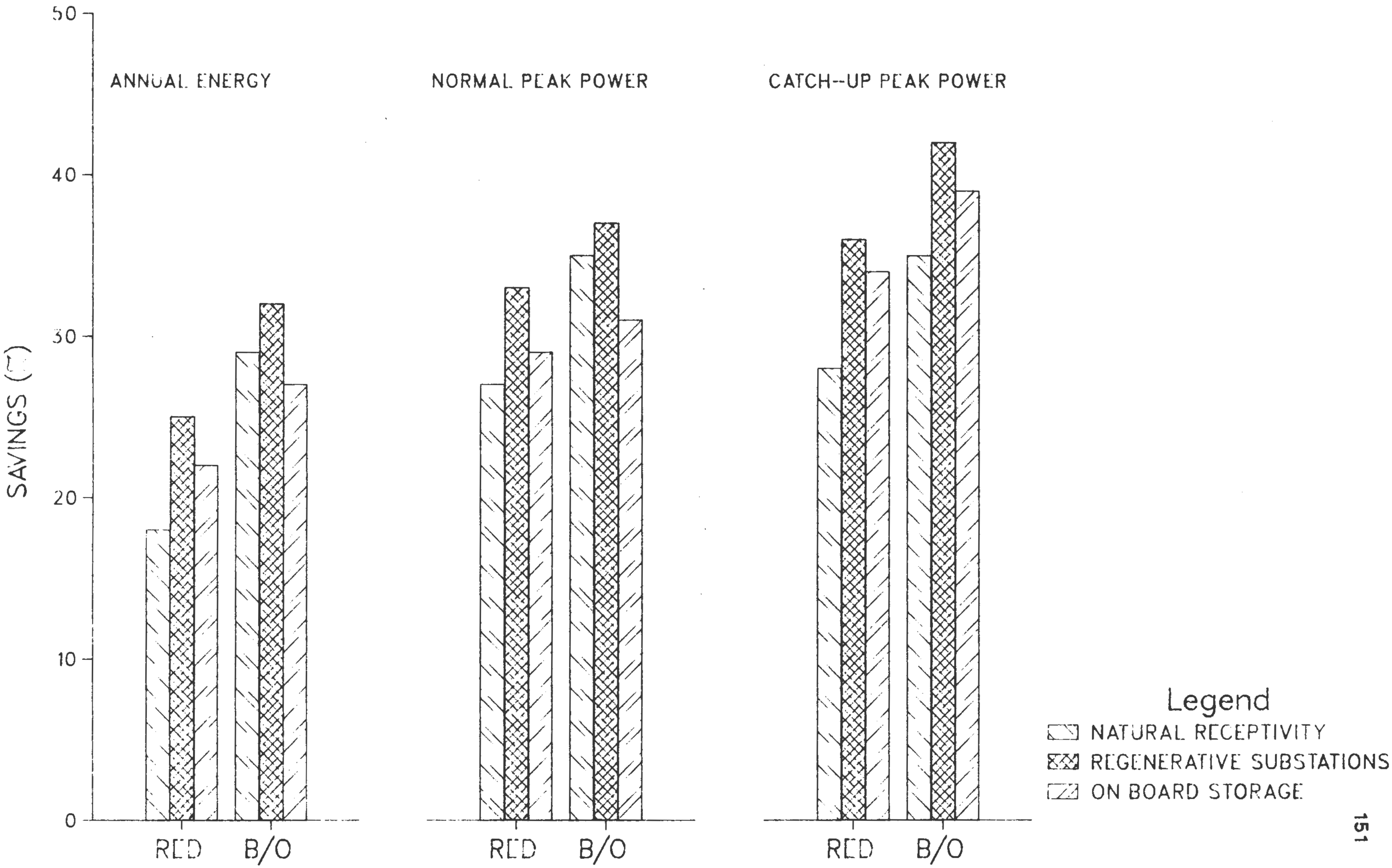


FIGURE 5-27

larger than annual energy for the following reasons:

1. Natural receptivity is highest during the peak operating periods at which time peak power demand is measured. Annual energy savings is measured during both peak periods and non-peak periods, during which receptivity is lower.

2. Assured receptivity is higher during the peak operating periods because natural receptivity is higher, and hence less power would flow back to the utility, suffering substation losses.

On-board storage percent savings has its highest value during the catch-up operation, since it is during this time that the speed limits are high enough to utilize the better efficiency of the highly regenerative chopper (no resistor to limit line voltage). During normal operation (PL2), speed limits are not in the range (>60 MPH) which would allow the highly regenerative chopper to be effective.

6. SUPPORT ENERGY

In Metrorail operation, the support energy is the time integrated power registered by the electric meters in the passenger stations, the office building, and the repair shops. It includes energy for heating, air conditioning, ventilation, lighting, elevators, escalators, signals and communications, and power to run special equipment and machinery. As in the case of traction energy, an audit was undertaken by analyzing metering information from PEPCO.

6.1. AUDIT

The support energy audit was conducted by analyzing metering information for part of the year 1980 supplied by PEPCO.

6.1.1. Description of Audit

The time interval selected for the audit was the same as that for the traction energy audit (see Section 5.1).

Of the thirty-seven support meters analyzed as part of the 1980 operation, thirty were in the DC jurisdiction, four were in the MD jurisdiction, and three were in the VA jurisdiction. During the analysis, it was found that pulse data were missing from the meters at Silver Spring, Landover, Cheverly, and Minnesota Avenue. Thus, precautions were taken during the audit to discount the effects of these meters.

6.1.2. Regression Analyses: Temperature

In order to determine the dependence of support energy usage on daily temperature, regression analyses were conducted using the support meter data. Each day was divided into two periods: revenue service time and non-revenue 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. Non-revenue service was all other times.

The regression formula was assumed to have the form:

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

during revenue service time, and:

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

during non-revenue service time, where P is the average power as obtained from the meter data, P_0 is the background power in units of KW, ADD is the average degree-day defined as the average temperature less 70°F, and MDD is the minimum degree-day defined as the minimum temperature less 70°F.

The results of the regression analyses are shown in Table 6-1. All stations which are above ground show a power increase with decreasing degree-days (heating), and those below grade show a power increase with increasing degree-days. For the below ground stations, this is attributed to tunnel ventilation, and for above ground stations it is attributed to heating and lighting. The lighting correlation is probably a secondary effect due to a relation between longer night hours and colder days.

The office building shows a large cooling effect because chiller plants at Gallery Place and Judiciary Square are metered here. The Garden City Shop shows a large heating effect.

Table 6-2 shows the temperature dependent coefficient of the regression analyses and load dependence on temperature for several consolidations of the support meters. The load differences can be interpreted as between winter (30°F) and summer (90°F), and the spring and fall seasons (60°-70°F).

6.1.3. Average PEPCO Support Power

Table 6-3 lists the average support power for the passenger stations, the office building, and repair shops for PEPCO jurisdictions during the principal operating periods. Table 6-4 lists the average support power for five PEPCO support meter consolidations which are the Red Line passenger stations, the Blue/Orange Line passenger stations, and the DC, MD and VA jurisdictions. The MD and DC jurisdictions are shown with and without office building and repair shop power.

6.1.4. PEPCO Support Power Model

The PEPCO support power model was developed for the passenger stations serviced by PEPCO. It includes a background power, lighting loads, and escalator loads.

TABLE 6-1 RESULTS OF TEMPERATURE REGRESSION ANALYSES FOR SUPPORT METERS

RED LINE PASSENGER STATIONS		LOCATION	JURISDICTION	REVENUE SERVICE TIME* P_0(KW)	REVENUE SERVICE TIME* P_2(KWPADD)	NON-REVENUE SERVICE TIME** P_0(KW)	NON-REVENUE SERVICE TIME** P_2(KWPMDD)
Dupont Circle	(MSA3)	U	DC	350	0.85	298	1.05
Farragut North	(MSA2)	U	DC	327	1.75	319	2.25
Metro Center	(MSA1)	U	DC	373	2.95	384	3.57
Gallery Place	(MSB1)	U	DC	214	0.55	195	0.44
Judiciary Square	(MSB2)	U	DC	246	0.39	228	0.59
Union Station	(MSB3)	U	DC	261	1.39	243	1.47
Rhode Island Ave.	(MSB4)	A	DC	103	-4.81	69	-5.11
Brookland	(MSB5)	A	DC	112	-1.55	96	-1.47
Fort Totten	(MSB6)	A	DC	100	-1.16	89	-1.18
Takoma Park	(MSB7)	A	DC	77	-0.97	62	-0.99
Silver Spring	(MSB8)	A	MD	115	N	104	-0.25
BLUE/ORANGE LINE PASSENGER STATIONS							
Pentagon	(MSC7)	U	VA	398	1.23	364	1.17
Arlington Cemetery	(MSC6)	A	VA	106	-0.36	77	-0.42
Rosslyn	(MSC5)	U	VA	370	1.20	346	1.21
Foggy Bottom	(MSC4)	U	DC	189	0.57	165	0.63
Farragut West	(MSC3)	U	DC	305	1.48	296	1.75
McPherson Square	(MSC2)	U	DC	265	0.99	260	1.21
Metro Center	(MSC1)	U	DC	290	1.59	276	1.65
Federal Triangle	(MSD1)	U	DC	183	0.98	167	0.72
Smithsonian	(MSD2)	U	DC	255	0.24	223	0.19
L'Enfant Plaza	(MSD3)	U	DC	305	1.05	279	1.15
Federal Center	(MSD4)	U	DC	196	0.73	184	0.65
Capitol South	(MSD5)	U	DC	247	1.86	242	1.91
Eastern Market	(MSD6)	U	DC	102	N	95	N
Potomac Ave.	(MSD7)	U	DC	147	0.37	142	0.39
Stadium Armory	(MSD8)	U	DC	226	0.77	197	0.84
Minnesota Ave.	(MSD9)	A	DC	110	-1.34	100	-1.30
Deanwood	(MS10)	A	DC	95	-0.70	76	-0.65
Cheverly	(MS11)	A	MD	86	-0.36	94	0.35
Landover	(MS12)	A	MD	54	N	48	-0.69
New Carrollton	(MS13)	A	MD	111	N	151	N
Gallery Place	(MSE3)	U	DC	141	0.36	146	0.35
Archives	(MSE2)	U	DC	60	1.26	72	1.29
L'Enfant Plaza	(MSE1)	U	DC	198	0.51	182	0.52
OFFICE BUILDING AND REPAIR SHOPS							
Office Building	(MOB)		DC	1972	12.16	1594	9.3
T-St. Repair Shop	(MRS)		DC	579	0.63	522	N
Garden City Shop	(MGCS)		MD	273	-11.14	181	-14.9

*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	

**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

$P = P_0 + P_2(DD)$

P : Average Power (KW)
P_0: Background Power (KW)
P_2: KWHPDD (Degree-Day Component Coefficient)
DD: Degree-Day

TABLE 6-2 TEMPERATURE DEPENDENT COEFFICIENTS OF REGRESSION ANALYSES LOAD DIFFERENCES FOR SUPPORT METER CONSOLIDATION

SUPPORT METER CONSOLIDATION	P_2(KWPADD) REVENUE SERVICE TIME NEGATIVE	POSITIVE	P_2(KWPMDD) NON-REVENUE SERVICE TIME NEGATIVE	POSITIVE
Red Line	8.49	7.88	9.00	9.37
Blue/Orange Line	2.76	15.19	3.06	15.98
DC Jurisdiction	10.53	33.43	10.7	29.76
MD Jurisdiction	11.50	0	15.84	0.35
VA Jurisdiction	0.36	2.43	0.42	2.73

LOAD DIFFERENCES (KW)

	P(30°)-P(70°)	P(90°)-P(70°)	P(20°)-P(70°)	P(80°)-P(70°)
Red Line	340	158	450	94
Blue/Orange Line	110	304	153	160
DC Jurisdiction	421	669	535	298
MD Jurisdiction	460	0	794	4
VA Jurisdiction	14	49	21	27

TABLE 6-3 AVERAGE SUPPORT POWER (KW) FOR PASSENGER STATIONS, OFFICE BUILDINGS AND REPAIR SHOPS DURING PRINCIPAL DAILY OPERATIONAL PERIODS

METER	JURIS-DICTION	WEEKDAY AM PEAK	MIDDAY	PM PEAK	EVENING	NIGHT	SATURDAY OPERATION	NIGHT	SUNDAY OPERATION	EVENING	NIGHT
RED LINE PASSENGER STATIONS											
Dupont Circle (MSA3)	DC	369	368	380	376	317	361	314	354	309	307
Farragut North (MSA2)	DC	360	357	359	354	318	336	312	341	318	313
Metro Center (MSA1)	DC	411	405	410	408	389	403	370	398	376	377
Gallery Place (MSB1)	DC	216	217	220	218	196	220	297	205	187	185
Judiciary Square (MSB2)	DC	257	255	256	251	229	240	225	236	223	223
Union Station (MSB3)	DC	278	283	280	273	244	270	242	267	242	242
Rhode Island Avenue (MSB4)	DC	70	63	63	94	89	76	84	61	83	76
Brookland (MSB5)	DC	102	92	104	109	100	104	101	97	98	96
Fort Totten (MSB6)	DC	86	83	83	104	93	88	90	83	88	87
Takoma Park (MSB7)	DC	77	72	70	86	70	76	69	70	77	67
Silver Spring (MSB8)	MD	117	109	108	125	106	110	107	105	113	105
BLUE/ORANGE LINE PASSENGER STATIONS											
Pentagon (MSC7)	VA	417	401	411	415	368	397	364	392	378	365
Arlington Cemetery (MSC6)	VA	106	95	107	104	79	100	82	98	93	81
Rosslyn (MSC5)	VA	388	385	391	384	352	376	343	358	332	330
Foggy Bottom (MSC4)	DC	195	188	189	186	168	185	165	185	170	168
Farragut West (MSC3)	DC	330	324	325	327	300	309	285	316	296	283
McPherson Square (MSC2)	DC	288	291	293	286	254	269	254	270	254	256
Metro Center (MSC1)	DC	309	309	309	306	277	309	279	308	280	279
Federal Triangle (MSD1)	DC	194	192	198	195	180	190	167	187	176	161
Smithsonian (MSD2)	DC	268	261	257	249	225	257	224	258	221	219
L'Enfant Plaza (MSD3)	DC	332	324	327	324	283	304	286	303	283	282
Federal Center (MSD4)	DC	208	203	209	203	182	200	180	201	183	181
Capitol South (MSD5)	DC	264	261	266	262	239	259	241	263	246	243
Eastern Market (MSD6)	DC	88	88	88	88	85	101	97	90	88	92
Potomac Avenue (MSD7)	DC	147	147	152	146	135	145	129	148	136	132
Stadium Armory (MSD8)	DC	229	231	236	233	202	230	200	227	203	196
Minnesota Avenue (MSD9)	DC	96	94	96	114	100	106	103	100	107	101
Deanwood (MS10)	DC	88	82	82	100	80	87	78	80	83	75
Cheverly (MS11)	MD	88	78	77	108	94	92	97	79	96	87
Landover (MS12)	MD	54	49	53	61	51	54	53	43	47	48
New Carrollton (MS13)	MD	146	125	124	215	216	155	200	121	191	179
Gallery Place (MSE3)	DC	148	145	144	145	146	144	148	143	144	145
Archives (MSE2)	DC	72	72	73	73	72	73	73	71	71	71
L'Enfant Plaza (MSE1)	DC	208	209	209	204	183	201	184	201	185	183
OFFICE BUILDING AND REPAIR SHOPS											
Total Office and Shop		3197	3382	3202	2806	2377	2427	2260	2085	2130	2085
Office Building (MOB)	DC	2382	2516	2380	1969	1651	1689	1459	1471	1419	1311
T-St. Repair Shop (MRS)	DC	557	640	606	603	510	533	533	411	507	515
Garden City Shop (MGCS)	MD	258	226	216	234	216	205	268	203	204	259

TABLE 6-4 AVERAGE SUPPORT POWER
FOR METER CONSOLIDATIONS AT VARIOUS OPERATING PERIODS

	WEEKDAY					SATURDAY		SUNDAY		
	AM PEAK	MIDDAY	PM PEAK	EVENING	NIGHT	OPERATION	NIGHT	OPERATION	EVENING	NIGHT
PASSENGER STATION (KW)										
Red Line	2343	2304	2333	2398	2151	2284	2111	2217	2114	2078
Blue/Orange Line	4663	4554	4616	4728	4271	4543	4232	4442	4263	4157
DC Jurisdiction	5690	5616	5678	5714	5156	5543	5097	5463	5127	5040
MD Jurisdiction	405	361	362	509	467	411	457	348	447	419
VA Jurisdiction	911	881	909	903	799	873	789	848	803	776
ALL SUPPORT METERS INCLUDING OFFICE BUILDING AND REPAIR FACILITIES (KW)										
DC Jurisdiction	8629	8772	8664	8286	7317	7765	7089	7345	7053	6866
MD Jurisdiction	663	587	578	743	683	616	725	551	651	678

6.1.4.1. PEPCO Passenger Station Lighting Loads

Table 6-5 shows a summary of the power used for lighting of the passenger stations serviced by PEPCO. This table was constructed using the following information from Metro[7]:

1. Underground stations with center (side) platforms have 70 (120) KW of lighting load.

2. Stations above ground with center (side) platforms have 30 (40) KW of lighting load.

3. The Pentagon and Rosslyn stations have two levels underground, and the lighting load is 130KW.

4. Parking lot lighting loads associated with passenger stations are estimated at 30 watts/space.

Based on this information in Table 6-5, a summary of the lighting loads for Red Line, Blue/Orange Line, and DC, MD and VA jurisdiction passenger stations is presented in Table 6-6.

6.1.4.2. PEPCO Passenger Station Escalator Loads

It is shown in Appendix 9.8 that if as many people ascend escalators as descend them in a given time period at the loading which would be experienced at Metro, the average power consumed in the time period is proportional to the sum of the heights of rise of all of the escalators. This conclusion is valid for the modular escalators supplied by Westinghouse to Metro under medium load conditions. The conversion coefficient from the height of rise to KW is 0.11 KW/ft. of rise.

In order to use this relation between height of rise and escalator power, time periods must be selected where ascending and descending load averages over the periods are relatively equal. These periods are: the AM and PM peak taken together, midday, evening, Saturday and Sunday operation. It is even more valid when considering several passenger stations, such as on the separate lines or the DC jurisdiction where all people must enter and leave the system within 30 minutes.

Using the relationship between escalator power and height of rise, a summary of average power consumed by the escalators is listed in Table 6-7. The heights of rise were calculated based on the Metro information in Appendix 9.9.

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[7] Richard Labonski and George Care, Private Communication, December 17, 1981.

TABLE 6-5 SUMMARY OF LIGHTING LOADS BY PASSENGER STATION

STATION (METER SYMBOL)	JURIS-DICTION	STATION LOCATION	STATION TYPE	NUMBER OF PARKING SPACES	STATION LIGHTING (KW)	PARKING LOT LIGHTING (KW)***	TOTAL LIGHTING (KW)
RED LINE STATIONS							
Dupont Circle (MSA3)	DC	U	S		120		120
Farragut North (MSA2)	DC	U	C		70		70
Metro Center (MSA1)	DC	U	S		120		120
Gallery Place (MSB1)	DC	U	S		120		120
Judiciary Square (MSB2)	DC	U	C		120		120
Union Station (MSB3)	DC	U	C		70		70
Rhode Island Avenue (MSB4)	DC	A	C	300	30	9	39
Brookland (MSB5)	DC	A	C		30		30
Fort Totten (MSB6)	DC	A	C	300	30	9	39
Takoma Park (MSB7)	DC	A	C	1000	30	30	60
Silver Spring (MSB8)	MD	A	C		30		30
BLUE/ORANGE LINE STATIONS							
Pentagon (MSC7)	VA	U	S**		130		130
Arlington Cemetery (MSC6)	VA	A	S		40		40
Rosslyn (MSC5)	VA	U	S**		130		130
Foggy Bottom (MSC4)	DC	U	C		70		70
Farragut West (MSC3)	DC	U	S		120		120
McPherson Square (MSC2)	DC	U	S		120		120
Metro Center (MSC1)	DC	U	C		70		70
Federal Triangle (MSD1)	DC	U	C		70		70
Smithsonian (MSD2)	DC	U	S		120		120
L'Enfant Plaza (MSD3)	DC	U	C		70		70
Federal Center (MSD4)	DC	U	C		70		70
Capitol South (MSD5)	DC	U	C		70		70
Eastern Market (MSD6)	DC	U	C		70		70
Potomac Avenue (MSD7)	DC	U	C		70		70
Stadium Armory (MSD8)	DC	U	C		70		70
Minnesota Avenue (MSD9)	DC	A	C	250	30	7	37
Deanwood (MS10)	DC	A	C	220	30	7	37
Cheverly (MS11)	MD	A	S	500	40	15	55
Landover (MS12)	MD	A	C	1000	30	30	60
New Carrollton (MS13)	MD	A	C	1900	30	56	86
Gallery Place (MSE3)*	DC	U	C		70		70
Archives (MSE2)*	DC	U	C		70		70
L'Enfant Plaza (MSE1)*	DC	U	S		120		120

Note: U - underground A - above ground S - side platform C - center platform
*Green/Yellow Line
**two level
***based on 30 watts per space

TABLE 6-6 SUMMARY OF LIGHTING LOADS BY METER CONSOLIDATIONS

SUPPORT METER CONSOLIDATIONS	PARKING LIGHTING	(KW) STATION LIGHTING	TOTAL LIGHTING
Red Line Passenger Stations	48	770	818
Blue/Orange Passenger Stations*	115	1830	1945
DC Passenger Stations	62	2050	2112
MD Passenger Stations	101	130	231
VA Passenger Stations	0	300	300

*Includes three Green/Yellow Line stations which were on during 1980: L'Enfant Plaza, Gallery Place and Archives.

TABLE 6-7 PASSENGER STATION AVERAGE DAILY POWER OF ESCALATORS

PASSENGER STATION (METER)	JURISDICTION	TOTAL ESCALATOR RISE (FT)	DAILY KW***
RED LINE PASSENGER STATION			
Dupont Circle (MSA3)	DC	540	59
Farragut North (MSA2)	DC	307	34
Metro Center (MSA1)	DC	576	63
Gallery Place (MSB1)	DC	99	11
Judiciary Square (MSB2)	DC	187	21
Union Station (MSB3)	DC	159	17
Rhode Island Avenue (MSB4)	DC	64	7
Brookland (MSB5)	DC	89	10
Fort Totten (MSB6)	DC	85	9
Takoma Park (MSB7)	DC	76	8
Silver Spring (MSB8)	MD	116	13
BLUE/ORANGE LINE PASSENGER STATIONS			
Pentagon (MSC7)	DC	481	53
Arlington Cemetery (MSC6)	VA	219	24
Rosslyn (MSC5)	VA	483	53
Foggy Bottom (MSC4)	DC	134	15
Farragut West (MSC3)	DC	229	25
McPherson Square (MSC2)	DC	266	29
Metro Center (MSC1)	DC	*	*
Federal Triangle (MSD1)	DC	106	12
Smithsonian (MSD2)	DC	237	26
L'Enfant Plaza (MSD3)	DC	720	79
Federal Center (MSD4)	DC	152	17
Capitol South (MSD5)	DC	166	18
Eastern Market (MSD6)	DC	139	15
Potomac Avenue (MSD7)	DC	156	17
Stadium Armory (MSD8)	DC	279	31
Minnesota Avenue (MSD9)	DC	86	9
Deanwood (MS10)	DC	67	7
Cheverly (MS11)	MD	117	13
Landover (MS12)	MD	43	5
New Carrollton (MS13)+	MD	71	8
Gallery Place (MSE3)	DC	**	**
Archives (MSE2)	DC	**	**
L'Enfant Plaza (MSE1)+	DC	**	**

*Included with MSA1 Metro Center.
**Escalators not on in 1980.
***Calculated on basis of 0.11 kw/ft.
+These escalators to lower levels were not in service in 1980.

The average power for all underground stations was determined for the peak revenue service periods and the non-revenue service periods on weekdays in order to verify the validity of the simple power formula for the escalators. The difference between the powers during these two weekday periods should equal the escalator power if the assumptions that all escalators are running during the peak revenue service periods and that of the passenger station loads only the escalators are turned off during the non-revenue service periods. This comparison is shown in Table 6-8. Agreement is within 2%.

6.1.4.3. PEPCO Support Power Model

In this study, support background power is defined as all support power less the lighting and escalator load on the average degree-day. This definition was selected in order to test lighting and escalator energy conservation strategies.

The PEPCO support background power was estimated by subtracting the escalator average power, as calculated using the simple escalator formula described in the previous section, and the full underground station lighting loads from the average support power used in the AM and PM peak revenue service periods taken together. A summary of the resulting support power background for the passenger stations of the Red Line, Blue/Orange Line, and the DC, MD and VA jurisdictions is tabulated together with the lighting and escalator loads in Table 6-9.

In the construction of Table 6-9, it was assumed that station lighting was operational for all periods, and lighting in stations above ground was used only in the evening.The latter assumption is not critical. Escalators were assumed off during non-revenue service time.

With reference to Table 6-9, the actual power and estimated power have been forced to agree during the peak periods because of the estimation method. However, the agreement during the other periods is good with the exception of that of the MD jurisdiction where the metering information was not complete.

Table 6-10 lists the metered power demand and energy use for the office building and repair shops. Since no conservation strategies will be applied to these installations in this study, this power will be considered background in the DC and MD jurisdictions.

TABLE 6-8
COMPARISON OF PREDICTED DAILY AVERAGE ESCALATOR POWER
WITH OBSERVATION USING SIMPLE ESCALATOR POWER FORMULA

SUPPORT METER CONSOLIDATION	KW(PEAK)	KW(NIGHT)	KW(PEAK)- KW(NIGHT)*	KW(ESC.)*
Underground Stations	5552	4943	609	595

*Based on the assumption that all escalators operate during the peak periods and that only the escalators in underground stations are turned off at non-revenue service time, the value 595KW computed using the simple escalator formula compares well with the actual measured power of 609KW.

TABLE 6-9 SUMMARY OF BACKGROUND, LIGHTING AND ESCALATOR POWER (KW) FOR SUPPORT METERS AT PASSENGER STATIONS

	PEAK**	MIDDAY**	EVENING	NON-REVENUE
RED LINE				
Background*	1470	1470	1470	1470
Lighting	620	620	820	620
Escalators	250	250	250	0
Total	2340	2340	2540	2090
Actual Total	2340	2300	2400	2130
BLUE/ORANGE LINE				
Background*	2555	2555	2555	2555
Lighting	1630	1630	1945	1630
Escalators	455	455	455	0
Total	4640	4640	4955	4185
Actual Total	4640	4550	4730	4270
DC JURISDICTION				
Background*	3275	3275	3275	3275
Lighting	1870	1870	1945	1870
Escalators	540	540	540	0
Total	5685	5685	5760	5145
Actual Total	5685	5615	5715	5160
MD JURISDICTION				
Background*	340	340	340	340
Lighting	0	0	230	0
Escalators	40	40	40	0
Total	380	380	510	340
Actual Total	380	360	510	465
VA JURISDICTION				
Background*	520	520	520	520
Lighting	260	260	300	260
Escalators	130	130	130	0
Total	910	910	950	780
Actual Total	910	880	900	800

*The background is determined by subtracting the underground station lighting load and escalator load from the average support power during peak periods.
**Only underground station lighting is on during these periods.

TABLE 6-10
AVERAGE POWER DEMAND DURING PEAK PERIODS AND DAILY ENERGY CONSUMPTION
OF OFFICE BUILDINGS AND REPAIR SHOP

	OFFICE BUILDING (DC) (MOB)	T-ST. REPAIR SHOP (DC) (MRS)	GARDEN CITY SHOP (MD) (MGCS)
POWER DEMAND (KW)			
AM Peak (8:00-9:00AM)	2280	610	290
PM Peak (16:00-17:00PM)	2205	590	235
ENERGY CONSUMPTION (KWH)			
Weekday	47510	13835	6865
Saturday	37375	12525	6570
Sunday	32025	11795	5410
ANNUAL ENERGY USE (MWH)	16000	4900	2400

6.1.5. The VEPCO Support Power Model

Since no detailed information is available on VEPCO support power, the model was patterned after that of PEPCO. The background support power was estimated using the average background of similar type passenger stations serviced by PEPCO. The types of stations considered were underground side platform, underground center platform, and above ground.

Table 6-11 presents a comprehensive listing of lighting and escalator loads (using the simple escalator power formula) in VEPCO passenger stations.

Table 6-12 presents a listing of background, lighting and escalator power for VEPCO service at passenger stations. The background support power was estimated in the same way as in PEPCO serviced passenger stations.

6.1.6. Algorithms for Estimating Support Power Demand and Energy Use

The models developed in Sections 6.1.4 and 6.1.5 can be applied directly to energy conservation strategies involving escalator and lighting power reduction. The following procedure is used.

Estimate of Peak Power Demand

Peak power demand is estimated by summing up the background power, the lighting power, and the escalator power during the peak demand period.

Estimate of Energy Use

Energy use is estimated by summing the background energy (background power x 24 hours/day), the lighting energy (integration of the lighting power over the day), and the escalator energy (integration of the escalator power over the day).

Table 6-13 shows an estimate of the support energy use and average peak power demand for normal operation on a weekly basis. The assumptions for this estimate are:

1. Lighting load of underground stations is continuous.
2. Lighting load of stations above ground is on during evening revenue service operation only (6:00PM-12:00AM).
3. Escalators operate only during revenue service.

TABLE 6-11
PASSENGER STATION LIGHTING AND ESCALATOR LOADS PROVIDED BY VEPCO

PASSENGER STATION	LOCATION	TYPE	LIGHTING LOAD (KW)	ESCALATOR RISE (ft)	AVERAGE ESCALATOR POWER (KW)(0.11/ft rise)
National Airport	A	C&S	70*	84	9
Crystal City	U	S	120	191	21
Pentagon City	U	S	120	169	19
Courthouse	U	C	70	219	24
Clarendon	U	S	120	114	13
Virginia Square	U	S	120	144	16
Ballston	U	S	120	168	18
TOTAL			740		120

A - above ground

U - underground

C - center platform

S - side platform

TABLE 6-12
SUMMARY OF BACKGROUND, LIGHTING AND
ESCALATOR SUPPORT POWER (KW) FURNISHED BY VEPCO

	PEAK	MIDDAY	EVENING	NON-REVENUE
Background	1065	1065	1065	1065
Lighting	670	670	740	670
Escalator	120	120	120	0
TOTAL	1855	1855	1925	1735

AVERAGE DATA ON THE PEPCO SERVICED PASSENGER STATIONS
USED IN DETERMINING BACKGROUND

LOCATION	TYPE	AVERAGE BACKGROUND (KW)	
U	C	147	
U	S	167	
A	C	84	} Average 81
A	S	77	

TABLE 6-13
ESTIMATE OF SUPPORT ENERGY USE AND AVERAGE PEAK POWER DEMAND BY UTILITY/JURISDICTION

		PEPCO			VEPCO
ANNUAL SUPPORT ENERGY (MWH)	HRS/WEEK	DC	MD	VA	
Background	168	49400(72)	5400(90)	4500(58)	9300(58)
Lighting					
Underground	168	16300	0	2300	5900
Above Ground	36	100	400	100	100
Total		16400(24)	400(7)	2400(32)	6000(38)
Escalators	114	3200(4)	200(3)	800(10)	700(4)
TOTAL		69000(100)	6000(100)	7700(100)	16000(100)

( ) indicates % of total support energy.

		DC	MD	VA	VEPCO
SUPPORT PEAK POWER DEMAND (KW)					
Station Background		3275	340	520	1065
Office and Repair Shop Background		2890	290	0	0
Station Lighting		1870	0	260	670
Station Escalators		540	40	130	120
TOTAL		8575	670	910	1855
AVERAGE POWER (KW) USED FOR ENERGY COMPUTATION					
Station Lighting					
Underground		1870	0	260	670
Above Ground		75	230	40	70
Station Escalators		540	40	130	120

6.2. CONSERVATION OPPORTUNITIES

Opportunities for support power conservation were identified in the lighting and escalator loads.

6.2.1. Lighting Load Reduction

Several recommendations were made by the General Manager's Lighting Task Force[8] on lighting energy conservation opportunities.

One recommendation was to replace the indirect fluorescent lighting with direct mercury vapor lighting in both side and center platform underground stations. The estimated reduction in power was 82KW/side platform station, and 39KW/center platform station.

The peak power demand reduction and annual energy savings on incorporating these lighting changes are shown in Table 6-14.

6.2.2. Escalator Load Reduction

A strategy for reducing escalator energy consumption would be to turn off all escalators under 15 ft. height of rise and the third escalator in areas where three escalators service the station from one entrance during off-peak periods.

Table 6-15 presents the results of this strategy. Since escalators are turned off during the non-peak periods, there is no effect on peak power demand reduction. The effect on support energy is very small (1%).

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[8] Final Report of the General Manager's Lighting Task Force, Richard T. Labonski, Chairman et. al., March 26, 1981.

TABLE 6-14

REDUCTION OF POWER DEMAND AND ENERGY USE BY EMPLOYING DIRECT MERCURY VAPOR LIGHTING IN UNDERGROUND STATIONS

	PEPCO JURISDICTIONS			VEPCO
	DC	MD	VA	
NUMBER OF UNDERGROUND STATIONS				
Side Platform	6	0	2	5
Center Platform	14	0	0	1
PEAK POWER DEMAND SAVINGS				
KW	1040	0	165	450
Percent of Support Power	12	0	18	24
ANNUAL ENERGY SAVINGS				
MWH	9100	0	1400	3900
Percent of Support Energy	13	0	18	24

TABLE 6-15
ENERGY SAVINGS BY REDUCING ESCALATOR OPERATION DURING NON-PEAK HOURS OF OPERATION*

	PEPCO JURISDICTIONS			VEPCO
	DC	MD	VA	
Normal Escalator Power (Peak Operation) (KW)	540	40	130	120
Escalator Power Reduction (Non-Peak Operation) (KW)	185	0	28	54
Annual Energy Savings				
MWH	750	0	100	200
Percent of Support Energy	1		1	1

*Escalators with heights of rise below 16 ft.and the third escalator of a three escalator grouping are turned off during non-peak.

7. ENERGY CONSERVATION BENEFITS AND COSTS

7.1. ENERGY CONSERVATION SAVINGS

The direct benefits of application of the energy conservation strategies discussed in Section 5.4 for traction energy, and Section 6.2 for support energy, will be reflected in the reduction of the power bill. Other less tangible benefits are also available, and these are discussed in Section 7.4.

Table 7-1 presents the peak power demand and energy use components of the energy use pattern for normal operation, and for several energy conservation strategies using the 1980 operation. These components have been divided by the servicing utility and jurisdiction. The lower value of the range of peak power demand is the normal or PL2 operation, while the higher value is for catch-up or PL1 operation. If catch-up operation were used on both Red and Blue/Orange Lines for a half-hour interval which exactly coincided with the half-hour demand interval, the peak demand for billing purposes would be nearer the higher value.

The strategies of passenger load factor improvement, by running shorter trains during off-peak periods and escalator use reduction during off-peak periods, will not affect the peak power demand since they do not occur in the peak. The remaining strategies affect peak period operation, and thus, the peak power demand.

Figure 7-1 summarizes the energy cost savings which are possible by employment of the energy conservation strategies considered in this report.

These savings were based on the operation according to the 1980 timetable and system, and are expected to be larger than the numbers in the figure for present day operation. The numbers on a percent basis would remain about the same. The savings are divided according to the demand and energy portions. It is interesting to note that if the demand ratchet in the DC jurisdiction had not been relaxed during the last rate negotiation, the dollar savings of the conservation strategies would remain at the energy use savings level. If the demand ratchets in the MD and VA jurisdictions would be relaxed in future negotiations, the energy cost savings would be higher. (The demand shown in the figure is due to the DC jurisdiction alone, since reduction of peak demand in MD and VA would not reduce the cost.)

As previously mentioned, the increase in peak power demand, by running a catch-up operation when the system falls behind schedule, can create extra demand

TABLE 7-1 PEAK POWER DEMAND AND ENERGY USE COMPONENTS FOR NORMAL OPERATION AND ENERGY CONSERVATION STRATEGIES

	PEPCO			VEPCO
	DC	MD	VA	
PEAK POWER DEMAND (KW)				
Normal Expenditure	36200-43000	5300-6000	4800-5700	
Savings				
Coasting	2300-7500	670-1640	150-990	
Top Speed Reduction	580-6750	200-700	80-890	
Regeneration				
Natural Receptivity	9300-12500	520-840	1520	
Assured Receptivity	10300-14500	1180-1450	1350-1800	
On-board Storage	8550-13000	1050-1370	1330-2060	
Lighting Reduction	1040	0	165	
ANNUAL ENERGY USE (MWH)				
Normal Expenditure	177400	33400	24200	34600
Savings				
Coasting	8000	2400	600	100
Top Speed Reduction	1700	900	200	100
Passenger Load Factor Improvement	18500	2800	2500	2100
Regeneration				
Natural Receptivity	30800	2600	4800	2900
Assured Receptivity	35400	4200	5300	4300
On-board Storage	29400	3900	5000	3500
Lighting Reduction	9100	0	1400	3900
Escalator Reduction	750	0	100	200

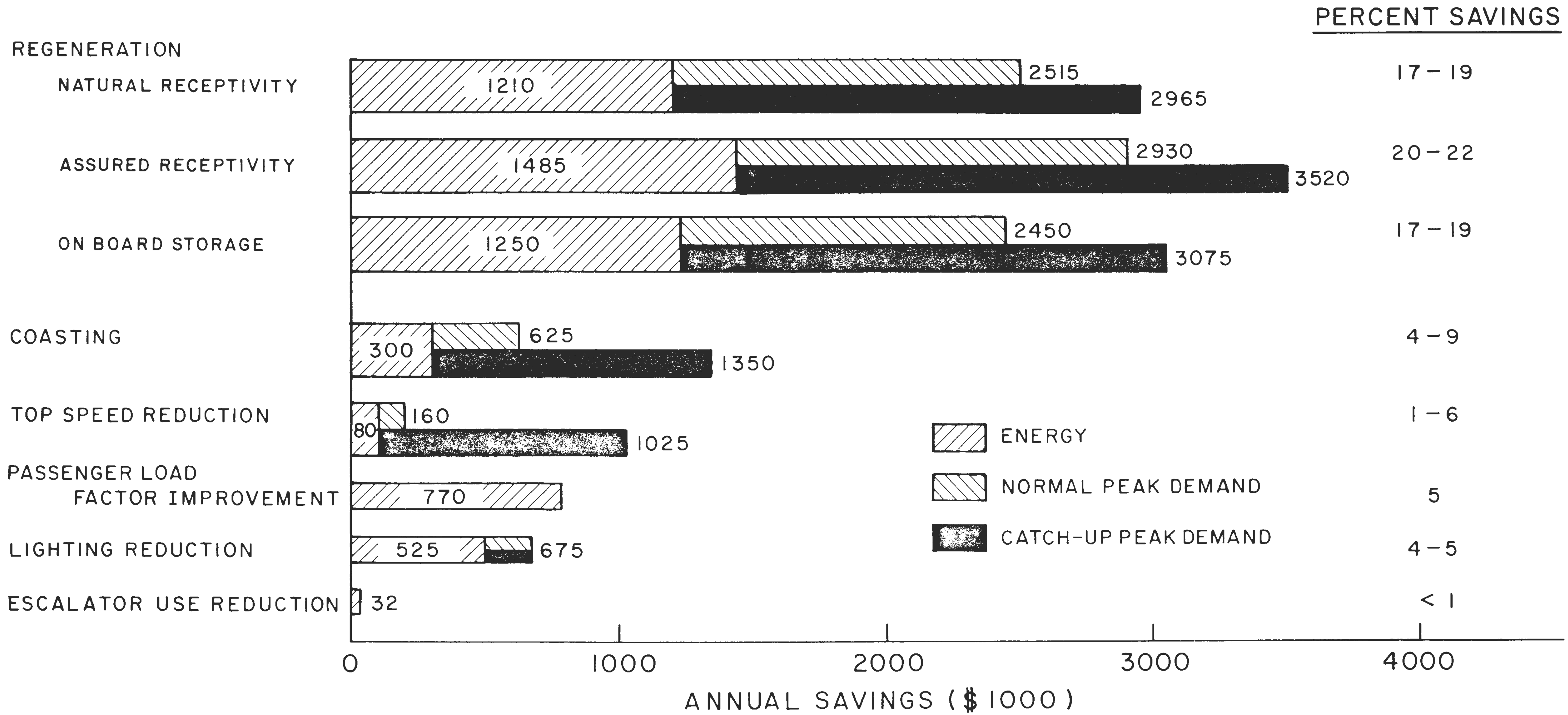

FIGURE 7-1 SUMMARY OF ENERGY COST REDUCTION FOR ENERGY CONSERVATION STRATEGIES

charges. The maximum magnitude of the extra demand level can be obtained directly from Table 7-1 by subtracting the extremes of the range for the power expenditure during normal operation. These values are 6800, 700 and 900 KW for the DC, MD and VA jurisdictions, respectively. The combined value of these charges at the present rate structure is $1.1M. Although it is highly unlikely that conditions would be such to achieve this high level of demand, substantial savings could be realized now in the DC jurisdiction by taking care not to exercise catch-up operation during peak periods.

7.2. ENERGY CONSERVATION COSTS

Certain energy conservation strategies show a high potential for energy cost savings. These strategies will require an investment in the form of equipment purchases, equipment modification and/or Metrorail manpower. Strategies which show high potential for savings and will require expenditures in order to be implemented are: Coasting, Passenger Load Factor Improvement, Regeneration and Lighting Improvement. In addition, Catch-up operation should be exercised during peak periods in order to avoid excessive demand charges. The costs associated with implementing these strategies were estimated with the help of WMATA engineering and purchasing personnel.

7.2.1. Coasting Modification

Although the coasting simulations using the EMM involved holding the brakes off until the coasting speed was achieved in the anticipation of a passenger station stop or a more restrictive speed, discussions with WMATA engineering[9] indicated that a similar effect might be achieved by lowering the speed error on the minus side of the speed regulator unit aboard the car. In order to accomplish this change, the speed regulator unit could be modified at the maintenance shop with two to four man-hours/board.

Using double the number of man-hours, for a more conservative estimate, with a cost of $18.75/man-hour, including overhead, the estimate for modification is $150/per married pair of cars.

If an additional amount of $10,000 is included for engineering, the cost to modify 294 cars for coasting is $32,050.

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[9] Edgar Green, WMATA Engineering.

7.2.2. Passenger Load Factor Improvement

The example used in this study for passenger load factor improvement, was the running of shorter trains during off-peak periods. This involved running alternate four- and six-car trains during the weekday midday operation, and alternate two- and four-car trains during the weekday evening, Saturday and Sunday operation.

To establish this service would require 50 coupling and uncoupling operations on the Red Line, and 140 coupling and uncoupling operations on the Blue/Orange Line per week, based on the 1980 timetable.

The estimated manpower per coupling, or uncoupling, is 15 man-minutes of labor plus 15 man-minutes supervisory, or a total of 1/2 man-hour at a rate of $13.75/man-hour which includes overhead.

Thus, the annual cost for this passenger load factor improvement strategy is $67,925.

7.2.3. Regeneration Strategy

Energy cost savings were estimated for three regeneration strategies: natural receptivity, assured receptivity with regenerative substations, and assured receptivity with on-board energy storage (flywheels). All of these strategies involve chopper control which the present cars do not have.

In the near future, WMATA will receive chopper-controlled cars which are capable of regeneration. These cars are part of a large order in which cam-controlled cars are in the majority. Based on the price of $1,638,120 for a married pair of cam-controlled cars, and $1,694,651 for the chopper-controlled cars, the cost differential of the chopper over the cam control is $28,265.

The percent energy savings achievable by on-board energy storage is roughly the same as that achieved using natural receptivity. Thus, the cost of flywheels could not be justified. Assured receptivity with regenerative substations is only slightly better (21% vs. 18% savings) than natural receptivity. Thus, the expense of inverters for substations cannot be presently justified.

7.2.4. Lighting Improvement

There are two aspects to the lighting improvement costs which were used as the basis for the lighting energy cost reduction estimates discussed in Section 6.2.1. The capital cost for the improvement is $33,000 per underground station, and $28,000 for surface station.[10] In addition, because of less labor and materials required in bulb replacement, there is an annual cost savings of $2,064 for side platform stations, and $1,216 for center platform stations.[11] Above ground stations savings are estimated at $521.

Based on these cost figures with 11 above ground stations and 23 underground stations, of which 14 of the underground stations are center platform and 9 stations are side platform, the capital cost is estimated at $1,076,000, and the cost savings in addition to energy is $41,331.

7.3. COST AND BENEFITS OF ENERGY CONSERVATION STRATEGIES

7.3.1. Performance Modification Strategies

Three performance modification strategies were considered in this study.

1. Reduction of accelerating rate was found not to be beneficial. By reducing the accelerating rate from 3.0 MPHPS to 1.5 MPHPS, the schedule time was increased by about 10% with a small increase in energy consumption. This result can be attributed to the poor efficiency of the cam-control propulsion system during acceleration. This strategy is not recommended.

2. Reduction of top speed to 55 MPH resulted in schedule time increases of 1/2% on the Blue/Orange Line, and 3% on the Red Line. This resulted in energy cost savings of $160,000 to $1,025,000 (1-6% of the power bill).

3. Coasting for speeds above 50 MPH resulted in schedule time increases of 1/2% on the Blue/Orange Line, and 3% on the Red Line. Energy cost savings using this strategy vary from $625,000 to $1,350,000 (4-9% of the power bill). This strategy could be achieved at a cost of $32,050 for modification of the speed regulation board for ATO.

It is recommended that coasting be implemented as a strategy for energy cost savings in Metrorail operation. There is an immediate pay back on the expenditure.

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[10] Final Report of the General Manager's Lighting Task Force, Richard T. Labonski, Chairman, et. al., March 26, 1981.

[11] Ibid.

In addition to the energy cost savings, the use of coasting is expected to reduce the stress on the propulsion system resulting in more reliable operation. Besides reducing the maintenance cost resulting from more reliable operation, reduction of on-the-road failures would mean less catch-up operation which can lower the power bill even further. This additional savings cannot be quantified.

7.3.2. Careful Application of Catch-up Operation

The use of catch-up operation, after train delays during peak operating periods, can lead to excessive demand charges if care is not exercised in its application.

Catch-up operation increases power demand by increasing the car-miles/hour and causing the KWHPCM to be higher during the demand interval. On the basis of the 1980 operation, the use of indiscriminate catch-up operation can result in a $1M higher power bill on an annual basis.

Because catch-up operation increases the stress level on all components of the propulsion system, care in its application can reduce on-the-road failures and maintenance cost. These savings cannot be quantified.

It is recommended that WMATA review its policy on the use of catch-up operation and structure it in accordance with the findings of this study.

7.3.3. Passenger Load Factor Improvement

Only an example of a passenger load factor improvement strategy was considered in this study. It was based on the 1980 timetable during off-peak operation, and reduced the number of cars per train. For the example considered, the annual cost of application of the strategy was $68,000 with an attendant energy cost savings of $770,000 (5% of the power bill); an immediate pay back.

Since the annual car-miles put on each car will be reduced, the expected maintenance cost of the vehicles are expected to be smaller.

A second class of passenger load factor improvement strategy was not considered, namely, turning trains at intermediate stops during peak operating periods. Energy cost savings using this strategy are expected to be of the same order of magnitude.

It is recommended that the whole area of passenger load factor improvement strategies be studied in more detail in order to optimize the cost-benefit to WMATA. There are more benefits than just energy savings because these strategies result in increased productivity. Further consideration of them involves defining all of the timetable and schedule constraints as well as assuring that ridership will not suffer. The high potential for energy cost savings alone justifies undertaking the more detailed investigation.

7.3.4. Regeneration Strategies

At the present time, it is not known whether the cost of modifying the present fleet with chopper control would provide a favorable rate of return on the basis of energy savings achievable by regeneration. The estimated minimum annual savings in the power bill, with the 1980 operating timetable, is $2.5M with a fully regenerating fleet of 294 cars. This savings is $8,500/car/year at that level of operation.

Although not part of the original study, an estimate was made on the energy cost savings which would be realized when ten of the chopper cars scheduled to be delivered to Metro by BREDA Toning, Inc., are in operation on the Red Line. Since the chopper cars must be run in married pairs, two chopper cars were placed in five of the six-car trains.

Both the base and the chopper cases were simulated using the EMM with the 1980 operational timetable. If the present timetable were used, the savings are expected to be larger.

Using the present power rate structure for the DC jurisdiction of PEPCO and the results of the simulation, the use of ten BREDA chopper cars in the mode just described affords an annual energy cost savings of $160,000 ($16,000/car). Some savings, although much smaller, would result in the power bill of PEPCO's MD jurisdiction.

It is interesting to note that without the relief Metro obtained on the DC rate (infinite ratchet to three month ratchet), annual energy savings would only be $82,000 ($8,200/car) which is the energy portion of the savings (no demand).

The results of the study are condensed in Table 7-2.

Because a regenerating car will feed the auxiliaries of the train of which it is a part, the use of two chopper cars per train will assure much of the regenerated

TABLE 7-2 ENERGY COST SAVINGS USING
TEN BREDA CHOPPER CARS WITH 1980 TIMETABLE

KWHPCM SAVINGS COEFFICIENTS (ΔE_R)	
Peak (PL2)	0.34
Off-Peak (PL2)	0.66
Catch-Up Peak (PL1)	0.52
DEMAND SAVINGS	
Car-Miles/hour	1644
KW Savings	560 - 855
Demand Cost Savings	\$78,000 - \$100,000
ANNUAL ENERGY SAVINGS	
Annual Car-Miles Peak	2,467,000
Annual Car-Miles Off-Peak	3,057,000
Annual Energy Savings	2,700 MHW
Annual Energy Portion Cost Savings	\$82,000
TOTAL ENERGY COST SAVINGS	\$160,000 - \$182,000

energy is used rather than dissipated in on-board resistors because of poor line receptivity. Thus, there is a better chance that all regenerated energy is used if two chopper cars are used per train.

This better receptivity is also the reason that annual savings on a per car basis is much higher if only a few cars are chopper controlled ($16,000/car) rather than the whole fleet ($8,500/car).

Our present study of WMATA is showing that because of the shorter interstation distances and shorter headways, the Blue/Orange Line is more receptive than the Red Line. It is also clear that full use of chopper cars during all operating periods will assure maximum energy savings.

Although other operational conditions may rule against it, our recommendation, on the basis of energy cost savings, is that the chopper cars be used two to a train during all operating periods, and the maximum number on the Blue/Orange Line.

Energy savings with regeneration using natural receptivity at WMATA shows a power bill savings of 17-19%. This number is in the same ballpark as was measured at the Sao Paulo, Brazil, rail transit system (18%)[12] which has an operation similar to the WMATA Metrorail.

There are ancillary savings which can be obtained by incorporating regeneration. Because less heat of braking will be dumped into the dynamic brake resistors aboard the car, which in turn ends up in the tunnels, less power for tunnel ventilation will be required. This should also reduce power costs.

It is recommended that after proper verification of energy savings obtained from the new chopper cars, that the cost-effectiveness of modifying some of the present fleet with chopper control be studied.

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[12] The Evolution of Chopper Controlled Propulsion Systems, I.R. Barpal, Westinghouse Electric Corporation, Proceedings of the International Conference on Advanced Propulsion Systems for Urban Rail Vehicles, Feb. 1980, sponsored by U.S.D.O.T.

7.3.5. Lighting Changes

The General Manager's Committee on Lighting recommended that the indirect fluorescent lighting at the passenger stations be replaced with direct mercury vapor lighting. The energy cost savings is estimated at $675,000/year (4-5% of the overall power cost) with an additional savings in replacement lamps estimated at $41,000/year, or a total annual savings of $716,000. The estimated capital cost is $1,067,000 which would be payed back in 1 1/2 years.

7.3.6. Escalator Load Reduction

The annual energy cost savings achieved by turning off all escalators with less than a 15 ft height of rise, and the third escalator in areas where three are serving the station from one entrance, in off-peak periods, is $32,000 (<1% of total power costs).

Unless this strategy is used for egress control, turning off "down" escalators during peak periods, is not recommended because heavily loaded down escalators can regenerate power.

8. PROGRAM PLAN FOR IMPLEMENTING ENERGY COST REDUCTION STRATEGIES

Specific strategies which are cost-effective in reducing energy cost have been identified and evaluated using simulation in this study. The recommended strategies are coasting, careful catch-up operation, passenger load factor improvement, regeneration, and lighting improvement. Application of these strategies are not necessarily additive. For example, if both passenger load factor improvement and coasting are implemented, the energy cost savings would not be the sum of the separate savings. It would be necessary to correct the savings for coasting by the reduction of car-miles which results from the passenger load factor improvement. However, coasting plus lighting improvement are additive.

A plan which leads from the present study to the full implementation of the strategies, is presented in the following sections.

8.1. IMPLEMENTATION OF A COASTING STRATEGY

The following steps should be undertaken in the implementation of a coasting strategy.

1. A two-car train should be modified for coasting operation at different coasting levels, including no coasting. The train should be instrumented to measure traction energy and running time. Tests should be performed during non-revenue operation at both PL1 and PL2 at three different coasting levels on the Red Line. Simulations using the EMM should be completed as well, for comparison. The simulation should be compared to the tests results for verification.

2. If the energy savings are borne out by the tests, a running time level should be selected by Metrorail which would not increase schedule time significantly. The speed regulator units should be modified at the proper minus speed band error. Energy cost savings could be verified by completing a regression analysis on PEPCO metering pulses, from the Red Line, for a month before, during, and a month after the modification period.

3. The remainder of the fleet should be modified for coasting and run as normal operating practice.

It is important that enough tests are made during the execution of this plan so that the statistical nature of the relationship between running time and energy consumption are taken into account.

8.2. CAREFUL CATCH-UP OPERATION

The following steps should be undertaken in the implementation of careful catch-up operation policy.

1. A test period should be selected during which no catch-up operation would be permitted on the Red Line. This period should include twenty weekday peak operational periods (6:00-9:30AM, or 3:00-6:30PM). Using PEPCO metering information, peak demand during these periods should be compared with peak demand generated during peak operating periods when catch-up operation was permitted.

2. Using these data, a policy should be formulated on the use of catch-up operation. This policy should include consideration of the demand interval, length of time that catch-up should remain in effect, and location of the trains to which it is applied.

8.3. 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 just energy cost savings. The following steps should be taken to implement passenger load factor improvement.

1. A committee should be established, consisting of scheduling, transportation, maintenance and energy management personnel, to recommend scheduling strategies which could meet Metro constraints, and at the same time increase the passenger load factor by reducing operational car-miles.

2. Each of the scheduling strategies developed should be tested for present day operations using the EMM to determine the energy cost savings.

3. The scheduling strategies which have high potential for car-miles savings should be evaluated in terms of the additional cost to Metrorail operations.

4. Those strategies which have high benefit/cost ratios should be implemented.

As a side issue in connection with proper scheduling strategies, it is important that WMATA know the present passenger load factor on the system. This information is available by sampling the gate counters (fare collection system) from time to time, and changing the origin-destination data into link-volume information.

A second method, which may result in better information on passenger load factor, may be developed by using the load weighing system aboard the transit car to estimate the number of passengers. Since the load weighing system sets the tractive effort to maintain a constant initial accelerating rate, it could be used as an estimator of the weight of the car between stations. A test train could be run through the system, during peak operation, to sample the passenger load factor directly. A study should be initiated to determine the feasibility of this concept.

8.4. REGENERATION

Two steps are required to assure that the BREDA chopper cars are used in a manner to achieve the best energy cost savings subject to the operational and maintenance constraints on them:

1. Energy savings on the chopper cars should be measured as soon as the cars are received. These cars must be measured for traction energy during revenue service in order to obtain high receptivity.

2. Once the chopper cars' energy savings have been verified against the prediction of the simulator, alternative options should be studied using the EMM in order to maximize the energy benefit of the chopper cars subject to the operational and maintenance constraints.

A study should be undertaken to determine under what circumstances it could be cost-effective to turn present cam-control cars into chopper cars. This study could only be undertaken after the energy savings on the BREDA chopper cars are verified.

8.5. LIGHTING IMPROVEMENT

The savings achievable by lighting improvements are of the same order as that of coasting. The capital cost to implement the lighting strategies are much larger than for the coasting strategy.

It is recommended that the lighting strategy be reviewed for possible implementation.