



U.S. Department of Transportation  
**Urban Mass Transportation  
Administration**

UMTA-PA-06-0083-86-2

**ENERGY MANAGEMENT GUIDELINES  
FOR  
RAIL TRANSIT SYSTEMS  
VOLUME I**

**SEPTEMBER 1986**

**UMTA Technical Assistance Program**

**ENERGY MANAGEMENT GUIDELINES**  
**FOR**  
**RAIL TRANSIT SYSTEMS**  
**VOLUME I**

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**SEPTEMBER 1986**  
**FINAL REPORT**

**Document is available to the U.S. public through the**  
**National Technical Information Service,**  
**Springfield, Virginia 22161**

**Prepared for**

**U.S. DEPARTMENT OF TRANSPORTATION**  
**URBAN MASS TRANSPORTATION ADMINISTRATION**  
**Office of Systems Engineering**  
**Washington, D.C. 20590**

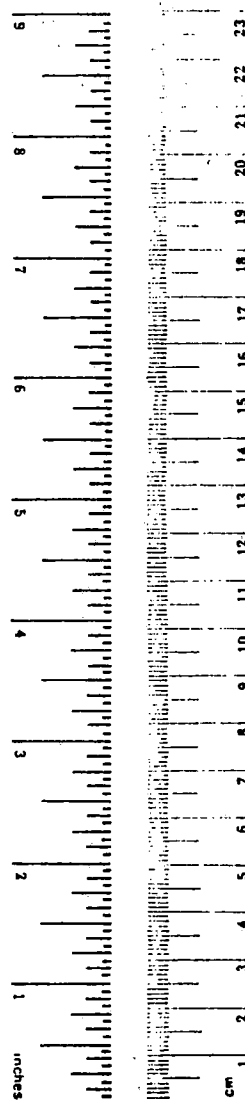
1. Report No. UMTA-PA-06-0083-86-2		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle "Energy Management Guidelines for Rail Transit Systems" Volume I				5. Report Date September 1986	
				6. Performing Organization Code	
7. Author(s) Richard A. Uher, Onkar N. Sharma				8. Performing Organization Report No.	
9. Performing Organization Name and Address Rail Systems Center, Mellon Institute Carnegie-Mellon University 4400 Fifth Avenue Pittsburgh, PA 15213				10. Work Unit No. (TRAI5)	
				11. Contract or Grant No. PA-06-0083	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Urban Mass Transportation Administration 400 Seventh Street, S.W. Washington, D. C. 20590				13. Type of Report and Period Covered Final Report 7/9/84-10/30/86	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>The cost of electricity is a significant portion of the operating costs of rail transit systems. The impact of increasing energy costs is felt by those systems presently in operation and will be felt by those in the planning or construction phases. Because of the number of nuclear power plants coming on line in areas served by transit, the influence of electricity costs on operating and design policies of rail transit authorities is expected to grow in future years.</p> <p>Concerned by rising energy costs, managers of several rail transit authorities have established energy management programs. The objectives of these programs are energy cost reduction and improved energy efficiency. Energy management is a process of understanding a system's energy requirements, with the goals of reduced energy cost and increased energy efficiency. Both goals enhance rail transit productivity. The bottom line is lower electric bills for the transit authority.</p> <p>As a rule, energy management can foster its largest payoff when it is initiated during the design and construction phase of a rail transit system. The high dollar savings occur because low energy cost technology and operating practices can be engineered into the system at the outset. However, changes in technology and operations of present transit systems can also reduce the electric bill. Reduction of energy cost can be achieved through energy conservation, load management, and power rate intervention. These guidelines describe the tools and methodologies for assessing energy conservation strategies and power rate structure modifications.</p>					
17. Key Words Rail Transit Systems Energy Management Power Rate Structure			18. Distribution Statement Report is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 85	22. Price

## METRIC CONVERSION FACTORS

### Approximate Conversions to Metric Measures

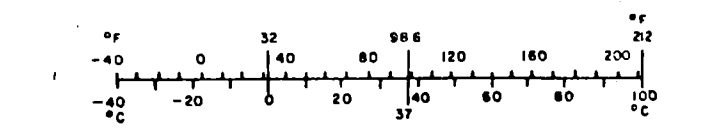
Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.09	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.8	square meters	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.6	square kilometers	km <sup>2</sup>
	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
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 <sup>3</sup>	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°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. 226, Units of Weights and Measures, Price \$2.25, SD Catalog No. C 13.10.286.



### Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
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
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	
<b>MASS (weight)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
<b>VOLUME</b>				
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 <sup>3</sup>	cubic meters	35	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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U.S. Department  
of Transportation

**Urban Mass  
Transportation  
Administration**

Headquarters

400 Seventh St., S.W.  
Washington, D.C. 20590

JUL 1 1987

Dear Colleague:

The Urban Mass Transportation Administration (UMTA), in cooperation with transit authorities, sponsored the STARS (Subsystems Technology Application to Rail Systems) Program in 1979 to reduce costs as well as improve the reliability and maintainability of rail transit systems.

Under the STARS Energy Reduction Projects, operational strategies and design guidelines for energy cost reduction and improved energy efficiency were developed. The Rail Systems Center of Carnegie Mellon University conducted many of these projects in recent years. These strategies and guidelines are now incorporated into the enclosed three volumes of Energy Management Guidelines for Rail Transit Systems.

We hope that this information will help to reduce the overall energy consumption of transit systems.

Sincerely,

-----  
Ronald D. Kangas  
STARS Program Manager

-----  
Fred L. Sing  
UMTA Project Manager

ENERGY MANAGEMENT GUIDELINES  
FOR RAIL TRANSIT SYSTEMS  
VOLUME I

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# 1. INTRODUCTION

## 1.1. BACKGROUND

The cost of electricity is a significant portion of the operating costs of rail transit systems. The impact of increasing energy costs is felt by those systems presently in operation and those in the planning or construction phases. The influence of electricity costs on operating and design policies of rail transit is expected to grow in future years.

Concerned by rising energy costs, managers of several rail transit authorities have established energy management programs. The objectives of these programs are energy cost reduction and improved energy efficiency. The purpose of these guidelines is to outline the procedures and methodologies to achieve these management objectives.

Energy management is a process of understanding a system's energy requirements, with the goals of reduced energy cost and increased energy efficiency. Both goals enhance rail transit productivity. Increased energy efficiency means moving more people for lower energy expenditures and lower energy cost. This results in smaller electric bills for the transit authority. The energy management goals translate into moving more people at lower energy cost. The cost of any program defined to meet these goals must be included as an offset against lower energy cost.

Energy management research and development for rail transit systems was initiated under Department of Transportation sponsorship at the Rail Systems Center (RSC) at Carnegie-Mellon University in 1976. The effort was established to help rail transit authorities manage energy within their organizations. Subsequently, through additional funding under the Urban Mass Transportation Administration and contracts directly with Transit Authorities, the RSC enlarged its capabilities in this discipline.

The output of this work is the tools and methodologies for assessing energy conservation strategies and power rate structure modifications. Section 5.0 of this volume contains a bibliography of projects, reports and papers published as a result of the program and other similar studies.

## **1.2. GUIDELINES CONTENT**

The Energy Management Guidelines Manual is organized into two separate volumes and an executive summary. The executive summary was written for the general managers of rail transit authorities and other people who have decision-making power for implementation of energy management.

Volume I is devoted to procedures. Besides this introduction, it contains four other sections. Section 2.0 develops the basics of energy cost. Sections 3.0 and 4.0 are concerned with the procedures for establishing energy management programs during rail system design and construction and for systems presently in operation. Section 5.0 contains a glossary of terms and Section 6.0 contains a bibliography of projects, reports and papers on the subject.

Volume II contains the methodologies, analyses techniques and strategies, which can be used to achieve the goals of increased energy efficiency and lower energy cost. Examples of the application of these techniques and strategies are also included. Section 1.0 deals with energy conservation strategies for reducing energy consumption. The role that modification of the power rate structure plays, through rate negotiations/intervention, is discussed in Section 2.0. Section 3.0 addresses the topic of load management, which can reduce power demand, thus lowering the demand component of the electric bill. Section 4.0 presents a description of the Energy Management Model (EMM) which is a tool used to simulate traction operation and its resultant energy consumption on a rail transit system. Section 5.0 discusses the methodologies and analytical tools necessary to conduct an energy audit on a rail transit system. The audit is an important step in identifying opportunities for energy cost reduction.

## 2. THE BASICS OF ENERGY COST AND EFFICIENCY

### 2.1. ENERGY COST

The factors that determine electricity cost in rail transit are related to variables of system design and operating practices (referred to as the energy use pattern), and the power rate structure of the electric utilities that serve the system. The energy use pattern is controllable within limits by transit management. The power rate structure, which sets the schedule of charges for electricity for energy use, power demand, and facilities is a matter of negotiations between the transit authority and the electric utilities subject to rate making jurisdiction of the public utility commissions.

The cost of electricity on rail transit systems is made up of facilities, power demand and energy use components. The facilities charges are generally fixed and may partially be funded by the transit systems' contributions-in-aid of construction. The energy consumption and power demand components result from operating the transit system. Energy consumption is the actual use of power integrated over time and it is measured by electric meters in units of kilowatt-hours (kWh). Power demand represents the generation, transmission and distribution facilities shared by transit with other customers or groups of customers of the electric utility serving the transit system. Power demand is measured and recorded by the meters and computed using a complex mathematical formula, which is usually different for every rail transit system. Power demand has units of kilowatts (kW).

The formula used by the electric utilities to compute the power demand component of the electric bill for rail transit systems in North America can be generalized to a few basic elements.

1. Specification of a *demand consolidation*, which is a way to combine the recordings of several meters for computing demand. *Maximum demand* is determined *coincidentally*, when in a given customer class and/or

jurisdiction<sup>1</sup>, it is the maximum of the sum of the average energy use recorded on all electric meters in the same demand interval; and, *noncoincidentally*, when it is the sum of the maximum average powers recorded on all electric meters in any demand interval.

2. Computation of a *monthly demand*, which is the maximum demand as determined using the demand consolidation method in a monthly billing period.
3. A *ratchet demand*, simply called a *ratchet*, calculated by a predetermined formula, and which represents a minimum demand level for billing purposes.
4. Computation of the *billing demand* which is the maximum of the monthly demand and the ratchet.

A survey of the power rate structure of ten rail transit agencies in the United States has shown that the demand interval varies from 15 minutes to 60 minutes.

In conclusion, it is the marriage of the power rate structure with the energy use pattern which determines energy cost, and in order to effect energy cost reduction, both aspects must be addressed by transit management.

## 2.2. ENERGY EFFICIENCY

The true measure of rail transit energy efficiency is related to the movement of people. The index most commonly used is the watt-hour per passenger-mile. This is a productivity index, for it relates mission oriented output (passenger-miles) to energy input (watt-hours). The index includes marketing effectiveness as well, since passenger-miles depends on how the system is used by its customers.

Energy management performance indices represent measures which can be used by transit authorities to determine the effectiveness of energy management strategies and/or gauge the energy productivity of the transit system. Indices need not be passenger-mile based.

---

<sup>1</sup>The jurisdiction is the area over which the regulatory body (usually the public utility commission) governs the setting of rates by the electric utility. The customer class is a category used by the utility to classify the customer according to his energy use pattern. For example, residential and industrial users are in different customer classes.

Requirements for such indices, which can provide a measure of energy management performance are that they

1. are easily measured and accumulated.
2. have some meaning in terms of energy productivity.
3. remain fairly constant gauges of energy productivity even with varying schedules and passenger loading.
4. be predictable using simulation models.

Indices which have been used in this work are generally quotients which have been obtained by dividing such things as total energy consumption, power demand or energy cost by vehicle-miles or car-miles, ton-miles, passenger-miles or passengers.

$$\text{Index} = \frac{\text{Energy, Demand or Cost Based}}{\text{Passenger, Vehicle, Weight Movement Based}}$$

Although indices can be put together using various combinations of numerators and denominators, only a few of them meet the requirements just specified.

A useful index which is reported by many rail transit systems is the kilowatt-hour per car-mile. There are two major problems with the reporting of this index. First, energy on some systems includes both traction and support components, while on other systems only the traction component is included. Secondly, kilowatt-hours per car-mile varies with the types of trains being run, the routes on which they run and the time of day and day of week on which they operate.

All indices, which are reported, are based on "average" properties of the transit system and are most useful when comparing the effects of energy conservation strategies with other types of operation.

## **2.3. ENERGY CONSUMPTION RELATED DESIGN AND OPERATING PARAMETERS**

The design and operating parameters which influence energy use, power demand and ultimately energy cost can be grouped into six broad categories:

1. General transportation system characteristics such as passenger volumes, headways, station dwell times, speed, accelerating and braking rates and sizes of trains,
2. Right of way characteristics such as miles of track, number of stations, station spacing, grades, speed restrictions and curves,
3. Power transmission and distribution system characteristics such as impedances, voltage ranges, type of transmission and distribution networks and substation equipment.
4. Vehicle characteristics such as empty weight, train resistance characteristics, auxiliary power required and rotational weight.
5. Vehicle propulsion and braking system type and characteristics.
6. Support power requirements.

Each of these categories are discussed in more detail in the following sections.

### **2.3.1. General Transportation System Characteristics**

Passenger volumes between the stations throughout the day influence both the dwell time at stations, running time between stations and vehicle weight between stations. During the peak periods, which usually occur during the morning and evening rush hours on weekdays, energy use on a kilowatt-hour per car-mile basis is usually the highest. This high energy use results from movement of heavier cars, shorter headways in passenger loading and, train interference because of additional traffic requirements to meet the peak.

The minimum headway is generally in effect during the peak rail transit operating periods. In terms of power demand, the peaks will occur during the time of minimum headway. Bunching, which occurs because of traffic interference, and subsequent "catch up" operation can even cause higher power demand in many cases.

Dwell times at the stations are generally in the range of 5 - 30 seconds. Dwell

time influences both the additional length of time the auxiliaries must run, and the schedule time between terminals. If the station is exposed to the outside environment, energy requirements for passenger comfort (heating and air conditioning) are determined by the doors opened time. Unfortunately, dwell times tend to be longest during the peak operating times.

Speed is one of the most significant parameters which determine energy requirements for moving trains. Maximum speed determines the kinetic energy which must be supplied to the cars as well as the work done against train resistance (aerodynamic drag and rolling friction). Schedule speed, proportional to the reciprocal of schedule time, is related to the time that auxiliaries must function, and thus, the total auxiliary energy required. Schedule speeds on most rail transit systems are 40 - 60% of maximum speed.

Acceleration and braking rates are less significant in the determination of energy consumption. Acceleration and braking rates are in the range 1.0 - 3.5 MPHPS. High speed taper of braking rates is practiced on several rail systems. A taper exists when braking begins at high speed at a low rate and gradually increases to some higher value at some lower speed. In some circumstances, regeneration of braking energy (where electric motors are turned into generators, and power is fed from the moving train to other trains or storage devices) is more effective if braking rates are lower. However, the effect on schedule time by reducing braking rates must also be considered.

As the number of vehicles (cars) per train increases, so does energy consumption. Because aerodynamic drag laws are such that lead and trailing vehicles have the largest effect (piston and suction) on drag, rather than the internal cars, the kilowatt-hours per car-mile is lower for longer trains. Heavy rail trains have from 1-12 cars and light rail trains have 1-4 cars (pair of cars).



### **2.3.2. Right of Way Characteristics**

Passenger station spacing is an important parameter in the determination of energy consumption. Since the train must be brought to a stop at each station, all kinetic energy is converted to heat and released to the environment. The exception is transit systems which have regenerative braking. In this case, much of the kinetic energy can be returned to the line to be used to power other trains.

Profile characteristics such as grades, curves and speed restrictions are very important to energy requirements. Maximum grades for heavy rail rapid transit lie in the range of 5-6%, while for light rail transit, maximum grades can be as high as 10%. Curves have their most important influence on energy consumption because of their effect on speed limits for reasons of safety and passenger comfort. Limiting speed means that trains must slow down to negotiate curves, thus, giving up their kinetic energy. Curve resistance, which is a part of train resistance, is less influential on energy consumption. The net energy required to propel trains increases in the negotiation of grades only when trains are required to brake on down grade sections. The gravitational effect would allow complete energy recovery (minus the electrical losses).

### **2.3.3. Power Transmission and Distribution Characteristics**

For rail rapid transit, power transmission refers to that portion of the electrical network between the metering points of the electric utilities and the transit substations, while power distribution refers to the portion from and including the transit substations to the power collection apparatus on the trains. In general, power transmission is accomplished at high voltage AC, while power distribution is effected at lower DC voltages (600-1000v).

Electrical transmission and distribution losses, which run at 5-15% of total power delivered to the metering points, must be considered in an overall energy balance. Reduction of these losses is generally accomplished by reducing the

effective impedances (resistive portions) between the source of supply and the trains. Many of the modern transit systems accomplish this impedance reduction by increasing third rail and return rail conductivity, the use of tie stations, which tie the third rail or trolley together at several points and normally tying the whole power distribution system together.

#### **2.3.4. Train & Vehicle Characteristics**

The principal vehicle parameters which affect energy consumption are empty weight, passenger loading, shape and cross sectional area, and auxiliary power.

Empty vehicle weight refers to the vehicle in operational condition without passengers. For heavy rail, empty vehicle weights range from 20-65 tons. For light rail, empty vehicle weights range between 20-30 tons. For lighter rail vehicles, the passenger load represents a larger percentage of the total weight. As a consequence, the energy expended per passenger-mile, is expected to be smaller for lighter weight vehicles.

The crush load, which represents a passenger loading of 1 passenger per square foot of area, is almost never realized in practice. Even in densely packed subway trains during peak operating hours, scheduling practice, human resistance and access to the cars during these periods rarely allow this condition to exist. A more reasonable number to use when considering vehicle gross weight is 60-80% of crush load during the peak. A few interstation trips may have 90-95% of crush load for short times during the peak period.

Vehicle aerodynamic cross section and shape influence the aerodynamic portion of train resistance, and thus energy consumption. This parameter is more important for higher speed operation.

### 2.3.5. Vehicle Propulsion & Braking System Characteristics

As used here, the term propulsion system refers to the total conversion of electrical power which is input at the power collector to mechanical power at the wheels of the vehicle. It generally includes power control equipment, traction motors, gear units and wheels. Figure 2-1 presents a block diagram of a general propulsion system, showing its principal components and energy flow paths.

Figure 2-2 shows the various power control units used on North American rail transit systems. The oldest, and most mature technology is resistor switching, which is accomplished by using a cam-driven (pneumatic or electric) series of switches to control motor voltage. The present state of the art technology is the chopper control, which acts as a fast operating switch to control the voltage to the motors. Both schemes, resistor switching and chopper control operate with DC traction motors. The DC traction motor, which is also a mature technology, is of two types: the series motor and the separately excited motor. Control of traction motors may also be effected in a gross manner by switching the motor circuit configuration. This latter method of control is illustrated in Figure 2-3, together with motor field control. By allowing less current to pass through the DC motor field relative to the armature, either by shunting the field or through separate field excitation, a larger tractive effort can be achieved at higher speed operation.

Thus, in DC motor operation, control of the tractive effort can be achieved by motor circuit switching, field control and chopper control or resistor switching. Selection of the particular method is generally based on supplier availability and initial cost to meet certain performance criteria. However, the selection will also effect energy consumption. Resistor switching tends to be more efficient on rail transit systems with long distances between stations (>1.0 mile), while chopper control tends to be more efficient on systems with short distances between stations (<1.0 mile). The use of chopper control to regenerate braking energy to power other trains, will make the chopper control train more energy efficient.

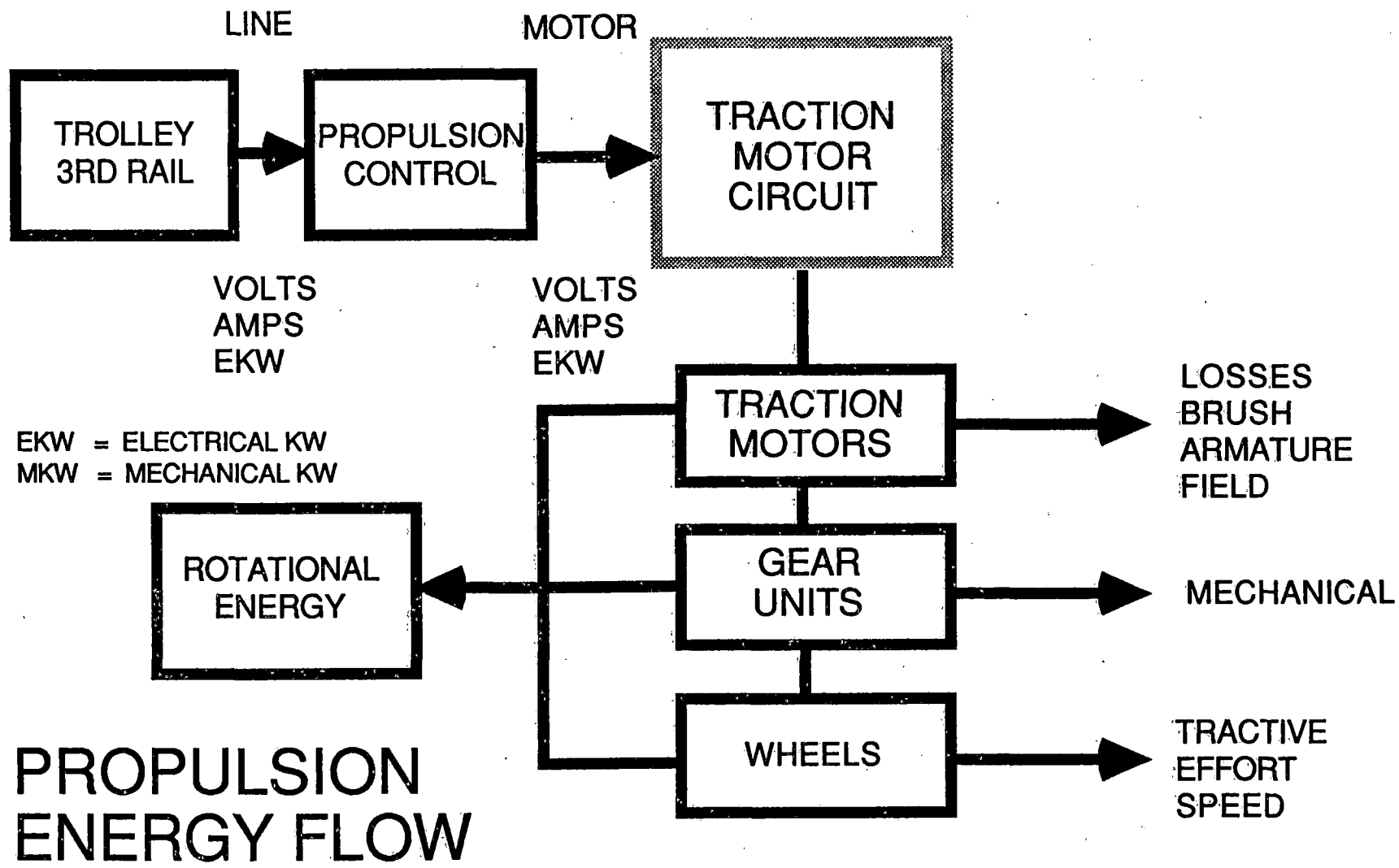


FIGURE 2-1

## PROPULSION CONTROL DIAGRAM

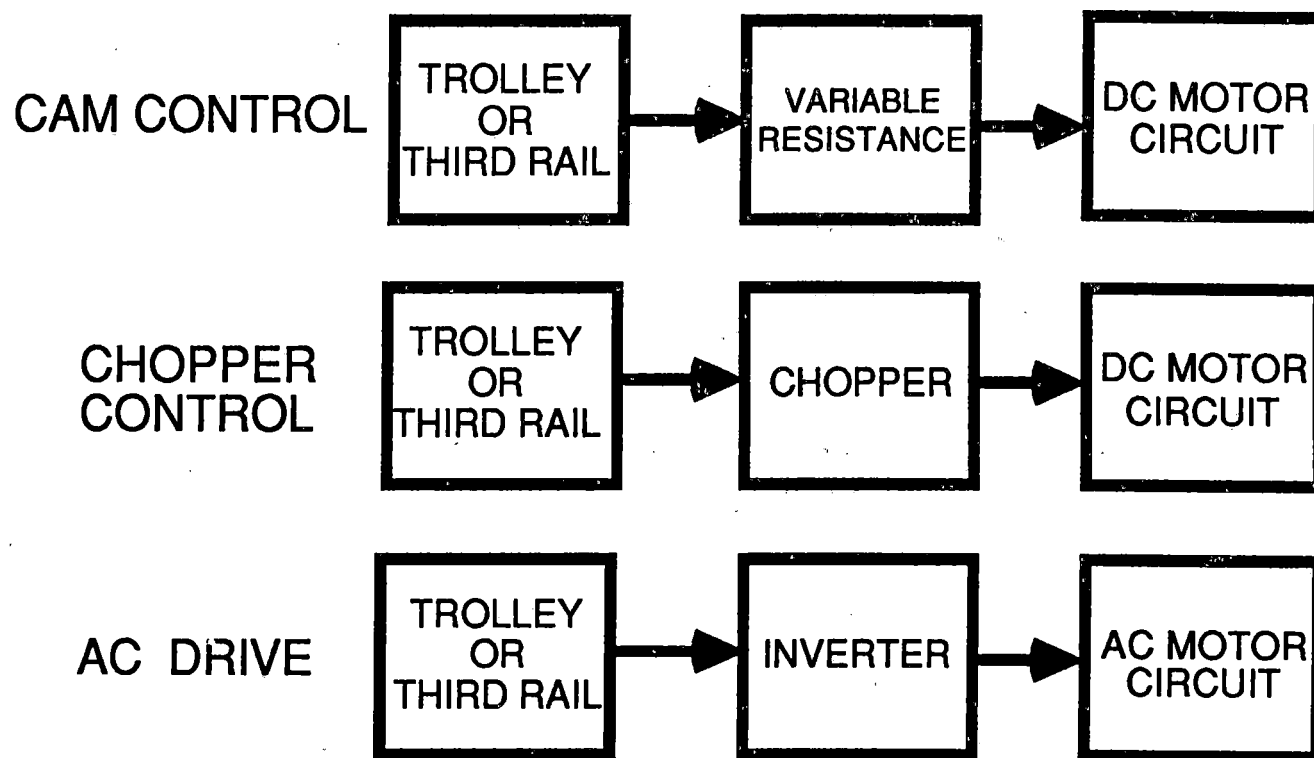


FIGURE 2-2

Braking systems on rail transit systems rely on the propulsion system to supply dynamic braking effort. Under normal operation, friction brakes are used to supplement dynamic braking and are "blended" into the system to keep the total braking rate at required performance levels. Under emergency conditions, it is normal practice to use friction brakes as the last resort, and the emergency braking rate is usually quoted exclusively on friction braking.

Friction braking and dynamic braking, which dumps electrical energy into resistor grids or into tracks (track brake), convert electrical energy into heat energy. Dynamic braking, which changes mechanical energy into electrical energy, is called regenerative braking. Some of this regenerated energy is used to propel other trains, thus reducing the amount of energy that the utility must supply. All regeneration on North American transit systems is accomplished using chopper controlled propulsion system.

The use of the AC drive (inverter controlled three phase AC induction motors) is becoming more common on new rail transit car orders in Europe. It is expected that North America will follow suit in the future.

The U.S. Department of Transportation has sponsored an AC drive development program over the past several years. Some of the goals of this AC drive program are as follows:

1. Demonstrate that low-maintenance, energy-efficient AC induction motors can be successfully applied in traction service.
2. Develop a system to be priced competitively with DC chopper control systems.
3. Demonstrate that reduced maintenance and energy usage with AC propulsion will realize substantial life cycle cost benefits.
4. Design a system flexible enough to meet a wide range of present and future transit applications.

The AC drive and chopper control are very competitive from the point of view

of energy consumption. Actual, site-specific analyses must be conducted to determine which will consume less energy. These analyses are not part of the UMTA program.

#### **2.3.6. Support Power Requirements**

Electrical energy use on transit systems can be divided into two broad categories, traction and support. All of the parameters, previously discussed, which affect energy use, referred to traction energy. Auxiliary support power aboard the car is also integrated into traction energy, since it must be metered along with propulsion power.

The support end uses are air conditioning, heating, lighting, escalators and elevators, tunnel ventilation, signal & communication equipment and running of mechanical devices.

The electrical services to the support functions just enumerated are provided to the passenger stations, wayside, office buildings, maintenance facilities and control facilities.

#### **2.4. TRACTION ENERGY BALANCE**

Traction end uses are the running of the trains and provision of auxiliary support power aboard the vehicles. All of this energy is delivered to the vehicles via the power transmission and distribution subsystem through the power collector. Figure 2-4 presents a diagram of the detailed end uses of power received at the power collector of a typical rail transit vehicle. Since this vehicle regenerates energy upon braking, the gross electrical input is the sum of the net electrical input and the regenerated energy.

# MOTOR CIRCUIT MODES

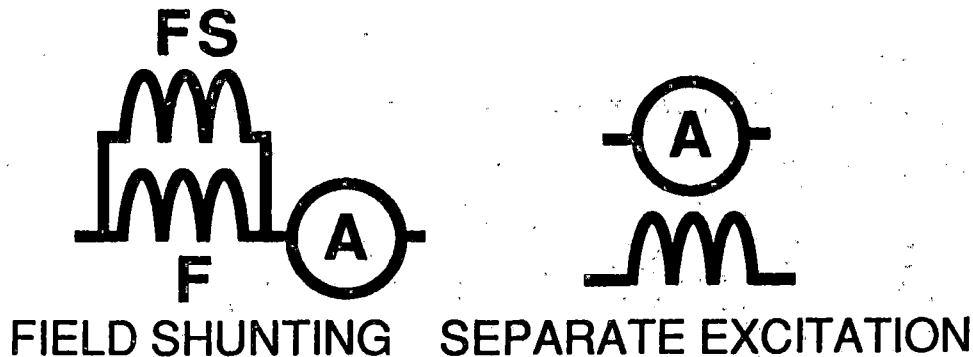
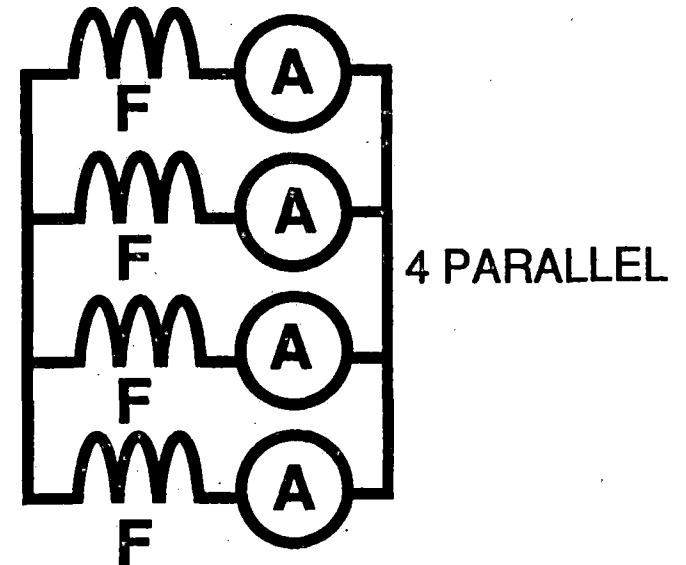
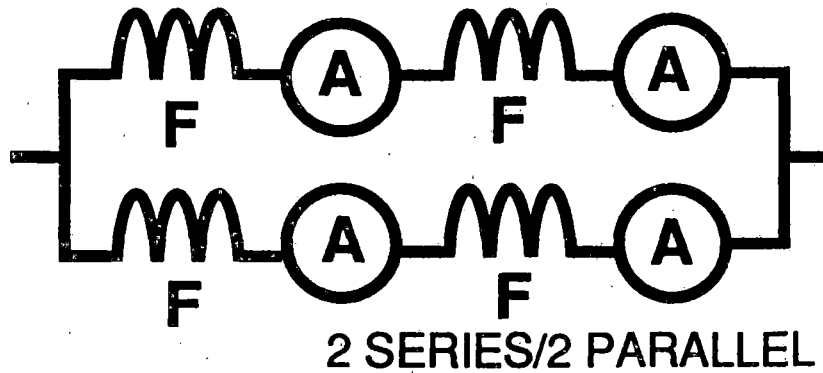


FIGURE 2-3



# RAIL VEHICLE ENERGY FLOW DIAGRAM

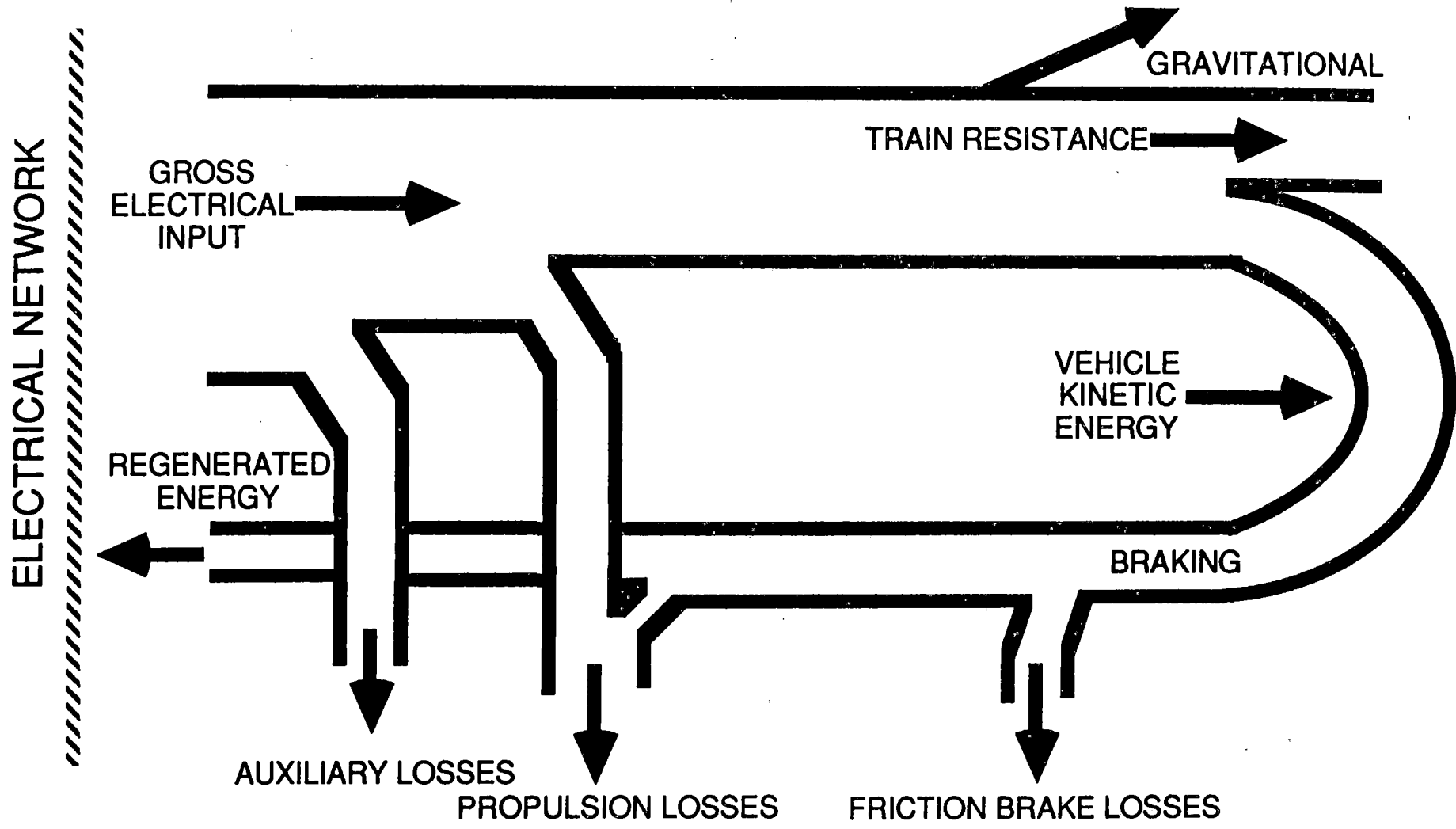


FIGURE 2-4

## **3. RAIL SYSTEM DESIGN AND CONSTRUCTION**

### **3.1. OVERVIEW**

Rail system design and construction refers both to new rail systems or to additions to or extensive modifications of old rail systems. As a rule, energy management can produce its highest payoff when it is initiated prior to design and construction, because low energy cost technology can be engineered into the system at the outset.

Design and construction of a rail system is usually divided into five phases, all of which generally overlap:

1. Planning
2. Design
3. Procurement and Construction
4. Testing
5. Initial Revenue Operation

There are activities associated with reduction of energy cost and improvement of energy efficiency in each of the five phases. During phases 1-3, analyses are conducted to determine the energy cost consequences of major planning, design, procurement and construction decisions. These costs must be included in the overall cost-effectiveness evaluations as part of the decision making process. It is also during this time (phases 1-3) that major energy conservation strategies are designed into the system, provided that these strategies are also cost-effective. During phases 4-5, verification of the energy cost and efficiency model of the rail system is conducted. What generally results from the verification process, is a fine tuning of the model, so that it can be used during full revenue operation of the system. The use of the model during revenue operation of new and old rail systems is discussed in Section 4.0.

The energy management activities appropriate to each of the five phases of rail system design and construction are discussed in the following subsections.

### **3.2. PLANNING PHASE**

During the planning phase of a rail system, an energy management plan is assembled. This plan contains an outline of all of the tasks necessary to integrate energy cost reduction and improved energy efficiency into the design, procurement and construction of the rail system and subsequent verification of this integration.

The following issues are addressed in the plan:

1. Identification of analytical studies to be undertaken during design, which may have a significant energy cost component.
2. Preliminary discussions with the electric utilities which will provide power to the rail system, to determine the range of options of power rate structure available.
3. Management controls to assure that short term design decisions, which have a major energy cost or efficiency impact, are considered. This may include appointment of an energy management officer.

The analytical studies undertaken during the design phase should include the investigation of cost-effective energy conservation and load management strategies.

The components of the energy management plan are discussed in the next section.

### **3.3. DESIGN PHASE**

During this phase of the design and construction process, energy cost and efficiency trade-off studies are conducted. The use of the Energy Management Model (EMM) or similar simulation tools for those studies involving traction energy is highly recommended. Studies should be conducted in the following areas.

### **3.3.1. Route Selection**

Although route selection is usually initiated during the planning stage of the design and construction, it is truly a part of design. There is an energy cost component to route selection, which has not generally been considered in weighing alternatives. Topography and route directness can have an important influence on energy cost during subsequent revenue operation. If the energy cost component of alternative routes is estimated and included among the other cost considerations in the alternative route analysis work, a more complete picture is obtained before a decision on the final route is made. Factors which should be considered are:

1. Grades and Curves vs. Tunnels
2. Grades, Curves and Out-of-Way Distance vs. Direct Routes
3. Gravity assistance during acceleration and braking

Grades cause energy to be expended whenever braking is required on the downhill sections. Curves cause energy to be expended because of curve resistance to motion and because of comfort and safety speed limits imposed in curved sections of the route. The speed limits require trains to brake, losing some of the energy of motion to heat.

Because of expensive right-of-way acquisition and/or terrain modification, less direct routes may be considered which add longer distances and impose track curvature. These less direct routes sometimes carry with them an energy cost penalty which would be paid over the lifetime of the system. This energy cost penalty should be factored into the analyses prior to making the decision for the less direct route.

During route selection in congested areas, such as urban centers, the effect of gravity assistance in acceleration and braking should be considered. As used here, the term gravity assistance refers to up-graded sections when trains are moving into lower speed (including stops at stations) and down-grade sections when trains are

moving into higher speed regions.

The energy effect of route selection alternatives can be estimated using train performance simulation, and simply comparing energy costs for the different routes considered.

### **3.3.2. Station Locations**

There can be significant energy cost implications in the location of passenger stations. The term location refers both to the vertical (above/at/below grade) and the geographical. Stations located far below the surface require energy for lighting, escalators, elevators and environmental control. Also, stations located deeper underground than adjacent stations could cause more traction energy to be expended because of adverse grades negotiated by trains in the ingress and egress to the station. Displacement of the station from the general direct route will also have energy cost implications. These costs are estimated using train performance simulation. The change in support energy required as alternative vertical station locations are considered should also be estimated to complete the analysis.

### **3.3.3. Track Network**

The track network refers to the number of parallel tracks, including turn backs and sidings, along the route. Selection of the track network can significantly affect both energy cost and efficiency. The use of turnback tracks at intermediate stations allows the flexibility of better passenger loading during both peak and off-peak hours. Likewise, regions of three or four parallel tracks or sidings allow running of local and express service to optimize passenger loading.

In addition to specific energy cost and efficiency components, selection of the track network has an effect on overall transit productivity.

### **3.3.4. Passenger Station Accommodations**

Accommodations and services for passengers in station areas will use energy. The energy cost is recurring over the lifetime of the station. There are several issues of energy use in passenger stations, which should be addressed in the design:

1. Lighting Selection vs. Architecture
2. Lighting Selection vs. Security & Safety
3. Air Conditioning/Heating vs. Passenger Comfort
4. Escalator and Elevator Control
5. Automatic/Manual/Convenient Switching Off of Selected Support Systems

Design of passenger stations for modern rail transit should consider the energy cost component.

Control of selected support systems, such as Lighting, Air Conditioning, Heating, Escalators and Elevators can allow portions of the system to be switched off at selected critical times, either when demand is reaching its maximum or when not required.

### **3.3.5. Power Transmission and Distribution**

Many considerations affect energy cost in the selection of the power transmission and distribution system's network configuration and components. These considerations are:

1. Physical layout
2. Inverter/Energy storage substations
3. Circuit conductivity
4. Nominal Voltage and Voltage tolerances
5. Power factor
6. Circuit monitoring

### 3.3.5.1. Physical Layout

The physical layout of the power transmission and distribution system can affect energy consumption. For support systems, it is important that substations be located near support equipment to reduce transmission and distribution losses. In addition, substation ratings should be chosen near the loads they will serve. If ratings are too high, no-load losses will be too high for the loads served. The same considerations apply to the traction distribution network. Substation location should be as physically near the track as practical. If the distribution system is DC, it should be normally tied together electrically. Tying the system together will reduce losses and allow regenerated power to be better used by other trains.

The physical layout must also guarantee uninterrupted and adequate power to meet transit needs in a reliable fashion. In many cases this is accomplished using a dual feeder system.

### 3.3.5.2. Inverter/Energy Storage Substations

Energy storage devices in substations can be used for load management purposes or for assuring that power regenerated by trains is absorbed during non-peak operating periods. Likewise, inverter substations, in which regenerated power can be returned to the electric utility, are also used to assure receptivity of regenerated power.

Both energy storage devices in substations and inverter substations lie in the advanced technology area. The value of reducing maximum power demand was recognized by the New York City Transit Authority in the late 1960's and early 1970's when they initiated research into a battery storage system for peak load shaving. In this proposed storage system, some of the required peak power has to be supplied from batteries, which are charged during off-peak operating times. Peak load shaving may be of value when the demand component of the electric bill is significant. This strategy for reducing power cost is very sensitive to the demand charge. No

prototypes of such systems are yet available.

Inverter substations and energy storage devices, which are used to assure receptivity of regenerated power, have not yet advanced to prototype stage. The value of these advanced technology devices in saving energy is still disputable. Although during periods of light transit system loading, when natural receptivity is low, energy may be saved using these devices; during periods of heavy loading, when natural receptivity is high, these devices may compete with other trains absorbing the power causing a net increase in energy consumption.

The exact value of energy savings using storage devices in substations or inverter substations depends upon a complex set of physical and operational characteristics of the transit system as well as institutional variables (in the case of an inverter substation, the utility may not give full credit for returned power) involving the electric utilities serving the system. As a consequence, it is necessary to perform a site-specific study using the EMM or similar tool, to determine the potential for energy savings. There is also a technical risk factor involved, since none of the devices are yet proven in the transit application.

#### **3.3.5.3. Circuit Conductivity**

Although it is desirable to have the conductivity of both traction and support power electrical circuits as high as practical to reduce electrical losses and aid fault detection, this discussion will be concerned with traction power distribution circuits. There is an economic tradeoff of the capital cost of building high circuit conductivity into the traction power circuits against the savings in energy cost realized by reducing losses and increasing the natural receptivity of the traction power system when using regenerative braking.

The conductivity of the traction power circuits can be made high by any or all of the following methods:

1. Increasing the conductivity of the third rail or trolley by using more



conductive material per unit length or by using a cable in parallel with the third rail or trolley, tying them together at many points.

2. Increasing the conductivity of the negative return by electrically connecting more running rails in parallel and/or by using cable in parallel with the running rails tying them together at many points.
3. Increasing the number of substations per unit length of route so that the distance between feed points and power collectors is smaller.
4. The use of tie stations between substations to effectively feed the power through more parallel paths to the trains.

Anyone of these methods for increasing traction power circuit conductivity involves more capital and sometimes more operating expense, which must be traded off against energy cost savings. Factors which must be accounted for in estimating the cost of achieving high traction power circuit conductivity include circuit protection requirements, maintenance requirements and the additional cost for achieving the conductivity in materials and components.

#### **3.3.5.4. Nominal Voltage and Voltage Tolerance**

Selection of the nominal voltage under which power is delivered to the trains is usually governed by the kind of traction equipment available on the market together with safety considerations. For modern traction systems for heavy and light rail, nominal voltages in the range 600-1500 VDC have been selected. These voltages have been 600, 750, 1000 (BART), and 1500 (European). Commuter rail systems in the United States have been run at 3000 VDC, but modernization programs have replaced these with 25kv AC.

Higher nominal voltages tend to reduce traction power distribution losses, but at the same time require more initial cost because of requirements for insulation, protection and grounding. Traction power systems outside the range 600-1500 VDC do not now exist in this country.

The second voltage consideration is the maximum and minimum traction power distribution voltage allowed because of its effect on traction or other components in

the system. The ratio of the maximum to nominal voltage affects the range of regeneration capability, and hence the natural receptivity of the system. Likewise, the ratio of the minimum to nominal voltage affects the losses in the power distribution system, with modern traction equipment. The lower ratio generally means more losses.

Standards for traction power distribution have generally been (+10%) and (-20%) on nominal voltage, and most components and equipment operating within these circuits are designed to these standards. In the light of the increased use of regeneration, the standards should be re-evaluated. For example, a larger maximum voltage would increase natural receptivity of regeneration, however, standard equipment which tolerates the higher voltage for substations, tie stations, propulsion and auxiliaries may be difficult to find.

#### **3.3.5.5. Power Factor**

Some electric utilities impose power factor penalties on their customers in the form of increased charges. With most traction and support power systems, power factor is not a problem. Installation of power factor control equipment generally eliminates this problem.

#### **3.3.5.6. Circuit Monitoring**

Circuit monitoring (power, voltage, current) is important when the data obtained are used to achieve some objectives. The concern here will be to monitor power and voltage of both traction and support power electrical circuits in order to reduce electrical energy cost.

Power demand monitoring, which forms the basis for computing energy cost, can be accomplished at three different levels; real time, batch processing and electric bill analysis. Only real time monitoring need be considered in rail design and construction.

Power demand monitoring in real time would be required for a load management system. The objective is to monitor the power demand trend over the early portion of the demand interval and predict the power demand for the interval. In its most sophisticated form, the monitor system would issue a warning or response upon prediction that the demand level will exceed preset values.

### **3.3.6. Preliminary Rate Structure Review**

It is during the early portion of the design phase that a preliminary evaluation of the power rate structure should be conducted. All of the electric utilities which could provide power to the rail system should be identified. Likewise, all of the public utility commissions, which have jurisdiction over rate and service matters should also be listed. In some cases, such as the Washington D. C. Metrorail, more than one utility provides power to the system and the system extends into more than one jurisdiction. There are several steps in the rate structure evaluation process.

The first step in the evaluation is to determine into which customer class the utilities intend to put the rail system. If a railway customer classification is already recognized within the jurisdiction, then it is likely that the new service would be grouped into that class. If such a class does not exist, then it is likely that the utility will want to put the service into one of the existing commercial/industrial customer classes. This may not be appropriate in terms of the rate based on the utilities' cost to serve the rail system as a customer. To conduct this first step of the evaluation, management from the rail system should meet with utility personnel. These meetings should be formalized in the sense that detailed reports should be put together for the record. Prior to the meeting, a rail system team should undertake some work to familiarize itself with tariffs, existing customer classes, operating revenues and expenses of the utility, customer class load characteristics, and significant rate making policies.

The second step in the preliminary rate structure evaluation is the review of the

specific rate that the utilities intend to charge the rail system. This review should be conducted to determine rate fairness to the transit system and for the purposes of determining the cost of energy for various scenarios of rail equipment selection and operational strategies, which may be investigated during the design process. The rate should reflect customer and load characteristics of the rail system. It should be just, reasonable, non-discriminatory, and based on the cost of providing service.

The third step is to conduct a tradeoff study on the ownership of the excess or special transmission lines from the utilities' substations to the feeds to the rail transit substations. It is a general rule that when the transit authority owns these lines, the meters are placed at the utility's substation and all power delivered to the transit substations, which feed from the utility substation, is recorded on a single meter. The power may also be metered at a higher voltage, which may mean a more favorable rate structure. By taking power delivery at a higher voltage level, a rail transit authority can assure itself over all lower costs of providing service.

The tradeoff study on the ownership of the transmission lines may involve many uncertainties. The results of the study will depend on the rate structure under which the rail system will receive its service. At this period in the design stage, this may be an unknown. What should be done, however, is to conduct the study on the basis of several possible scenarios, each of which is likely to occur.

During the preliminary rate structure review, several meetings should be held with the electric utilities which will serve the system. These initial meetings will set the tone for subsequent rate negotiations.

### **3.3.7. Vehicles**

The vehicles to be used to make up the train consists which are used for revenue service are an important consideration in assessment of energy consumption. There are several ways that the rail vehicle influences energy consumption. One way

is through the physical characteristics, principally weight and physical dimensions. Selection of propulsion and braking subsystems also has a large influence on energy consumption while the trains are running. The auxiliary power requirement on-board the car influences traction energy since that power must be delivered to the car via the traction power distribution system (third rail or trolley). Finally, characteristics of the car or fleet that can indirectly affect energy consumption are grouped under operational flexibility. These characteristics generally refer to the ability to match car-miles to passenger-miles using the minimum number of car-miles. Such things as quick uncouple/couple operations and the ability to use cars as head ends and in interiors of trains provide this operational flexibility.

#### 3.3.7.1. Vehicle Weight

Vehicle empty weight contributes to the energy consumed by trains. Percentagewise, energy savings which result from vehicle weight reduction are less than the percent weight removed from the car. However, the number of miles accumulated by the car during its lifetime is substantial.

An index, defined as

$$\frac{\% \text{ Energy Consumption Reduction}}{\% \text{ Weight Reduction}}$$

is sometimes used as a measure of the rate of change of energy consumption with weight. Typically, this index ranges between 0.1-0.4 for rail transit, which means that if 10% of the weight can be taken out of a transit car, a 1-4% savings in traction energy consumption is possible.

Transit systems with longer distances between stations will show less energy reduction with car weight reduction than those with shorter distances. Weight reduction should be considered as a strategy in reduction of total life cycle cost, rather than just energy, which would include capital expenditures (for design and manufacturing), cost of money, and energy and maintenance cost. Maintenance cost

should include both vehicle and track. The influence of vehicle weight reduction on safety is also an issue which must be addressed.

### 3.3.7.2. Vehicle Streamlining

Much traction energy is used to overcome train resistance. Vehicle streamlining, which includes reduction of frontal cross sectional area of the train, better aerodynamic shaping and better smoothing of inter-vehicle gaps in a train, has been discussed as a technique for reducing the aerodynamic portion of train resistance.

An index defined as

$$\frac{\% \text{ Energy Consumption Reduction}}{\% \text{ Reduction in Aerodynamic Drag}}$$

is a good measure of the rate of change of energy consumption with improvement of train aerodynamic performance. For rail transit, this index lies between 0.05-0.15, which means that a 10% reduction in aerodynamic cross sectional area would result in 0.5-1.5% decrease in train energy consumption. The actual value depends on both the maximum speed at which trains operate and the interstation run distances. As in the case of vehicle weight reduction, vehicle streamlining decisions should be based on a life-cycle cost basis, rather than on energy savings alone.

### 3.3.7.3. Propulsion and Braking Systems

Propulsion systems for rail transit can take several forms. In terms of numbers, the dominant form is the cam-controlled resistor switching with DC series motors. The present state-of-the-art in rail transit propulsion involves solid state control in the form of DC drives and AC drives.

In terms of numbers, chopper control using DC series motors is dominant of all solid state control. It is expected that in the future, inverter controlled induction motors may be the dominant drive for rail transit application.

The purpose of a propulsion system in rail transit is the conversion of input electrical power to mechanical power at the wheels, which drive the vehicle. A secondary purpose is the conversion of mechanical power input through the wheels during braking to output electrical power. The conversion of electrical to mechanical power is called the power mode and the conversion of mechanical to electrical power is called the braking mode. The action of the system in the braking mode is a form of dynamic braking which is simply termed "electrical braking".

There are efficiencies associated with the conversion processes in both the power and braking mode. The efficiency is always expressed as the ratio of the output power to input power. As illustrated in Figure 3-1, in the power mode, efficiency is the ratio of the mechanical power output at the wheels to the input electrical power; while in the braking mode, it is the ratio of the mechanical power input at the wheels to the output electrical power. The efficiency is always less than unity.

In the power mode, the input electrical power may come from the third rail or trolley or a storage device aboard the vehicle. In the braking mode, the output electrical power may be delivered to the third rail or trolley, storage devices aboard the vehicle, or resistors, in which it is dissipated. If it is delivered to the third rail, trolley or storage devices aboard the vehicle, it is called regenerated power, which means it has the potential of being reused by other trains or the same vehicle. Regeneration with natural receptivity refers to the condition where only other trains on the system use the regenerated power. Regeneration with assured receptivity means that some positive action is taken to assure that regenerated power is used productively. This positive action may be on-board energy storage systems or regenerative substations, which deliver regenerated power back to the electric utility.

Every propulsion system has a maximum tractive effort and electrical braking effort curve. This curve is the plot of traction force at the wheels versus the speed

# PROPULSION SYSTEM EFFICIENCY

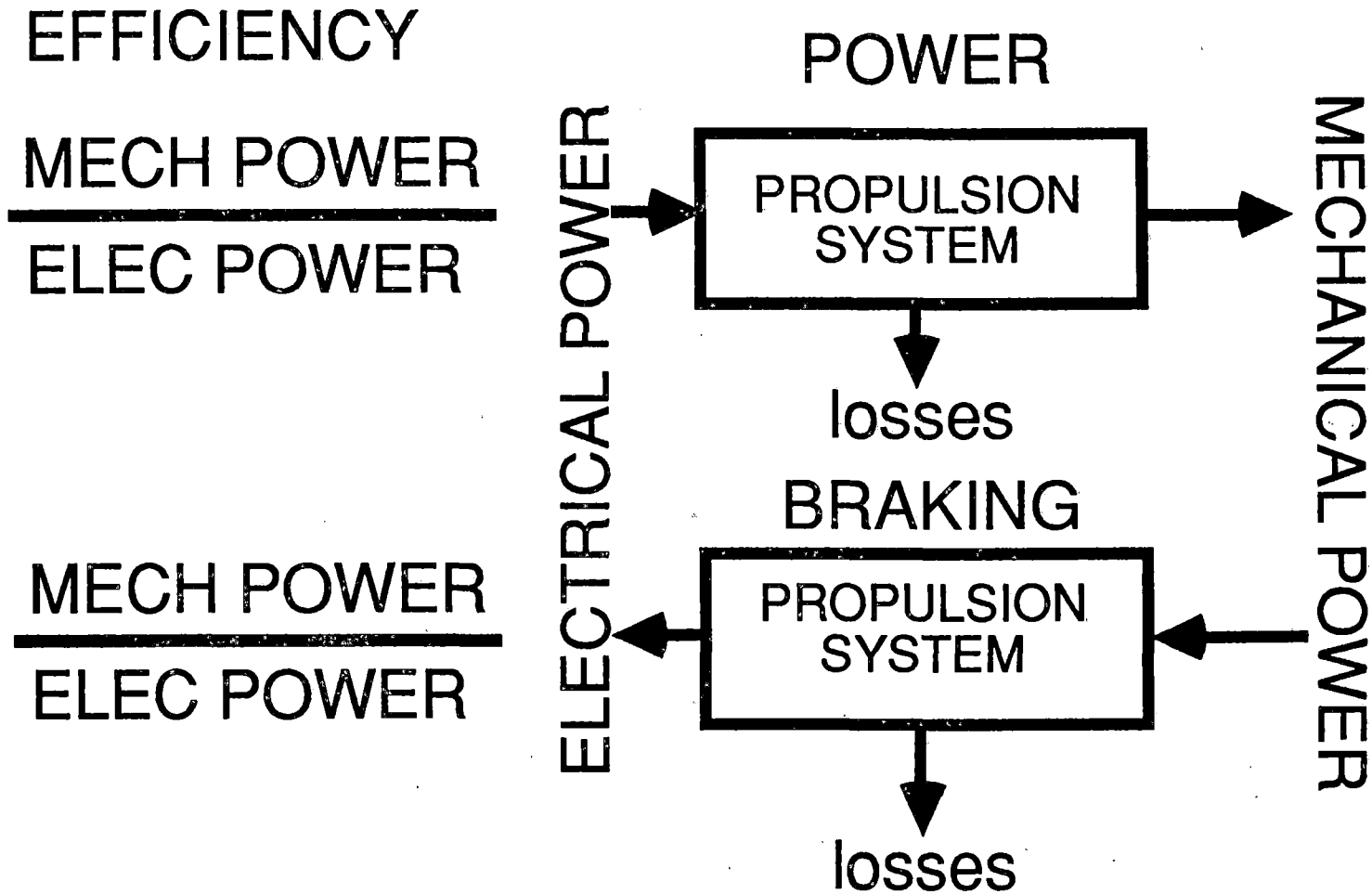


FIGURE 3-1



at which the vehicle carrying the propulsion system is operating. Examples of these kinds of curves are shown in Figure 3-2. The propulsion system is able to access any point within the power and braking regions of Figure 3-2. The efficiency of conversion of input to output power depends on the particular tractive effort and speed at which the propulsion system is working. Typical efficiency curves for a propulsion system in the power mode are shown in Figure 3-3 (cam-control) and Figure 3-4 (chopper control). Efficiency is plotted as a function of speed for several values of maximum tractive effort. Similar curves for the braking mode are also shown in Figure 3-5.

Although braking on rail transit cars is a blended combination of electrical and mechanical (friction) components, the electrical portion is performed by the propulsion system. The braking system usually refers to friction braking. The purpose of the braking system is to convert mechanical power into heat. Some of the electrical power, converted from mechanical power by the propulsion system in the braking mode, may also be dissipated in heat in resistors on board the vehicle. Since heat is the end use, this portion of the electrical power plus the mechanical power dissipated as heat in the friction brakes are considered together. The less power dissipated as heat in braking means the more power available for regeneration, which is of primary interest in the braking mode.

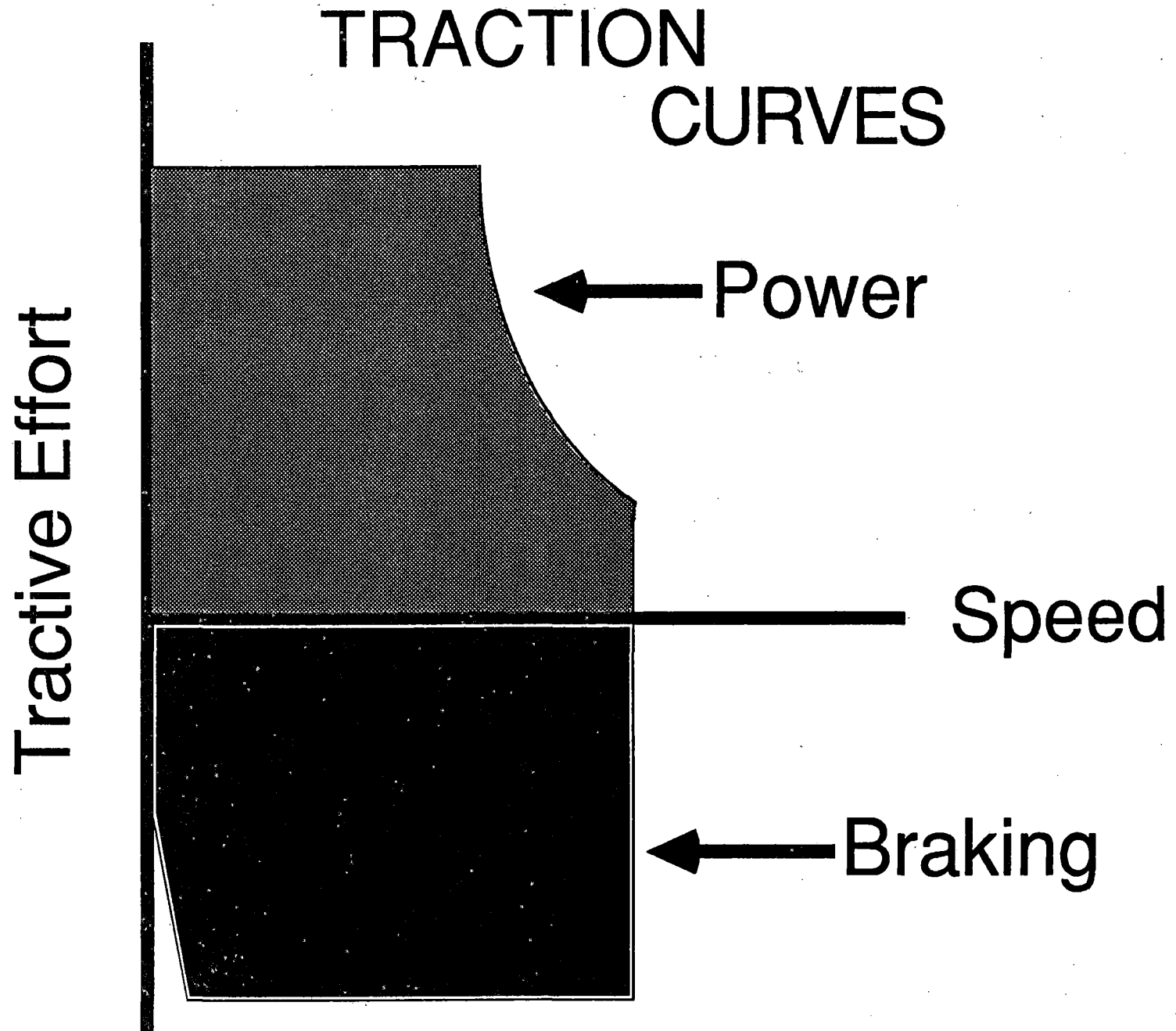


FIGURE 3-2

# PROPULSION EFFICIENCY

CAM-CONTROL POWER MODE

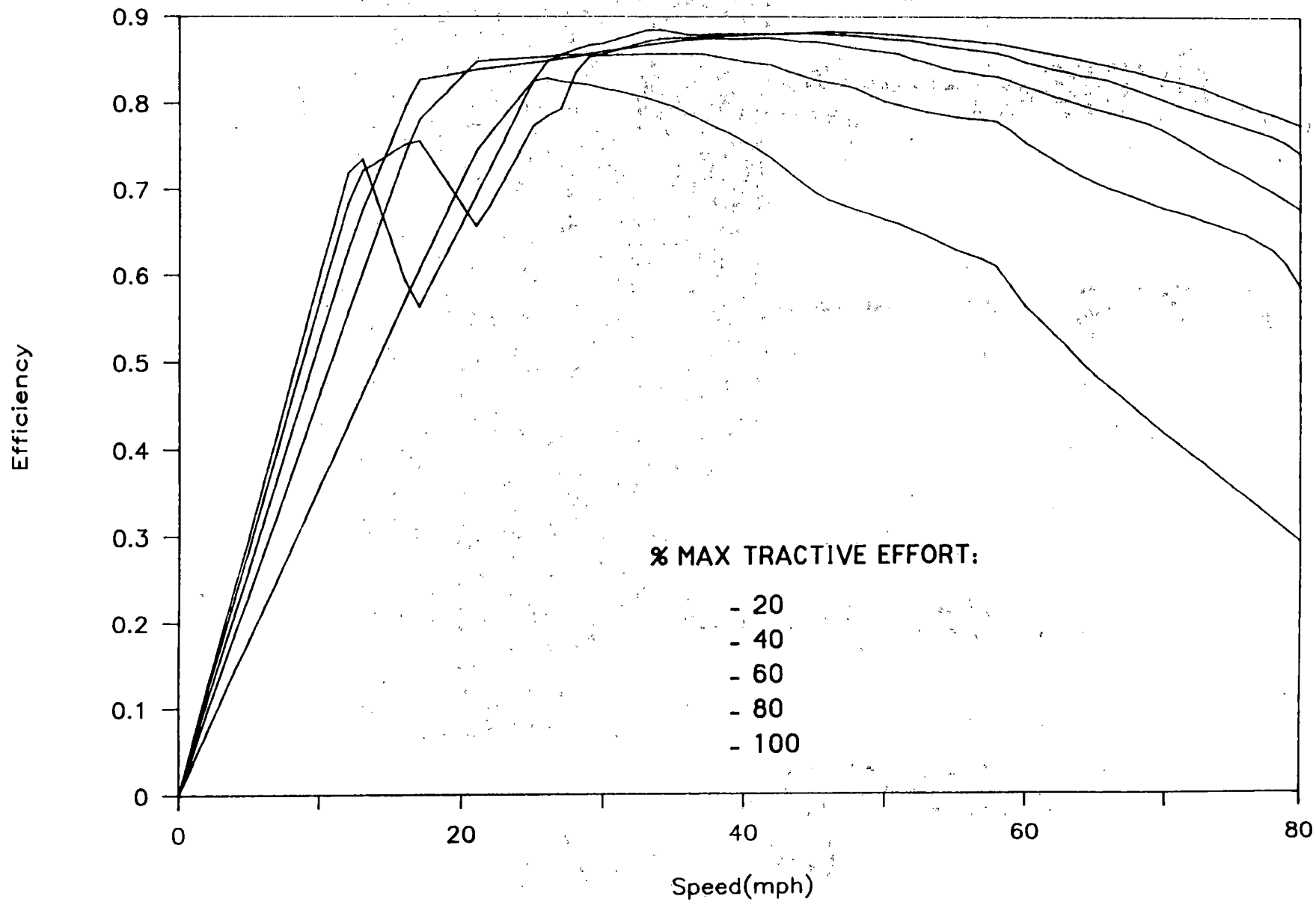


FIGURE 3-3

# PROPULSION EFFICIENCY

CHOPPER POWER MODE

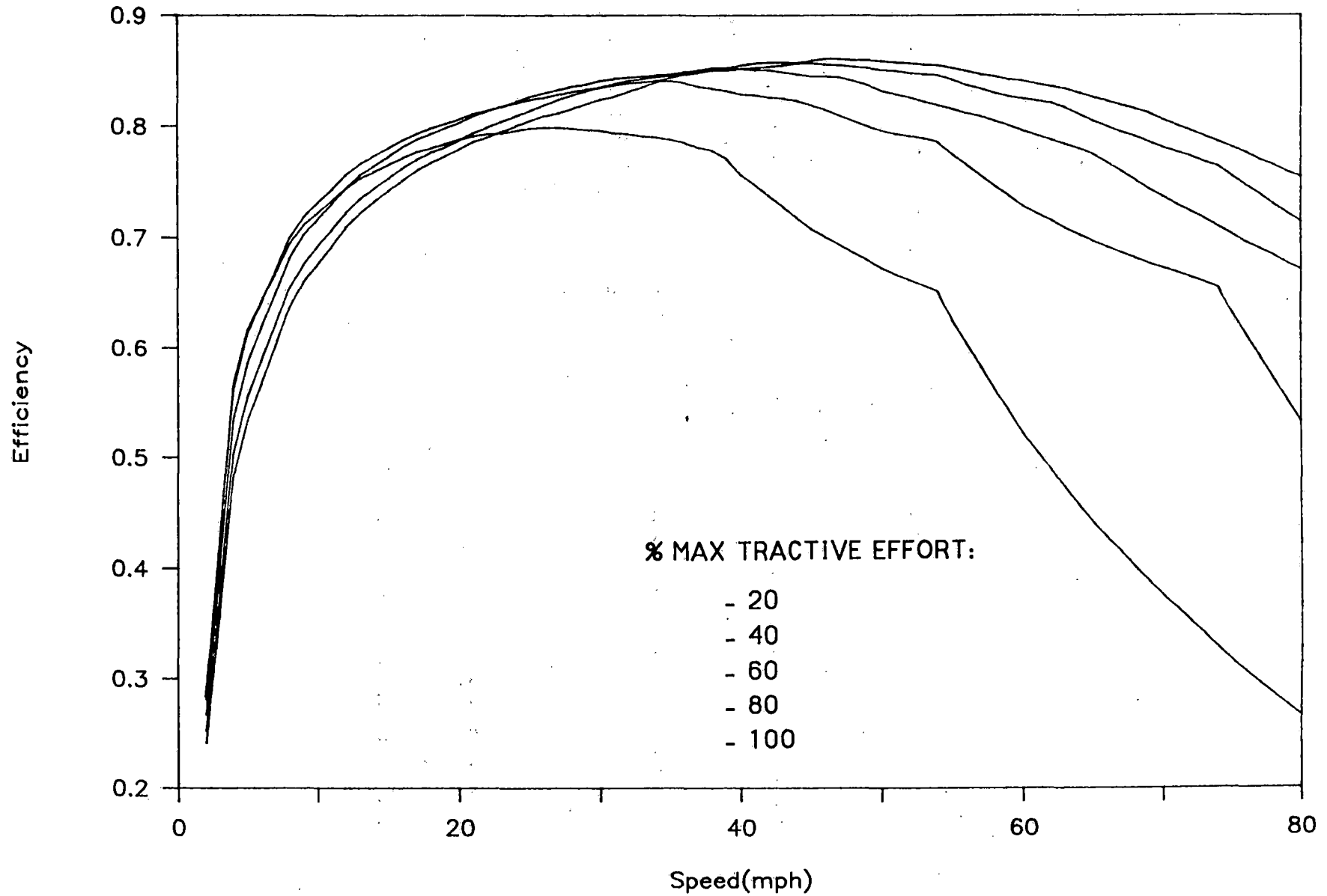


FIGURE 3-4

#### 3.3.7.4. On Board Energy Storage

During the decade of the 1970's flywheel energy storage systems were considered for uses in buses, dual mode vehicles, subway cars, trolleys and other vehicles. Two R-32 cars of the New York City Transit Authority (NYCTA) were equipped with propulsion systems which included flywheel energy storage devices. The units were equipped by Garrett Corporation and were evaluated in service by the NYCTA. Energy savings greater than 30% were reported as a result of the experience.

On board energy storage is a form of regeneration of braking energy with assured receptivity. In the case of the NYCTA experiment, all of the regenerated energy was stored in the rotating flywheel. However, this is not the only way to assure receptivity. Another method involves building a smaller flywheel and using the energy storage capability of that device only to supplement natural receptivity.

Figure 3-6 shows a block diagram of power flows using a train (vehicle) with on-board energy storage. The cost-effectiveness of employing such a system depends upon a complex set of physical and operational characteristics of the specific transit system. As a consequence, it is both necessary and desirable to perform site-specific evaluations on the whole question of assured receptivity. Competing methods of assured receptivity include off-board storage and regenerative substations should also be considered.

# PROPULSION EFFICIENCY

CHOPPER BRAKING MODE

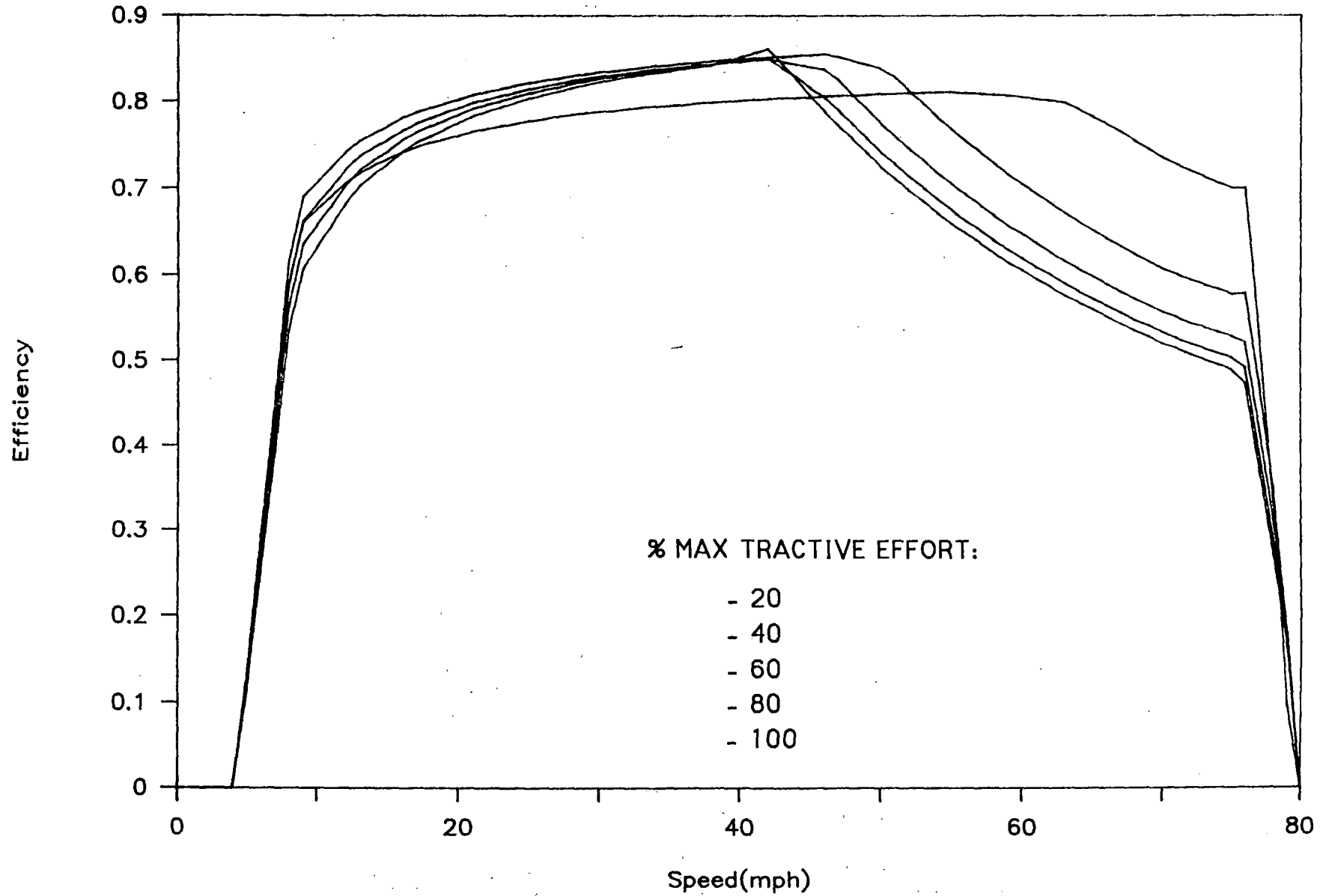


FIGURE 3-5

# ON BOARD ENERGY STORAGE

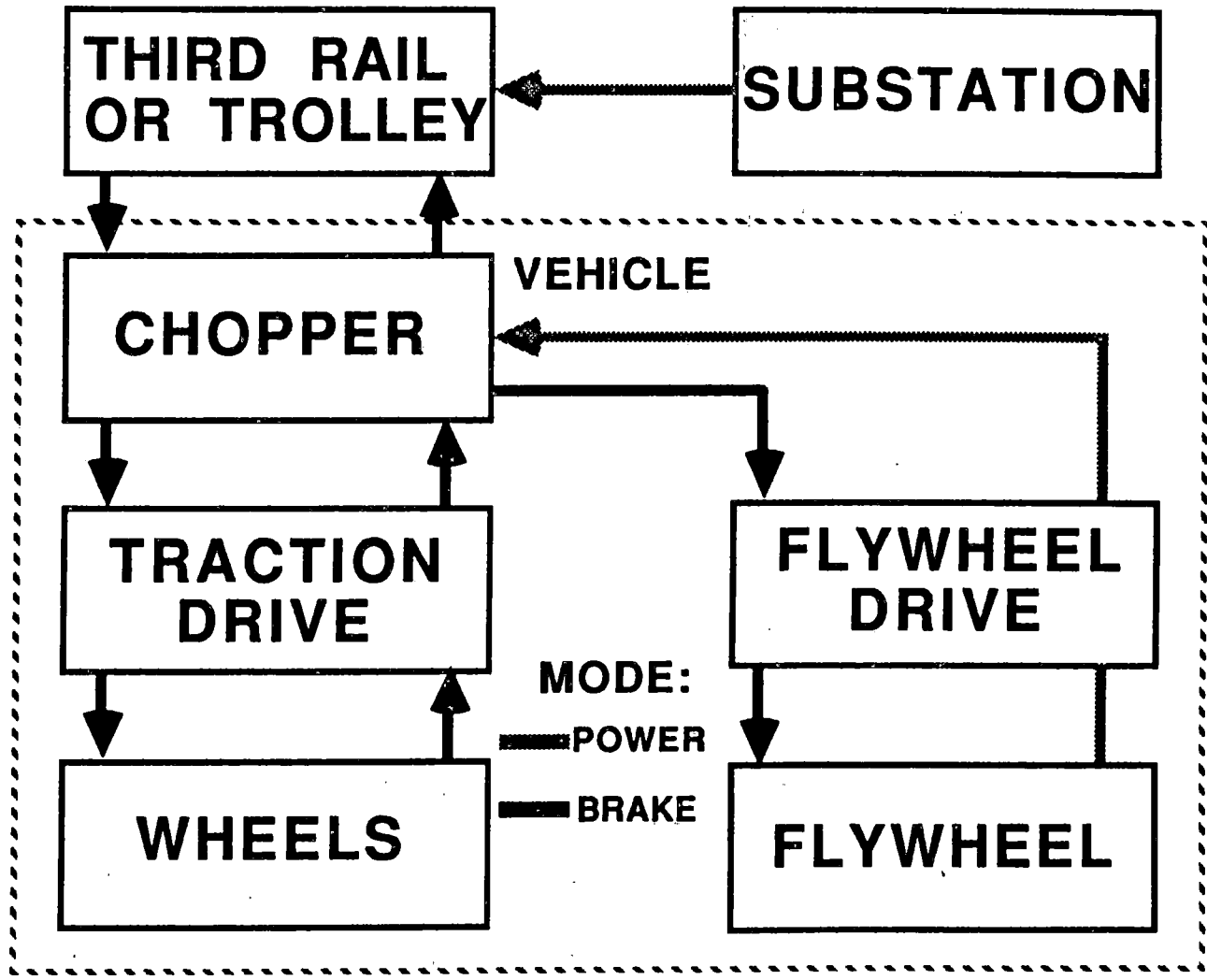


FIGURE 3-6

### 3.3.7.5. Auxiliary Power

Auxiliary power on-board the vehicle is used to maintain passenger comfort levels by heating, cooling and lighting and to support the functions of other vehicle subsystems such as propulsion, braking, train control and door operation. This power is provided through the third rail or trolley and is usually considered part of the traction power. On-board auxiliary power during train operation can account for 5-15% of traction power.

When the vehicle is not in use, it would be desirable to shut down as much auxiliary power as is practical. The degree of sophistication of the device which controls the amount of auxiliary operation during periods of vehicle non-use can vary. The control device may be as simple as initializing a train line using an operator's key; or conceivably, on an automatic train control system, sending signals to the trains to control auxiliary operation.

Auxiliaries which are running at full power when the trains are in storage or lay up can use significant amounts of energy. Assuming that auxiliaries normally use 10% of the total traction energy while the train is in operation and with the operating assumptions stated in Table 3-1, it can be seen from the table that the percent of non-operating auxiliary energy use to total traction energy use is about 9%. Of course, when in operation, heating and air conditioning would use more power because of the doors opening and closing. This fact, together with the requirement that some of the auxiliary operations (10-15% on WMATA) must continue even while non-operational, reduces the potential energy savings.

### 3.3.7.6. Operational Flexibility

In terms of design of the vehicle, operational flexibility refers to those characteristics which allow the flexibility to match car-miles to passenger-miles in such a way as to avoid passenger crowding on one hand and to avoid running empty trains on the other. The ability to make and break consists of cars is the principal



TABLE 3-1 NON-OPERATING AUXILIARY ENERGY ANALYSIS

	WEEKDAY			WEEKEND		
	PEAK	OFF-PEAK	NON-OPER	OFF-PEAK	NON-OPER	
FRACTION OF VEHICLE FLEET						
Operating	1.00	0.60	0.00	0.50	0.00	
Not operating	0.00	0.40	1.00	0.50	1.00	
HOURS PER DAY IN PERIOD						
	4	14	6	18	6	
PROPULSION ENERGY PER HOUR						
	0.90	0.54	0.00	0.45	0.00	
AUXILIARY ENERGY PER HOUR						
Operating	0.10	0.06	0.00	0.05	0.00	
Not operating	0.00	0.04	0.10	0.05	0.10	
TOTAL BY PERIOD						
PROPULSION ENERGY	3.60	7.56	0.00	8.10	0.00	
AUXILIARY ENERGY						
Operating	0.40	0.84	0.00	0.90	0.00	
Not operating	0.00	0.56	0.60	0.90	0.60	
TOTAL						
TRACTION ENERGY*	WEEKDAY			WEEKEND		WEEKLY
	12.40			9.00		80.00
NON-OPERATING AUXILIARY ENERGY	1.16			0.90		7.60
TOTAL	13.56			9.90		87.60
PERCENT NON-OPER AUX TO TOTAL	9			9		9

\* TRACTION ENERGY = PROPULSION + AUXILIARY ENERGY WHILE OPERATING

determinant here. Considerations are:

1. Quick disconnects (electrical, pneumatic, etc.) between cars in a train. These should be reliable and involve low labor input.
2. The ideal situation is for all cars to have the ability to function as the head end. Cost tradeoffs for married pairs, internal vs head end cars should always take the operational flexibility, and subsequent energy savings into account.

The fleet availability for revenue service also has an impact on energy consumption. If the fleet has low operational availability, enough cars may not exist for proper energy conserving scheduling; that is, scheduling which optimizes the ratio of passenger-miles to car-miles without undue passenger crowding.

Another consideration is vehicle reliability. If vehicles do not have reliable propulsion systems, train performance reliability would have to be achieved by running more cars per train than otherwise and as a consequence, cause higher energy consumption.

### 3.3.8. Train Control

Train control may be manual (MTC) or automatic (ATC). In the new heavy rail systems, train control is automatic. In the new light rail systems and older heavy and light rail systems which are being modernized, train control is usually manual. In all cases, an attendant is on-board and usually rides in the head end cab. Even in the most sophisticated ATC rail systems, the attendant performs other functions, such as opening and closing doors.

There are two general considerations in the design of train control systems, which will influence both power demand and energy consumption. These are train interference and train performance.

### 3.3.8.1. Train Interference

There is a global problem on a rail transit system which has an energy component. The problem is running a set of non-perfect trains over non-perfect track with non-perfect control systems in such a way as to maximize passenger flow and comfort and minimize delay time and operational cost. Until recently, most of the concern has been to maintain capacity and reduce delay time. Because of reduction of federal subsidies to transit authorities, reducing operational cost is also important, and energy cost is one of the easiest of operational costs to reduce.

Whether the train control system is manual or automatic, train interference is one of the largest problems in day to day operations. If the trains all ran according to the planned schedules, minimal train interference would occur. Usually interference begins with an event such as a system malfunction, with the system being equipment, processes, passengers and employees working together. Trains become delayed and begin interfering with other trains. Operational strategies are called upon to bring the system back to its normal state. Most of these strategies are geared toward reducing delay time and maintaining system capacity. During the transition period from system malfunction to train interference to normal state, energy consumption is of little consequence, since returning quickly and safely to normal operation is most important.

The energy component of the global problem of train interference is explained using Figure 3-7. The system is in its normal state. An event causes the system to enter a train interference state. The objective is to select a strategy for recovery to the normal state which minimizes both energy and delay time.

A situation where the use of "catchup operation" existed on WMATA illustrates how selection of certain strategies can increase energy cost. In 1980, if a delay occurred, catchup operation was initiated during which the system ran 10% faster than normal, which in turn increased traction energy consumption by about 20%. Since the

# GLOBAL ENERGY PROBLEM

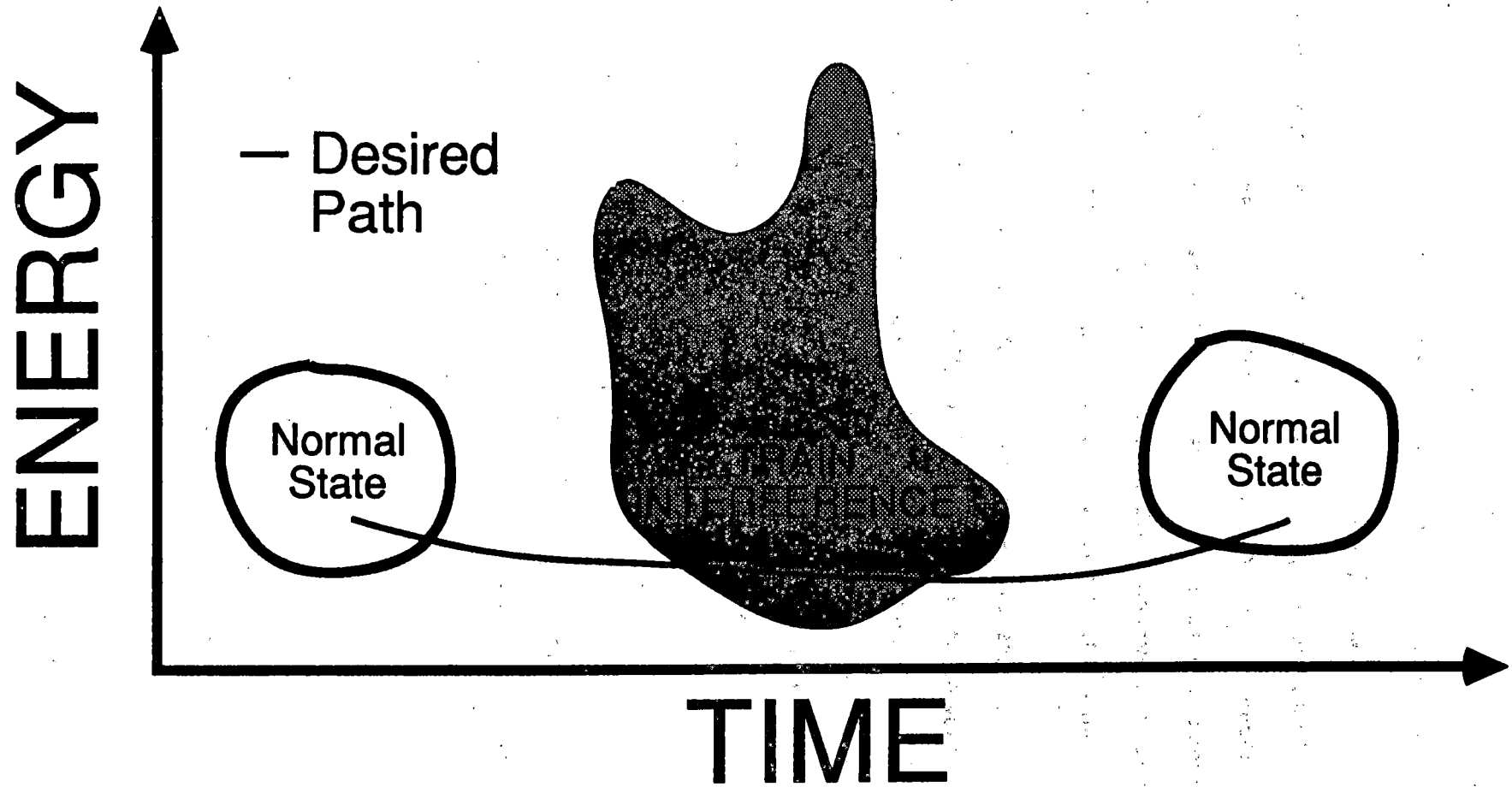


FIGURE 3-7

chance for delay and subsequent catchup operation was most probable during peak operating periods, it was catchup operation which set demand charges, which were much higher than would otherwise be realized.

### 3.3.8.2. Train Performance

There are many ways to drive a train between the terminals on a rail line and still maintain the schedule time. Generally, transit authorities use their equipment to minimize the running time between stations, subject to speed restrictions, grades, traffic interference, program stop requirements and other operational policies. This minimum run time does not result in minimum energy consumption.

Strategies of train running which result in run times greater than the minimum are known as performance modification strategies. Energy use reduction by performance modification can be illustrated by reference to Figure 3-8. The accessible region is the area in the energy consumption vs running time plane which can be realized by a given train with a given set of passenger loadings as it runs between stations, and operates within all of the rules. Any point in the accessible region can be reached by operating the train differently through the system.

In the language of optimization theory, the border of the accessible region is the non-inferior curve. It represents the extremum of energy consumption for a fixed running time, which is greater than the minimum running time. Within the accessible region is an operating region in which the train actually operates most of the time. Because of both operational and equipment variances, the running time and energy consumption of seemingly identical trips will vary. In a statistical sample, most of the trips will fall within a closed curve labeled NORMAL in Figure 3-9.

An energy reduction strategy, which involves performance modification, when practiced, results in points in the Energy-Time Domain (E-T plane) falling within another region, labeled STRATEGY in the figure. However, the new operating region is shifted downward and to the right in the accessible region, representing a decrease

# PERFORMANCE MODIFICATION

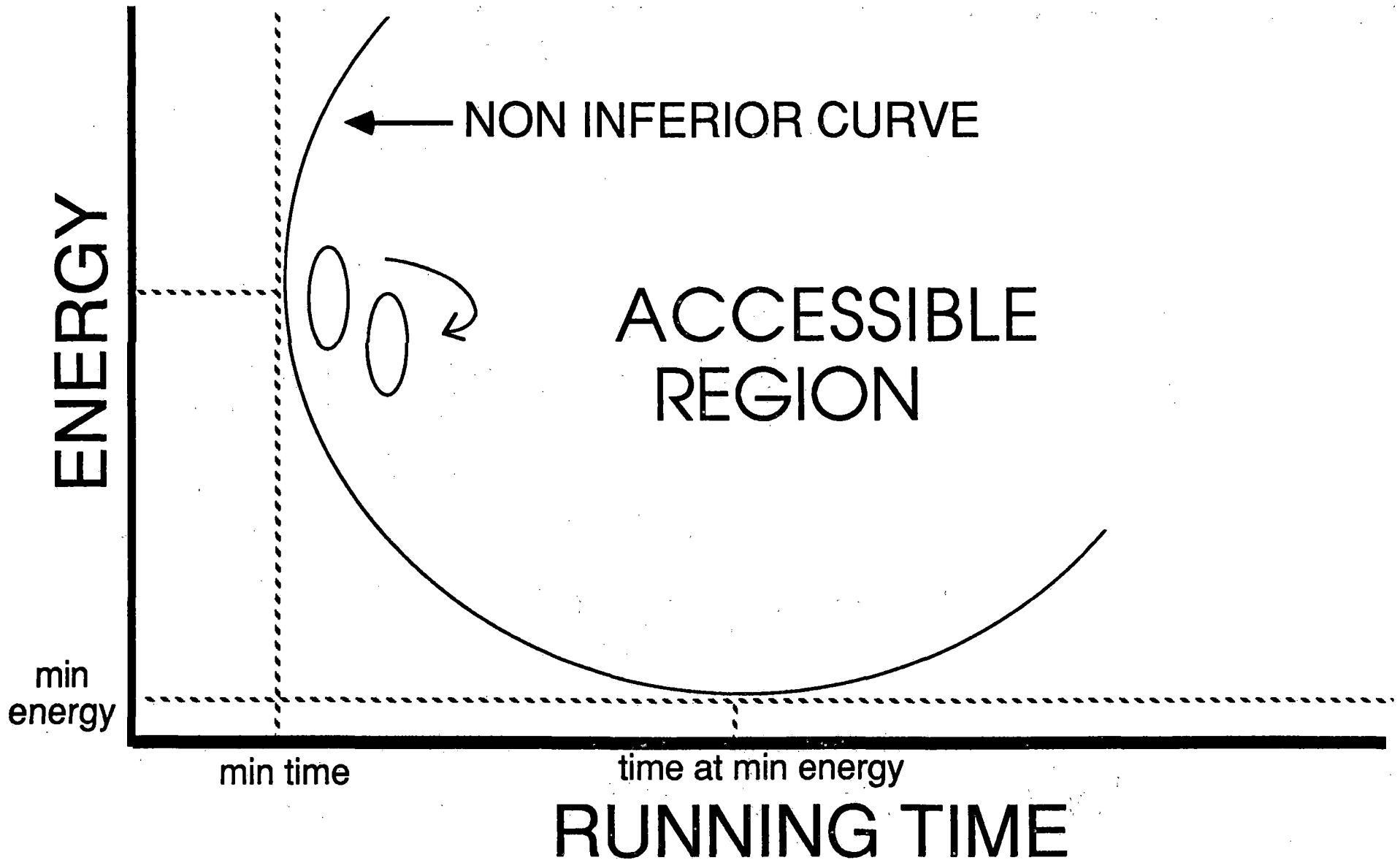


FIGURE 3-8

# MAGNIFIED E-T PLANE

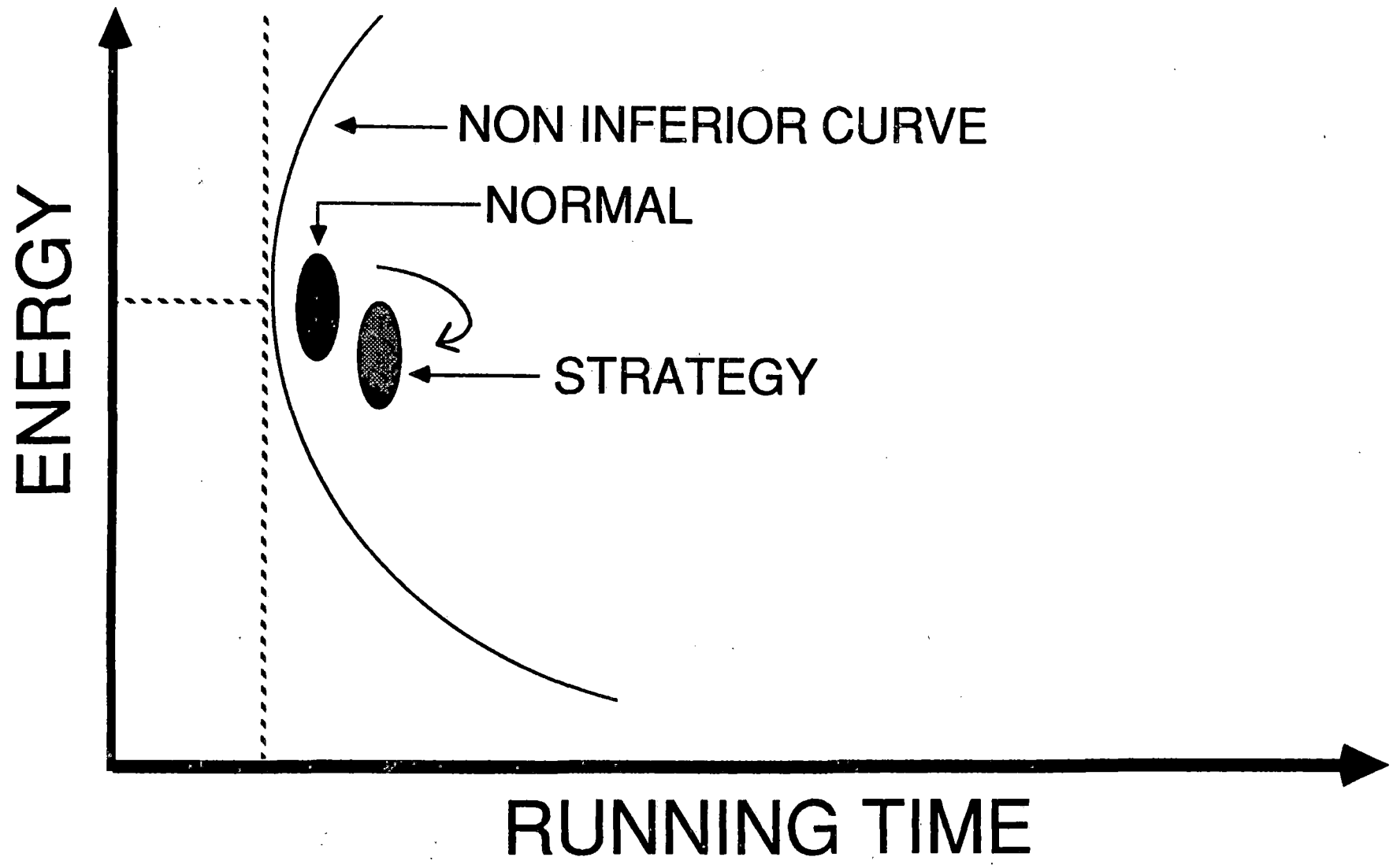


FIGURE 3-9

in energy consumption and an increase in running time. For a performance modification strategy to be successful it should cause the train operation to be such as to minimize the increase in running time and to maximize the decrease in energy consumption.

The schedule time, which involves running, dwell and turnaround time, and determines both system capacity and train requirements, will not increase as fast as running time. In fact, if dwell and turnaround times can be shortened to compensate for increased run times, the overall schedule time, and consequently the system capacity can remain the same without the need for an additional train. In practice, this slack usually exists. If the slack cannot be found, performance modification strategies for energy cost savings would probably not prove cost-effective because of the requirement for an additional train.

Performance modification strategies to reduce energy consumption are not new. Several kinds have been implemented in the past on rail transit systems. The energy savings effects are influenced by whether or not a rail system can regenerate energy. More details are presented in Volume 2, Chapter 1.

#### Speed Reduction

Speed reduction strategies are the easiest of the performance modification class to implement on rail transit. One method is to simply limit the top speed of trains to something less than maximum speed capability. A second method would be to selectively lower speed limits along the route. Another way is to lower the speed limits along the route in such a way that the energy saved for fixed running time is maximum.

#### Acceleration Reduction

Two kinds of acceleration reduction strategies are natural with the propulsion systems traditionally used with rail transit equipment. The first kind involves



choosing an initial accelerating rate lower than the system capability. This is usually accomplished by limiting traction motor current. The second kind is lowering the high speed accelerating rate by preventing traction motor field weakening.

Reduction of initial accelerating rate does not usually save much energy. However, reducing acceleration at high speed does save energy. Propulsion systems are less efficient in constant speed running than during accelerating at high speed, so that the more time spent by accelerating at high speed with low accelerating rate, means the less time spent in the constant speed running condition. If the acceleration rate reduction means reducing the top speed of the train in a short interstation run, then the strategy has more of an energy savings effect.

#### Deceleration Reduction

Reducing the decelerating rate can save energy with trains which regenerate braking energy. Reducing the decelerating rate means that the energy per unit time generated during the braking cycle is smaller, providing a higher probability that it will all be absorbed by other trains requiring power. Even under non-regenerative conditions reduction of braking rate can save energy because of the requirement for lower top speed on short interstation runs (lower brake rate means an earlier brake initiation).

#### Coasting

Coasting is an old, proven method to reduce energy consumption with a minimal increase in running time. There are several methods of coasting. In one method, termed anticipatory coasting, the train accelerates, perhaps to the speed limit, and begins a no power, no brake (coast) operation in anticipation of a lower speed restriction or a station stop. In another method of coasting, referred to as sawtooth coasting, the train accelerates until it reaches the speed limit and then alternately coasts and accelerates within a speed band whose top speed is the speed

limit and whose lower speed is the coast speed. The difference between the top and coast speeds is usually a fixed speed band.

During coasting, only the forces of train resistance and sometimes a minimum electrical brake retard the train motion.

Sawtooth coasting is the easier of the coasting strategies to implement since no anticipation of a stop or upcoming speed restriction is required in the form of a wayside signal. For most interstation runs on typical transit systems, only one coast operation usually occurs.

#### Optimum Performance Modification

Low energy consumption and minimum running time are conflicting objectives on a rail transit system. The problem of finding the minimum energy run for a fixed run time which is greater than the minimum run time is finding a trajectory on the route whose energy lies on the lower portion of the non-inferior curve in Figure 3-8. The problem can be solved by Monte Carlo or steepest decent techniques and amounts to varying the tractive effort as the train runs through the system in such a way that the resulting energy input to the train is minimal. For trains which regenerate braking energy, and depend on other trains to use this energy, the problem is not trivial. If optimum performance modification is ever implemented, a microcomputer will be required on every train. Implementation would only be feasible with automatic train control systems.

Of the performance modification strategies discussed, top speed reduction, coasting and optimum performance modification present the largest opportunities to save energy in new rail systems. Coasting or optimum performance modification is least expensive when included in the initial design. Sawtooth coasting can be effected by incorporating a large speed error into the speed maintaining unit so that transition from power to brake occurs over a large speed band in which coasting

occurs. Optimum performance modification requires more sophisticated equipment.

### **3.3.9. Planned System Operation**

During the design phase, a system operating plan is developed. The plan usually contains several alternatives for future operation, beginning with initial revenue operation and continuing for several years. It is the basis for vehicle, train control and power distribution equipment procurement. Both train performance and operation are specified and are used as the basis for estimating the energy use pattern, which is subsequently used for electric utility rate negotiation.

#### **3.3.9.1. Train Performance**

It is customary to design a rail transit system with higher performance capability than will actually be used. This custom is carried down to the subsystem, component and electrical facilities. Normal, day-to-day operation is always below full capability.

For transit systems with ATC, several modes of train performance are usually specified. These modes are usually called performance levels. The highest level is set close to the maximum capability of the train. Different performance levels imply different run times. The highest level means the lowest run time and usually, the highest energy consumption.

Performance levels are traditionally based on acceleration, deceleration and speed. Higher values of each of these quantities mean lower run times. This traditional method of setting performance level is not necessarily the most energy efficient. A more energy efficient method may be to incorporate coasting or optimum performance modification. In this case, the highest performance level would approach the minimum run time with the least amount of coasting (or optimum performance modification), while the lowest level would contain the most coasting.

For manual train control systems, performance levels can be incorporated into

the master controller of the train or into the operating rules. Again, coasting levels could substitute for speed, acceleration and deceleration reduction, improving energy efficiency.

For both manual and automatic train control systems normal operation is based on a performance level which is less than maximum. This is usually done in order to maintain reserve for emergencies, which means some type of makeup operation. Any event which results in train delay may be followed by a period of abnormal operation to bring the system back to its normal state quickly. This makeup operation could result in high levels of power demand and higher energy cost. If initiated during peak operating periods traction power demand could increase substantially.

The strategy for makeup operation on the PATCO system was skipping of stations of some trains to increase running time. This method uses less energy than normal-operation.

### **3.3.9.2. Train Operation**

Train operation refers to the operating timetables which govern train makeup and movement on the system. These timetables and resultant schedules are generated to meet predicted passenger flows and minimum headway rules. The operating timetables contain departure times and the composition of each train leaving each terminal during each period of the day on weekdays, Saturdays, Sundays and Holidays. Rough values of passenger loadings can be developed using these timetables and the predicted passenger flows. Passenger station level times and train turnaround times at terminals are also specified as are the requirements for cars during the different operating periods.

There are many factors which constrain the development of an operating timetable. Energy should be an important consideration in the development of these timetables since traction energy use patterns and ultimately energy costs are

associated with them. The power demand component is (approximately) linearly related to the car-mi/hour developed during peak transit operating times and the energy use component is (approximately) linearly related to the total car-mi developed. The peak transit operating periods are the morning and evening rush hours on weekdays.

In setting up operational timetables to meet predicted passenger flows, there are two important principles which must govern the setting of schedules:

1. Passenger loadings between stations must be a maximum without undue passenger crowding
2. Predicted passenger flows are no sacred cows. In fact, they are probably one of the weakest knowns in the system.

Energy cost will be least when schedules are developed to best match car-miles to passenger-miles without crowding. Ultimately, this matching can only be done under actual revenue operating conditions.

Other constraints, such as passenger transfer requirements between lines or modes may also be included.

To maximize passenger load factor, the number of cars per train should be tailored to meet passenger demand. The use of terminals other than the ends of the line is another strategy for reducing car-miles.

It is desirable, not only from an energy use but also from an overall transit productivity perspective, to optimize passenger load factor (passenger-miles/car-miles). During peak transit operating periods, application of this strategy may mean running some trains over shorter distances (turnbacks) and reducing the number of cars per train to conform to the decreased passenger load before and after the peak passenger flow periods. Operational costs of making, breaking and turning trains will, of course, offset the energy savings. More innovative and dynamic scheduling is required.

In rail transit systems which utilize regeneration of braking energy, certain schedules may be better than others in matching generating trains on the average to trains requiring power on the average. With all other things being equal, those schedules which result in least energy consumption should be selected.

#### **3.3.9.3. Energy Use Pattern Estimation**

The alternative train performance and operation scenarios of the system operating plan can be used as the basis for the energy use pattern estimate. One energy use pattern estimate is made for each scenario.

The energy use pattern is simply an estimate of the monthly demand for billing purposes and energy use on a month by month basis. It begins with the estimates of the daily load curves for each meter for weekdays, Saturday and Sunday. A basis for calculating peak demand is also stated. Usually peak demand is estimated by taking the maximum demand created by either normal or makeup train operation. Some method for estimating the cooling and heating effects on peak demand should also be incorporated into this estimate. Not all meters may reach peak during the peak transit operating time. For example, meters which record power for yards or storage tracks are more likely to peak during off-peak transit operating time when cars are in storage or much yard movement occurs.

For cost estimating purposes, the meters must be grouped according to the actual power demand consolidation which is to be used by the electric utility. If the demand is on a non-coincident basis, then each meter must be considered separately.

### **3.4. PROCUREMENT AND CONSTRUCTION PHASE**

During this phase of the design and construction process, the results of the energy cost tradeoff studies are incorporated into procurement and construction decisions. Energy efficiency, when appropriate, is incorporated into the specification for the vehicles, train control, power distribution and passenger station equipment. There is an important rule which should be followed here: IF A METHOD DOES NOT

EXIST FOR PROVING THAT A SPECIFICATION HAS BEEN MET, THEN DO NOT MAKE THE SPECIFICATION.

The models which were used for the energy cost tradeoff studies should remain active to help evaluate the bids submitted by the suppliers during this stage. This model should be made available to the serious bidders, especially if the same model will be used to evaluate the bids.

Test plans should be developed to evaluate the energy use of the equipment and systems. Suppliers should also have copies of these test plans before the bid. The test plans should clearly specify the methodology and conditions of the test.

Since energy use patterns of the alternative scenarios of rail system operations have been developed as part of the system operating plan, serious negotiations with the electric utilities who will supply power can continue. These negotiations will include interim rates during prototype testing and startup of revenue operation, when system power requirements will be unpredictable. Requirements for power demand monitoring should also be discussed at this time.

#### **3.4.1. Energy Specifications for Equipment**

There are four major areas in which energy use can be specified either covertly or overtly in the supply. These areas are: vehicles, train control, power distribution and support equipment.

##### **3.4.1.1. Vehicles**

The major energy considerations in the vehicle will be its empty weight, passenger capacity, train resistance, auxiliary equipment, propulsion and braking equipment and operational flexibility. It is not useful to consider each of the factors individually, since ultimately it is the energy consumption, over specified routes under specified operating conditions, which determines the energy cost of the car over its lifetime. Thus, weight rewards and penalties may be useful in limited

applications.

The modern approach is to provide the vehicle supplier with selected scenarios from the system operating plan and let him predict energy consumption. It is difficult to handle regeneration in this manner, because the receptivity does depend on the vehicles being used. A better approach would be to have the vehicle supplier provide the detailed energy/performance data to the transit authority and let them estimate the energy consumption with the same model used to calculate energy use patterns in the system operation plan. In this way all of the vehicle characteristics which affect energy consumption can be integrated at once into the estimates.

Verification will take two forms:

1. That the model can adequately predict energy consumption and system performance, and
2. That the data presented by the equipment supplier are valid.

Both forms of verification can take place after the vehicles are put into operation. Penalties and rewards can be assessed in accordance with how number 2 above was met.

#### **3.4.1.2. Train Control**

For automatic train control systems, specifications take the form of the performance modification desired, such as coasting or optimized performance modification. The performance levels of the system is specified incorporating the modification strategies. Low energy cost makeup operation must also be specified.

#### **3.4.1.3. Power Transmission & Distribution Equipment**

Given a power transmission and distribution system from the electric utility meters to the power input device on the train, there are three major items which will affect the energy cost in the operating system: the power necessary to support the power transmission and distribution system, the losses and the receptivity provided under all conditions. The first two items are straight forward. The support power is



easily tabulated and includes such things as transformer-rectifier cooling power requirements, substation auxiliary power and control power. The losses depend on impedances in substations, transmission lines, distribution lines, and third and running rails including ground return.

Regeneration receptivity is influenced by allowed voltages on the transmission and distribution system, impedances and operating conditions.

Given all of the above parameter values, the energy consumption at the metering points can be estimated for equipment from different suppliers with the EMM or similar models.

Power monitoring equipment may also be purchased as part of the power transmission and distribution equipment. It is important that the specification for this monitoring system be well stated. Failure in this area will make such a system inoperable.

#### **3.4.1.4. Support Equipment**

The installed support loads can be divided into the following categories: VENTILATION, HEATING, LIGHTING, AIR-CONDITIONING, ESCALATORS & ELEVATORS, TRAIN CONTROL & COMMUNICATIONS, FARE COLLECTION and MISCELLANEOUS.

Much has been done over the past ten years on efficient lighting. The problem in obtaining efficient lighting is one of aesthetics. It is usually the architect who specifies lighting in the station areas. If lighting cannot provide the desired effect that the architect has designed into the station, lighting efficiency will suffer. A second problem is security. Adequate lighting discourages crime.

Escalators and elevators are now equipped with regeneration, which saves energy. Escalators can also be equipped with automatic start and stop features. These types of escalators have been used more in European transit operations and

have not yet achieved popularity in domestic use.

Air conditioning and heating with large power requirements can sometimes be used in load management systems as a load to be shed. Chiller plants provide a good example of such a load. By using chillers to cool to lower, but comfortable temperatures during the hours just before the AM and PM peak operating periods, the chiller plant could be unloaded during peak periods to keep the temperature just below the maximum for passenger comfort.

Three criteria must be satisfied before this strategy can be used:

1. The equipment can easily be loaded and unloaded.
2. The cost for loading and unloading must not exceed the savings.
3. The equipment load must be part of the peak load.

#### **3.4.2. Energy Efficiency Verification Test Plans**

Test plans should be produced to determine energy related characteristics of the vehicle, train control, power transmission and distribution system, support equipment power and any monitoring equipment.

##### **3.4.2.1. Vehicle Procurement**

Tests should be conducted to verify vehicle empty weight, train resistance, measurement of propulsion efficiency and verification of auxiliary equipment power requirements.

The empty weight is determined with the vehicle in full operating condition without passengers.

Train resistance is measured using coast down tests. The train is accelerated to maximum speed on level tangent track. Power is removed and the speed is measured as a function of time as the train coasts. This test should be repeated several times changing the number of cars per train. The range of the number of

cars per train should cover the range to be used in revenue service operation.

The measurement of propulsion efficiency can be done in either the laboratory or on the vehicle. In the laboratory, the propulsion motors drive similar traction motors as generators and the power needed simply covers the losses in the system. The disadvantage of this method is that the effects of the gear units, couplings and wheels are not included in the overall efficiency but must be measured separately.

The alternate method is to conduct the tests on the vehicle by running at different speeds on different grades at different accelerating rates. Friction brakes may also be used to increase drag on the vehicle to reach tractive effort/speed points which are otherwise not accessible.

Finally, the power requirements of the auxiliary equipment are verified. Since it is impractical to measure these requirements under all operating conditions, several test runs simulating revenue operation should be conducted. On-board heating and air conditioning power requirements will depend on both ambient temperature and passenger loading. It may be possible to determine some ambient temperature dependence.

#### **3.4.2.2. Train Control**

Verification of energy consumption at various performance levels, which could be used in revenue operation should be conducted. Several tests should be carried out to obtain a statistical relationship between energy consumption at the third rail or trolley and running time.

If the performance levels do not incorporate coasting or optimum performance modification directly, but yet this capability has been included in the procurement, these strategies should be tested separately.

### **3.4.2.3. Power Transmission and Distribution Equipment**

The measurements which should be conducted on the power transmission and distribution system are those which verify no-load losses, impedances and voltage tolerances.

Substation efficiency should be measured under several load conditions including no-load. It is not necessary to carry out these measurements on all substations, but only on those which may contain different transformer-rectifier units. This test should be conducted by measuring the input and output voltage and current.

Since the input power is AC, it is important to obtain real and reactive components of power. It may be best to conduct these verification tests using the suppliers test facility.

The conductivity of the trackside power distribution circuits should also be measured. Since the ground return circuit will involve the running rails and earth conductivity, these measurements must be carried out on the whole system, once it is installed. The measurement should be taken between adjacent substations, or substation to tie station, if tie stations exist between substations.

If switchpoint heaters or other equipment are receiving power through the trackside power distribution circuits, these power draws should also be measured.

### **3.4.2.4. Support Equipment Power**

Some verification of support equipment power requirements should be made. If possible, arrangements can be made with the utility to observe the meters as various equipments are operating.

At least, all of the equipment on each of the metered circuits should be tabulated, with their appropriate electrical characteristics.

### 3.4.3. Specifications for Load Management and Power Demand Monitoring

The power monitoring equipment necessary for a load management system or procured as part of the electric power dispatcher's equipment should have the same reliability that the equipment used for metering on the electric utility's side. For most transit authorities, equipment procured for these purposes is not functional.

The purpose of power monitoring equipment is to measure the power flowing into the system. The equipment can be used for several reasons; but for energy management activity, verification of electric bills, understanding the causes of maximum power demand and the monitoring component of a real-time load management system are the primary uses. Any such monitoring system must observe the power flows in the same way as the electric utilities, since it is the utilities' observation of the energy use pattern that results in the electric bill.

If the monitoring equipment is bringing the data to a central location for further analysis, the same demand intervals, consolidations and timing must be used as the utility. Some cooperation between the utility and the transit authority beforehand could go a long way to avoiding arguments later.

Both power consumption and supply voltage should be monitored. In the interest of cost savings, it may be possible, upon agreement with the electric utilities, to use their potential and current transformers to monitor power and voltage.

A power monitoring system will require maintenance if it is expected to continue operating effectively after it is installed. Maintenance will take the form of checking and recalibrating meters according to standards and manufacturer's requirement. This system is the only independent check on the power bill, which is a single expenditure whose magnitude is usually 10-25% of the total rail operating cost.

#### **3.4.4. Power Rate Structure Negotiations for Test Operations**

Test operations on the new or addition to the rail system will produce an energy use pattern substantially different from that which will be seen during revenue operation. The electric bill for test operations could be quite high relative to the actual use if some arrangements are not made beforehand to alert the utility of the pattern.

During the initial negotiations with the utility the rates during this phase of design and construction should be discussed separately from the revenue operation rate structure.

### **3.5. TEST OPERATIONS**

#### **3.5.1. Energy Use Pattern Update**

The results of the energy related tests discussed in the previous sections will result in some modification of the energy related input parameters into the model used to estimate energy use patterns for alternative train operation scenarios under future revenue operations. If these modifications are substantial, the energy use patterns for these scenarios should be reestimated. These reestimates could influence decisions that were made during the design phase.

#### **3.5.2. Power Rate Structure Negotiations for Revenue Operation**

The energy use patterns predicted for revenue operations should now be the best estimates available for discussion with the electric utilities. If these are the basis for cost of service determination by the utility, the rates for initial revenue operation will be finally set on these predictions.

### **3.5.3. Load Management System Algorithm Development**

If a load management system will be used in transit operations, the algorithm development will occur during the testing phase. Tests which are designed to determine the adequacy and timing of responses to predictions of maximum demand, should be developed during this time.

## **3.6. INITIAL REVENUE OPERATION**

### **3.6.1. Energy Audit**

An energy audit should be conducted after about two years of revenue operation. The details of carrying out the audit are discussed in Volume 1, Section 4.1.1.

### **3.6.2. Verification of Energy Use Pattern**

The results of the energy audit should be compared with the predicted energy use patterns. Methods of making these comparisons are discussed in Volume 1, Section 4.1.2.

### **3.6.3. Energy Use Pattern Update**

Changes which have occurred in the train operation scenarios because of experience obtained in revenue operation together with model changes, which were mandated by the verification process, require updating of the energy use pattern forecasts. These should be carried out at this time.

### **3.6.4. Power Rate Structure Negotiation**

Rate intervention will still occur on those issues which have not been resolved in the past. Solid energy use patterns are now available for true cost of service analysis by the utility. These should be conducted in line with the next rate hike request.

## **4. RAIL SYSTEM OPERATION**

The application of energy cost reduction to rail transit systems which are presently operating is somewhat different from those in the design and construction phase. There are two steps:

1. Energy management study, and
2. Implementation of energy cost reduction.

The energy management study has four phases:

1. Energy audit.
2. Simulation and Verification of Normal Operation.
3. Power Rate Structure Evaluation.
4. Identification of Energy Cost Reduction Opportunities.

The study must be carried out before implementation of energy cost reduction. If conducted properly, the study will develop most of the facts and estimates needed by decision makers to begin implementation of energy cost reduction strategies.

After the energy management study is completed, the implementation phase begins. It is in this step that predictions of energy conservation cost and effectiveness of step 1 are validated through prototype installation and testing. Full implementation of those strategies which are validated as cost-effective can then proceed.

### **4.1. ENERGY MANAGEMENT STUDY**

The energy management study is the beginning of any energy management program applied to systems already in operation. It is here that the components of energy cost, obtained by the marriage of the energy use pattern and the power rate structure are understood. The costs and benefits realizable by application of energy conservation and load management strategies are also predicted. All of this is accomplished in four stages.



#### **4.1.1. Energy Audit**

Through the use of an audit procedure, the actual energy use pattern of the rail system is established. The detail to which this can be accomplished depends on the detail of data available. If the data are available, this audit should take the form of a detailed computer analysis of metering information (which can be obtained from the electric utilities serving the system) at each power delivery point over successive demand intervals over a long period of time (at least a year or more), and a detailed estimate of energy end use at each meter. The audit must include traction energy, used to run the trains and provide auxiliary support power aboard them, and support energy, used to provide support services.

If the detailed metering information is available, a statistical analysis should be conducted which covers each demand interval of the day, by weekday, Saturday, Sunday and Holidays. Such things as average, standard deviation and maximum of these load curves should be determined and understood in terms of normal and abnormal system operation. This means that unusual high values of demand should be explained in terms of unusual system operation.

A second useful analysis is regression analysis which relates energy consumed per unit time to car-miles accumulated per unit time and the ambient temperature in that unit time. The best car-mile data are the accumulations of car-miles over the unit time of the demand interval. Ambient temperatures are averaged over three hours, and these data may be obtained from the weather bureau. Detail at the level of the demand interval allows the KWHPCM to be developed for various periods of the day and week.

If car-mile data are not available on a demand interval basis, then daily car-mile data can help. The level of detail will influence the level of credibility.

A useful, but lower level type of analysis, which can be conducted if detailed

metering information is not available, is electric bill analysis. This method provides information on a monthly basis, rather than on a demand interval basis.

All of the data which results from testing or monitoring of energy use of traction or support equipment is also valuable information. These data can be used to build up the complete picture of the energy use pattern. The details of the energy audit methodologies are described in Volume 2, Chapter 5.

The energy use pattern results from a system operating scenario, which involves train operation and performance. Periods of relative stability in the operating scenario should be separated when conducting the audit. For example, changes in train schedules serve as a transition between two periods of relative stability.

#### **4.1.2. Simulation and Verification of Normal Operation**

In order to provide a base for reduction of electric power use caused by application of energy conservation techniques, it is necessary to estimate by simulation the energy use pattern. The support and traction power which do not depend on train operation are treated as background power, which may have ambient and time of day variation, while the traction power which results from train operation is estimated using the EMM or similar tool.

Typically, several time intervals of operation would be simulated depending on the level of detail required. These time intervals are weekday peak (morning and evening), weekday off-peak (midday and evening), weekday startup and shutdown, Saturday, Sunday and non-operating. Since the EMM can only simulate traction power during train operation, other sources of power use, which may appear as traction power, must be estimated separately. These power sources would include auxiliaries aboard the trains during turnaround at terminals and layover during off-peak and non-operating times and traction background power such as no load losses

of substations and switchpoint heating fed from the third rail.

During peak transit operating time (weekday morning and evening rush hours), typical abnormal operations may be simulated to use as the basis for power demand; if abnormal operation power requirements are higher than normal operation. If not, then normal operation power demand is used.

The verification procedure is the comparison of the estimates of the traction energy use pattern obtained through simulation, with the results obtained in the energy audit. The level of detail of this comparison depends on the detail achieved in the energy audit. Usually the KWHPCM is the quantity compared. If enough data are available on car-miles and meter readings, the comparisons could be made by calendar time periods during which system operation was relatively stable by periods of the day and by transit lines on the system. The credibility of the estimates is enhanced by more opportunities for comparisons.

#### **4.1.3. Power Rate Structure Evaluation**

The power rate structure is dependent on the particular electric utilities which serve the transit system and on the regulatory agencies which govern the sale of electricity to all of the utilities' customers. The basic regulatory principle on which power rate structure should be evaluated is that the rail transit system be required to pay no more for their electricity than the cost to the utility to serve it.

The evaluation begins by reviewing the history of power rate structure at the transit system. It includes reviewing the original negotiations and/or master agreement and subsequent rate increases that had been implemented for various components of the tariff.

Once the history is known, it is then appropriate to review the following information:

1. Customer classification,

2. Utilities' overall grouping of customers and their classification,
3. Load and customer characteristics of the rail system,
4. Utilities' class of service cost allocation methodology,
5. Relative class rate of return provided by the utilities' groups of customers,
6. Relative marginal cost recovery provided by the utilities' groups of customers,
7. Rate making treatment of the transit system's contributions-in-aid of construction,
8. The transit system's load at the time of the utility's peak load,
9. The transit system's non-coincident peak,
10. The utility's allocation of its generation, transmission and distribution plant investment to the transit system,
11. The relative size of the transit system's load and revenue contributions to utility,
12. Determination of the transit system revenue requirement,
13. Rate design components of the tariff applicable to the transit system and their ability to trace the unit cost of providing service,
14. Consolidation of the transit system demand for cost allocation and billing determinants purposes,
15. Minimum or ratcheted billing demand provisions,
16. Seasonal differential in rates,
17. Power factor penalty provisions,
18. Applicability of alternative lower revenue requirement, cost of service methodology, and rate design for the transit system,
19. Role of mass transit legislative findings,
20. Improvement in employment and environment attributed to transit,
21. Opportunities for real estate developments and higher economic activity along the transit system route, and
22. Higher tax base for state and local governments from higher employment and real estate activity.

In order to complete this comprehensive review process, cooperation and assistance of the utility providing electric service is crucial. Once the review process has been completed, the transit authority should seek, through direct negotiations with the utility or intervention in formal rate proceedings, before the public utility commission:

1. Distribution of less than average authorized rate increases based on cost and non-cost considerations,
2. Recognition of the unique customer and load characteristics of the transit service as a separate customer class,
3. Changes in cost of service methodology that appropriately reflects the cost causation on the utility system,
4. Changes in rate design to permit recovery of the system's assigned cost responsibility,
5. Tariff charges that more closely track the unit cost of providing service,
6. Recognition of appropriate billing determinants for rate making purposes, and
7. Recognition of the transit system's coincident demand for billing cost allocation purposes.

All of these issues may not be resolved in the context of a single rate proceeding. Utility rate making is a continuous problem and each rate proceeding presents the transit management with an opportunity and a challenge to reduce its power cost.

#### **4.1.4. Identification of Energy Cost Reduction Opportunities**

This stage of the energy management study is the final one. The energy cost savings of energy conservation and load management strategies are determined along with the costs associated with implementing them. Savings associated with rate intervention, either by negotiating with the electric utilities or by presenting a case to the regulatory agency, are also estimated along with the costs of the action. A plan for implementing those actions which are identified as cost-effective is also included.

The EMM or similar tool is particularly useful at this stage. Estimates can be made of the energy cost reduction to be achieved for various strategies. Thus, the overall benefit of these strategies are determined. The cost of implementing the strategies must also be considered.

The cost for implementation, which will include operating and initial investment is related to the energy cost savings as a simple investment problem. The payback time is determined, and investments payed back quickly are considered favorable, while those requiring long payback periods are not favorable. Because of uncertainties in future power costs and the risks involved, three years can be used as one magic number for payback to judge favorability.

The typical classes of strategies whose cost and effectiveness should be estimated are:

1. Performance modification.
2. Operating timetables which improve passenger load factor by reducing car-miles and increase regeneration receptivity.
3. Reduction of auxiliary power use aboard trains.
4. Reduction of support power use.
5. Regeneration of braking energy.
6. Load management
7. Reduction of peak power demand.

The details of all of these strategies are discussed in Volume 2, Chapters One and Three.

The initial and operating costs associated with implementing these strategies are incurred in new equipment, modified equipment and/or engineering and labor manpower.

Evaluation of the power rate structure leads to an estimated cost savings,

should the issues identified in the evaluation be resolved. The estimates here are necessarily much softer than those made on the operations side. The degree to which rate relief can be realized is always uncertain. Since any rate relief achieved by the transit authority shifts the burden to other customers of the electric utilities, there is an inducement for them to oppose the case.

Commissions look on customers who do not intervene as satisfied with their rate structure. All of these things must be carefully considered before attempting rate intervention.

Once the strategies for energy cost reduction have been identified, a plan must be developed for their implementation. The plan usually includes further testing for verification of cost and effectiveness if significant costs are involved in implementation. The plan should also include a monitoring component which will assure that the strategies, once implemented, do reduce energy costs by the amounts estimated. This feedback mechanism adds additional credibility to energy management programs.

## **4.2. IMPLEMENTATION OF ENERGY COST REDUCTION**

Completion of the energy management study, outlined in the previous section, implies a decision point for transit management on which strategies to select for implementation. All of the theoretical estimates of cost and benefit are now available.

### **4.2.1. Prototype Operation and Validation**

This step is important to minimize the technical and financial risk of applying the selected conservation strategies. A low cost experiment should be conducted during which both the actual energy savings and performance changes can be measured under actual operating conditions. The results should be compared with the simulated case. Some considerations should be given to the following experiments.

#### **4.2.1.1. Vehicle Performance Modification**

To validate the simulation of coasting and optimum performance modification, a single train (preferably one or two cars), should be modified for the performance modification. The train should be instrumented to measure traction energy (recording watt meters) and running time (clock). Tests should be run during non-revenue service time at several different performance modification levels. Simulations using the EMM should be done under the same conditions, for comparison. This simulation should be compared to the tests results for validation.

It is important that enough tests be conducted so that a solid average energy savings and running time increase be established, since the (decreased energy, increased running time) points in the accessible region are statistical in nature.

#### **4.2.1.2. Operating Timetable Revision**

The improvement of passenger load factor by proper scheduling of trains has an impact on transit productivity which is more than energy cost savings. The following steps should be taken to validate passenger load factor improvement strategies:

1. An internal committee should be established, consisting of scheduling, transportation, maintenance and energy management personnel, to recommend strategies which can meet overall productivity requirements.
2. Each of the strategies should be simulated to determine energy savings and cost to operations.
3. A three month prototype test should be conducted during which energy use and/or peak demand is monitored, either via the electric bill or batch process monitoring of metering information.

#### **4.2.1.3. Reduction of Support Power**

The savings obtained by reduction of support power either aboard the vehicle or in the passenger stations, shops and office buildings can easily be measured by monitoring the circuits which feed the support power. This can be done with both full and reduced support power using an integrating kilowatt-hour meter to determine the difference.



#### **4.2.1.4. Regeneration of Braking Energy**

Prototype demonstrations of regeneration either with natural receptivity or assured receptivity are expensive. If the transit system does not have solid state propulsion equipment, the first order of business is to procure a few cars, usually added on to an order of conventional cars. A prototype test program similar to that outlined in the case of applying the vehicle performance modification strategy should be conducted with some differences.

A train, consisting of cars with solid state propulsion, and a train consisting of conventional cars should be instrumented with recording kilowatt-hour meters and clocks to measure energy and running time. These should be run over the same routes during peak and non-peak operation to determine energy savings. Simulation should also be conducted to which to compare the test results. As in the case of vehicle performance reduction, enough measurements must be taken to establish average energy use with statistical confidence.

#### **4.2.1.5. Load Management - Real Time Monitoring**

A real time power demand monitoring system can be installed as an experiment and then expanded if verification of its operation is achieved. Since two of the major cost items are the potential and current transformers, some initial arrangement might be made with the electric utility to use their equipment during the testing phase.

During the testing phase, it will be necessary to develop algorithms which can predict power demand given power samples in the early part of the demand interval. The EMM, or similar tool, will be helpful in the development of these algorithms.

#### **4.2.2. Full Implementation and Monitoring**

The prototype operation and verification outlined in Step 5 should reduce the technical risk for implementing energy conservation and/or load management on a wider basis. However, the program does not end here. Continued monitoring of the energy cost savings is still required, together with any system performance changes which result from the program.

It is at this stage of the program that the negotiation capability of the transit authority with the electric utilities must be strongest, since the reduction of revenue to the utilities because of the program will be felt. Changes in the power rate structure may bring other opportunities to reduce energy cost as well. Thus, the energy management study should be updated from time to time, typically on a five year basis. If the original study were conducted properly, updating should not be difficult.

#### **4.2.3. Rate Intervention**

If the transit authority decides to proceed with rate intervention, the first step is to meet with the utility to negotiate issues which can be settled outside of regulatory hearings. The remainder of the tasks may be conducted before and during the next rate proceedings:

1. Select a local law firm who has some experience in rate proceedings. Since part of the intervention will be an educational process of the regulatory commissioners, a law firm which can ease this process is most appropriate.
2. Review and analyze the utility's rate increase proposal. This review should be based on the cost to serve principle and be considered in the light of the other issues to be addressed at the rate proceeding. This analysis should include:
  - Appropriate cost of service.
  - Revenue requirement.
  - Appropriate changes in structure such as demand interval, ratchet, time of day rates, etc.
  - Appropriate rate of return.

- Appropriate state and local taxes.

3. Testify in front of the regulatory agency and prepare rebuttal testimony.

## 5. GLOSSARY OF ENERGY RELATED TERMS

- AC drive -** A propulsion system which uses three phase a.c. induction motors to drive the vehicle.
- Assured receptivity -** The taking of positive action during regeneration in the form of additional equipment to capture the power, which would normally be lost if the action were not taken. The positive action can take the form of energy storage systems both on - and off - board trains, or regenerative substations, by which power can either be delivered back to the electric utility or used to power other portions of the transit system.
- Auxiliary energy -** The energy required to provide support services both on and off - board the trains.
- Billing demand -** The maximum of the monthly demand and the ratchet.
- Cam control -** A motor control system which uses steps of resistance to provide variable voltage d. c. for input to the motors.
- Chopper control -** A motor control system using solid state devices (rather than resistors) to change fixed voltage d. c. to variable voltage d. c. for input to the motors.
- Coincident demand -** A demand consolidation in which the maximum demand is the maximum of the sum of the average energy use recorded on all electric meters in the same demand interval.
- Contributions-in-aid-of-construction -** Refers to the monies put up by the transit authority during the construction and procurement phase to purchase equipment or build facilities which will be owned and operated by the electric utility.

Demand -	Power demand.
Demand consolidation -	A way of grouping the recordings of the electric meters for the purposes of computing power demand.
Demand interval -	A period of time over which the energy flowing through a meter is averaged to determine power demand.
Energy Audit -	A procedure by which the end use of all energy necessary to run the system is determined.
Energy balance -	The requirement that the sum of all energy inputs into a system which does not store energy be equal to all energy outputs.
Energy conservation -	A term which refers to the reduction of the energy use portion of the electric bill.
Energy efficiency -	The amount of useful work done per energy expenditure. For example, in transit, this may mean the number of passenger - miles per watt - hour of energy or the number of car - miles per kilowatt - hours of energy, etc.
Energy end use -	A function which uses part of the energy flowing into the system as a whole.
Energy management -	A process of understanding a system's energy requirements, with the goals of reduced energy cost and increased energy efficiency.
Energy Management Model (EMM) -	A tool used to simulate traction operation and resultant energy consumption on a rail transit system.
Energy use -	The time integrated value of power.
Energy use pattern -	The variation of energy use with changes in operating practices and system design principles. The pattern is generally recorded by the utility's meters as a function of time.

- Field shunting -** The process of reducing the current through the field of a d.c. motor by placing an electrical shunt in parallel with the main field.
- Kilowatt-hour per car-mile -** An index which represents the energy expended in moving a transit vehicle an average of one mile on the transit system.
- Load management -** A term which refers to the control of the power demand portion of the electric bill.
- Monthly demand -** The maximum demand in a monthly billing period.
- Natural receptivity -** The condition during regeneration, whereby only the other trains on the system use the regenerated power.
- Noncoincident demand -** A demand consolidation in which the maximum demand is the sum of the maximum average energy uses recorded on all electric meters in any demand interval.
- Performance modification -** The changing of the performance of a train as it runs along a particular route.
- Power demand -** The portion of generating, transmission and distribution capacity that the electric utility reserves for a customer or customer class. It is also the average energy per unit time interval.
- Power rate structure -** The schedule of charges for electricity for energy use, power demand and facilities.
- Propulsion energy -** The energy required to drive the trains.
- Ratchet, or ratchet demand -** A demand calculated by a predetermined formula, which represents the minimum monthly demand.
- Regeneration -** The conversion of mechanical power

during train braking to electrical power, which may be used by other trains on the system, stored aboard the train(flywheel), stored in devices off - board the train or sold to the electric utilities supplying power to the system.

**Support energy -**

The energy used to provide support services to transit system operation.

**Traction energy -**

Usually the energy required to run the trains and provide the auxiliary support services aboard them.

**Watt-hour per  
passenger-mile -**

An index which represents the average energy expended in moving a typical passenger one mile on the transit system.

## 6. BIBLIOGRAPHY

1. Aigner, Dennis J., Poirier, Dale J., *Electricity Demand and Consumption by Time-of-Use: A Survey*, Electric Power Research Institute, Palo Alto, California, 1979.
2. Associated Engineers - A Joint Venture, "Subway Environmental Design Handbook", Tech. report, United States Department of Transportation, UMTA, 1975.
3. Bary, Constantine W., *Operational Economics of Electric Utilities*, Columbia University Press, New York & London, 1963.
4. Bernstein, Stanley, *A Theoretical Analysis of the Rolling Resistance Vehicles from Fundamental Mechanics*, PhD dissertation, Carnegie-Mellon University, 1979.
5. Booz-Allen & Hamilton, "Energy Use in Ground Transportation", Tech. report, Booz-Allen & Hamilton, June 1983, Performed for U.S. Department of Transportation, UMTA.
6. Boyce, David and Nguyen, Khanh, "Energy Consumption and Cost of the Journey-to-Work With and Without a Suburban Rapid Transit Line", Presented at fifty-seventh Annual Meeting of Transportation Research Board, Washington D.C., January 18, 1978.
7. Boyle, Daniel K., "Indirect Energy Considerations in Transportation Projects", *Transportation Analysis Report*, Vol. 30, July, 1983, pp. 1-25.
8. Boyle, Daniel K., "Rail Rapid Transit and Energy: A Re-examination of Current Conventional Wisdom", *Transportation Analysis Report*, Vol. 29, August, 1983, pp. 1-31.
9. Congressional Budget Office, "Urban Transportation and Energy: The Potential Savings of Different Modes", Tech. report, Congress of the United States, December 1977.
10. "Cost-Benefit Methodology for Evaluation of Load Management Options", Prepared by Gordian Associates, Inc., New York, New York. April 12, 1980.
11. "Costs and Benefits of Load Management to Society", Prepared by Various Researchers for Electric Power Research Institute. September 15, 1980.
12. "Costs and Rates Workbook, Part II: Learner's Guide, Part III: Case Studies", Prepared by ICF, Incorporated for Electric Power Research Institute, September 1981.
13. "Customer Attitudes and Response to Load Management", Prepared by Angel Economic Reports and Heberlein-Baumgartner Research Services for Electric Power Research Institute. July 1984.
14. Daniel, Mann, Johnson and Mendenhall, "Transit System Energy Requirements", *IEEE/ASME Joint Railroad Conference*, April 1975.



15. Davis, Christian F., Brown-West, Orikaye G. and Makuch, Mark F., "Energy Efficiencies of Transportation Modes", Tech. report, The University of Connecticut, October 1982.
16. DiRenzo, John F. and Peskin, Robert L., "Energy Saving Opportunities in Transit Design, Construction, and Operation", *American Society of Civil Engineers, Institute of Transportation Engineers, Proceedings*, 1982, pp. 51-65.
17. Donato, G. and Simmons, W. R., "The Generation of Heat in a Rapid Transit Tunnel". Prepared for presentation at the American Transit Association Rail Transit Group Conference, Philadelphia, PA, April 22-25, 1968.
18. Eisenhaure, David and O'Dea Stephen, "A Limited Investigation into Regenerative Braking and Energy Storage for Mass Transit Systems", Tech. report, U.S. Department of Transportation, UMTA and National Science Foundation, March 1978.
19. "Energy Conservation: Transportation 1978-January 1983", Published Search of NTIS, March 1983. (Citations from the NTIS Data Base).
20. "Energy Efficiency of Various Transportation Modes", Published as Transportation Research Record 689, Transportation Research Board, 1978.
21. Faruqui, Ahmad, Aigner, Dennis, J., Howard, Robert T, "Customer Response to Time-of-Use Rates", Prepared for Electric Power Research Institute. March 1981.
22. Fels, Margaret Fulton, "Comparative Energy Costs of Urban Transportation Systems", *Transportation Research*, Vol. 9, 1975, pp. 297-308.
23. Flanagan, R. C. and Suokas, L. A., "Regenerative Drive for Subway Trains", *Journal of Engineering for Industry*, August, 1976, pp. 737-760.
24. "Forecasting and Modeling Time-of-Day and Seasonal Electricity Demands", Special Report prepared by Electric Power Research Institute, December 1977.
25. Galler, Donald, *Energy Efficient Control of AC Induction Motor Driven Vehicles*, Alexander Kusko, Inc., Needham Heights, MASS, 1977.
26. Gay, William F., "Energy Statistics: A Supplement to the Summary of National Transportation Statistics", Tech. report, U.S. Department of Transportation, Transportation Systems Center, August 1976.
27. General Electric Company, "Assured Energy Receptivity Program", Tech. report, NTIS, U.S. Department of Commerce, August 1975.
28. General Electric Corporate Research and Development, "A Study of Flywheel Energy Storage for Urban Transit Vehicles", Tech. report, U.S. Department of Transportation, UMTA, September 1977, Distributed by NTIS.
29. Goeddel, D. L and Ploetz, G, "Analysis of Life-Cycle Costs and Market Applications of Flywheel Energy-Storage Transit Vehicles", Tech. report

- UMTA-MA-06-044-78-2, U.S. Department of Transportation, UMTA, July 1979.
30. Grant, J. C., "Rapid Transit Energy Demand", *Railway Engineer*, August, 1976.
  31. Healy, Timothy J., "Energy Use of Public Transit Systems", Tech. report, NTIS, U.S. Department of Commerce, August 1974.
  32. Henderson, Clark, "Energy Study of Rail Passenger Transportation", Tech. report, Stanford Research Institute International, August 1979, Prepared for U.S. Department of Energy, Systems Efficiency Branch, Transportation Programs Office.
  33. Henderson, Clark, Ellis, Hazel T., Wilhelm, James P., "Energy Study of Rail Passenger Transportation, Volume 2: Description of Operating Systems", Tech. report, Stanford Research Institute International, August 1979, Prepared for U.S. Department of Energy, Systems Efficiency Branch, Transportation Programs Office
  34. Hill, D. H., Groves, R. M., Howrey, E. P., Kline, A. C., Kohler, D. F., Leptrowski, J. M., Smith, M. A., *Evaluation of the Federal Energy Administration's Load Management and Rate Design Demonstration Projects*, Electric Power Research Institute, Palo Alto, CA 94304, 1979.
  35. Hirst, Eric, "Energy Intesiveness of Passenger and Freight Transport Modes: 1950-1970", Tech. report, Oak Ridge National Laboratory, April 1973, Distributed by NTIS.
  36. Hoan, Hoc H. Polis, Michael P. and Haurie Alain, "Reducing Energy Consumption through Trajectory Optimization for a Metro Network", *IEEE Transactions on Automatic Control*, IEEE, October 1975, pp. 590-598.
  37. King, Charles M. and Kusko, Alexander, "Flywheel Propulsion Simulation", Tech. report, U.S. Department of Transportation, UMTA, May 1977.
  38. Kirby, Brendan, "A Comparison of the Effect of Three Energy Management Schemes on the Energy Consumption of a Typical Rapid Transit Train", Master's thesis, Carnegie-Mellon University, August 1977.
  39. Knorr, R. E., et al, "Projections of Direct Energy Consumption by Mode 1975-2000 Baseline", Tech. report, Argonne National Laboratory, August 1979, Distributed by NTIS.
  40. Labonski, Richard T., "A Review of the Metrorail Energy Management Program", *Metro Energy Management Program*, American Public Transit Association, June 1981.
  41. Lave, Charles A., "Rail Rapid Transit: The Modern Way to Waste Energy", *Annual Meeting of January 1977*, Transportation Research Board, January 1977.
  42. Levinson, Herbert S., Strate, Harry E., Edwards, Syd R. and Dickson, William, "Indirect Transportation Energy", *Journal of Transportation Engineering*, Vol. 110, No. 2, March, 1984, pp. 159-174.
  43. Lieb, John G., "A Comparative Analysis of the Energy Consumption for Several Urban Passenger Ground Transportation Systems", Tech. report.

- U.S. Department of Transportation, UMTA, February 1974, Distributed by NTIS.
44. Males, Rene H., Uhler, Robert G., "Load Management: Issues, Objectives and Options", Electric Utility Rate Design Study for Electric Power Research Institute. February 1982.
  45. Malko, J. Robert, Smith, Darrell, Uhler, Robert G., "Costing for Ratemaking, Topic Paper, Rate Design Study", Prepared for Electric Power Research Institute. August 1981.
  46. Marlowe, E. W., "On-Board Energy Storage in Rail Rapid Transit", Tech. report, National Capital Transportation Agency, 1964.
  47. Masefield, Sir Peter, "Energy for Traction", *IMechE*, March, 1975, pp. 39-49.
  48. McShane, W. R., Block, A. and Ihlo W., "The Energy Advantages of Public Transportation", Tech. report, Ploytechnic Inst. of New York, March 1980, Prepared for UMTA and distributed by NTIS.
  49. Meister, John. M., "Regeneration Experience at the Sao Paulo Metro". Presented at American Public Transit Association Rapid Transit Conference, Chicago Illinois, June 7, 1978.
  50. Mellitt, B., Goodman, C. J., Arthurton, R. I. M., "Simulation Studies of Energy Saving with Chopper Control on the Jubilee Line", *Proc. IEE*, Vol. 125, No. 4, April, 1978, pp. 304-310.
  51. Mellitt, Brian and Goodman, Colin, "Specifying Choppers that Cut the Energy Bill", *Railway Gazette International*, January, 1983, pp. 38-41.
  52. Mellitt, Brian, "Simulation Can Save".
  53. Nene, Vilas, "Comparative Evaluation of Energy Management Models for Transit Systems", Tech. report, Transtech International Inc., February 1984, Performed for U.S. Department of Transportation, UMTA.
  54. New York City Transit Authority, "Optimization of Power Resources", Tech. report, U.S. Department of Transportation, UMTA, March 1979.
  55. Niemeyer, E. Victor, "Cost/Benefit Analysis of Load Management", Tech. report, Electric Power Research Institute, May 1981.
  56. Parsons, Brinckerhoff, Quade & Douglas, "Assured Energy Receptivity Study", Tech. report, NTIS, U.S. Department of Commerce, June 1975.
  57. Parsons, Brinckerhoff - Gibbs & Hill, "Optimization of Power Resources", Tech. report, Parsons, Brinckerhoff - Gibbs & Hill, May 1976.
  58. Phelps, David R., "Assured Energy Receptivity: A Project Overview", Tech. report, NTIS, U.S. Department of Commerce, September 1975.
  59. Pollard, John, Hiatt, David and Rubin, David, "A Summary of Opportunities to Conserve Transportation Energy", Tech. report, U.S. Department of Transportation, Office of the Secretary, August 1975.
  60. Port Authority of New York and New Jersey, "Rail Planning Division", Final Report, Path Energy Conservation Study. November 1978.

61. "Potential Cost Advantages of Load Management Topic 6", Prepared by Task Force No. 6 for Electric Power Research Institute. March 4, 1977.
62. "Railroad Electrification on Utility Systems", Prepared by Power Technologies, Inc. for Electric Power Research Institute. March 1983.
63. "Rail Transit Energy Management Guide", 1981 APTA Rapid Transit Conference. June 1981, Philadelphia.
64. Rainone, Louis, "Survey entitled Energy Management Guideline for Design and Construction", Prepared February 1981.
65. Rainone, Louis R., "Energy Management During Design and Construction", Presented at the APTA 1981 Conference.
66. Sathi, N., Uher, R., "AC Drive Vs. Can Control Energy Paper", Prepared for Westinghouse. June 1983.
67. Schaefer, John C., "Equipment for Load Management: Communications, Metering, and Equipment for Using Off-Peak Energy", Tech. report, Electric Power Research Institute, October 1979.
68. Shapiro, Phillip S. and Pratt, Richard, "The Energy Saving Potential of Transit", Prepared for Presentation at the 56th Annual Meeting of the Transportation Research Board January 1977.
69. Sharma, Onkar N., "Rail Transit Power Rates and Energy Management", Presented before the 1980 Rapid Transit Conference, San Francisco.
70. Sharma, Onkar N., "Keeping Control of Power Costs", *APTA 1984 Annual Meeting*, American Public Transit Association, 1984.
71. Sherret, Alistair, "BART's Operating Energy Consumption, Costs and Revenues", BART Impact Program Publication. Peat, Marwick, Mitchell & Co., January 1977.
72. Shonka, D. B., Loebel, A. S. and Patterson, P. D., *Transportation Energy Conservation Data Book*, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1977, Distributed by NTIS.
73. Sone, Eng Satoru, "Diversity Brings Success in the Drive to Cut Energy Costs", *Railway Gazette International*, January, 1983, pp. 31-34.
74. Stickler, J. J., "Staff Study, BART Excess Propulsion System Losses", Tech. report, BART Electrical Power and Propulsion Branch, January 1982, Prepared for U.S. Department of Transportation, UMTA.
75. "Systemwide Energy Conservation Studies", Final Report of Pequod Associates, Inc for Massachusetts Bay Transportation Authority. March, 1981.
76. Sunstein, D. I. L. and Uher, R. A., "Cost-Effectiveness Model Development for Energy Storage Devices in Rapid Transit Systems". September 1980.
77. Talukdar, Sarosh N. and Koo, Robert L., "The Analysis of Electrified Ground Transportation Networks", A publication of Transportation Research Institute..

78. "Technical and Economic Analysis of a Rapid Transit Battery Storage Substation Project". Prepared for New York State Energy Research and Development Authority by AiResearch Manufacturing Company.
79. Uher, R. A., "Site Specific Analysis of Regeneration PATCO & PAT Castle-Shannon Trolley". April 1979.
80. Uher, R. A., "Energy Conservation in 3 Electric Powered Transportation Systems", Presentation to the Office of University Research, DOT. January 1979.
81. Uher, R. A., "A Brief Analysis of Gravity-Assisted Acceleration and Braking". December 1980.
82. Uher, R. A., Sathi, N., Sathi, A., "WMATA: Energy Cost Reduction Study". 1982.
83. Uher, R. A., Sathi, N., "Load Management for Electric Rail Transit Systems". December 1982.
84. Uher, R. A., Sharma, O. N., "Power Rate Structure Aspects of Energy Cost for Rapid Transit Systems". February 1982.
85. Uher, R. A., Yang, H., Wenneker, G., "Definition of an Operations Decision Support System for the PAT". 1983.
86. Uher, R. A., Sathis, N., "Traction Energy Cost Reduction of the WMATA Metrorail System", IEEE 1983 Conference.
87. Uher, R. A., Sathi, N., "Energy Conservation Using Vehicle Performance Modification in Electric Rail Transit", IEEE Paper, Mexico, June 1983.
88. Urban Technology Center, Scholl of Engineering and Applied Science, Columbia University, "Energy Conservation in the New York Subway System". September 30, 1976.
89. "The Urban Transportation and Energy: The Potential Savings of Different Modes". Hearing before the Congressional Subcommittee on Transportation, 1975.
90. Viswanathan, C. N., Longmans, R. W. Domoto, G. A., "Energy Conservation in Subway Systems by Controlled Acceleration and Deceleration", *Energy Research*, Vol. 2, 1978, pp. 133-151.
91. Weinstein, C. H., "The Energy Crisis and Rail Transportation", Tech report, Institute of Electrical and Electronics Engineers, Inc., 1976.
92. Weinstein, C., "Technical and Economic Analysis of a Rapid Transit Battery Storage Substation Project", Tech. report, AiResearch Manufacturing Company, April 1982, Sponsored by United States Department of Energy, Prepared for New York State Energy Research and Development Authority.
93. "Peak Load Leveling Demonstration for Subway Substations Using Lead-Acid Battery System", Submitted by NYCTA and Westinghouse R&D Center. Pre-Proposal to UMTA, December 6, 1976.
94. White, Peter, "Energy Conservation in Urban Public Transport", *Transportation Planning and Technology*, Vol. 7, January, 1982, pp. 143-152.