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A LIMITED INVESTIGATION INTO REGENERATIVE BRAKING AND ENERGY STORAGE FOR MASS TRANSIT SYSTEMS

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16. Abstract

This study examines the technical and economic aspects of a regenerative braking/flywheel energy storage subway system. In order to define the analytical models accurately, it was necessary to gather data on the trains, rail network, schedules, and ancillary equipment. Data on projected costs of flywheels, motors, rails, and other equipment were also gathered for use in the economic analysis. During this data gathering phase, it was decided that the Massachusetts Bay Transportation Authority (MBTA) Red Line would be the source of the most representative and complete data. The problem was to determine what, if any, combination of energy storage devices and high conductivity rails would yield a subway system with a lower life cycle cost. The primary goal of the study was to compare the system costs of wayside storage with those of on-board storage. Using data provided by MBTA, power levels vs. time and rail losses were calculated and used to determine the sizing and location of energy storage units. From the amounts of energy storage required, the costs of the flywheels and i/o equipment were calculated. Utilizing these modules for load leveling was also considered. However, since the energy storage required for load leveling is much greater than that required for regenerative braking, a separate study is needed to examine this in detail.

The study indicates that for systems with station densities and traffic patterns similar to the MBTA Red Line, the inclusion of wayside flywheel modules has a significantly lower first cost, and can be justified on a purely economic basis. This report also addresses recommendations for future study, contains a bibliography, and Appendices A and B: "Vehicle Energy Requirements" and "Report of Inventions", respectively.

17. Key Words

Brakes and Braking - Regenerative; Energy Conservation; Energy Storage; Flywheels; Life Cycle Costing; Load Leveling; Rail Conductivity; Subways - Life Cycle Costing; MBTA

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PREFACE

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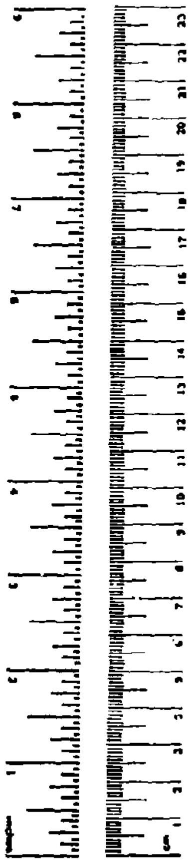
METRIC CONVERSION FACTORS

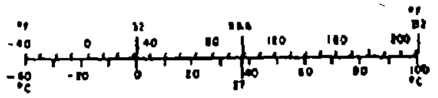
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

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



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INTRODUCTION AND SUMMARY

1.1 Background and Statement of Problem

Regenerative braking for subway trains has been recognized for years as a potential means to reduce energy consumption. Instead of the energy of braking trains being dissipated as heat, the energy is converted back into electricity and returned to the rails. In modern systems there could be further energy saving by reducing the load on the air-conditioning systems. However, recent work has brought to light a number of problems and trade-offs in the practical design of such a system. A study by General Electric for Transit Development Corporation(1) determined that the lack of natural receptivity and high resistance in the rail network was a major barrier to regeneration. Natural receptivity is the ability of the power distribution network to accept regenerated power without the addition of other equipment. The receptivity of a system can be improved by the addition of wayside resistors or energy storage nodes that will give the system a level of assured receptivity. The General Electric study concluded that the use of conservative stations; that is, energy storage nodes, would lead to the system configuration requiring the least power. The use of higher conductivity rails would further reduce the power required. If a wayside energy storage node were placed in each station, energy could be transmitted to this node with good efficiency, allowing for more economic operation of the subway system. Flywheels were suggested as the storage node because of their high power density. The problem is then to determine what, if any, combination of energy storage devices and high conductivity rails would yield a subway system with a lower life cycle cost.

1.2 Approach

This study examined technical and economic aspects of a regenerative braking/flywheel energy storage subway system. A representative line of the Massachusetts Bay Transportation Authority (MBTA), the Red Line, supplied the data for analysis. Using data provided by the MBTA, power levels vs. time and rail losses were calculated and used to determine the sizing and location of energy storage units. From the amounts of energy storage required, the costs of the flywheels and i/o equipment were calculated.

The technical part of the study was broken down into two distinct stages: 1) data was gathered from the MBTA and other sources on car driving cycles, network parameters, power flows in and out of trains, and variations in system load from the seconds' range to the months' range; 2) a rail network model was defined in such a way as to allow investigation of the number and locations of energy storage units, the suitability of the flywheel modules to load level the MBTA system, and the effects of better rail conductivity.

Initially, the program was to include analyzing an entire line statistically, but even with the best rail available with present voltages, not enough cars can be averaged together to make the statistics meaningful.

The economic study first attempted to identify and document all incremental savings and costs of such a system. The trade-offs between minimum costs and minimum energy consumption, particularly in light of changing fuel prices, were then analyzed so as to define economic values for various system improvements as a function of energy costs.

1.3 Summary

The conclusions on storage of regenerative braking energy, storage for daily load leveling, and use of high conductivity rails are summarized in this section.

A strawman flywheel module that would be located at passenger stations on the MBTA Red Line was sized and the costs and energy savings were calculated. It was determined that such a module could save a net of 210,000 kilowatt hours of electricity each year at the traffic densities for one leg of the Red Line, worth about $10,500 at current electricity costs. For the stations that handle the combined traffic from Ashmont and Quincy, the energy savings becomes 420,000 kilowatt hours. The cost estimates were based on "Economic and Technical Feasibility Study for Energy Storage Flywheels"(2) released by North American Rockwell in 1975, which examined current, near-term and long-term projections of technology and cost. Their near-tern projections, covering the early 1980's, were the basis of the costs in this report. The "strawman" flywheel module is expected to cost $70,000 and require $2,500 of maintenance per year. Over a twenty-year period, this investment has a present value of $92,000 using the 10% discount rate suggested by OMB Circular A-94. Using the same discount rate, the energy savings for stations serving combined traffic have a present value of $175,000. However, it is likely that the cost of energy will escalate more rapidly than the economy in general, so the analysis was repeated assuming energy inflation rates 2% and 4% faster than average. With these inflation rates, the present value of the savings rises to $203,000 and $238,000, respectively.

Thus, in a system where the trains are capable of regenerative braking, the addition of flywheel modules can probably be justified on a purely economic basis.

The wayside concept was compared qualitatively with the on-board concept, as implemented by the New York City Transit Authority and AiResearch, and shows promise of improved safety, lighter trains, fewer components, and lower cost.

An analysis of the energy required to load level the MBTA was also performed. Approximately twenty times more energy storage would be required for daily load leveling than for the storage of braking energy. Since a load leveling flywheel storage system would have substantially different characteristics than a flywheel system used solely to recover braking energy, the economics of load leveling would more appropriately be studied separately.

The effects of improved rail conductivity were also examined. For the case where a flywheel is located in each passenger station, the rail losses are insignificant even with steel rail. There are locations on the Red Line where the use of composite rail would allow the elimination of a storage module. However, it is more economic to install the extra flywheel modules than to install composite rail unless the rail were being replaced anyway.

The hypothesized strawman flywheel module would consist of a flywheel rotor, appropriate bearings, an electromechanical power conversion system, and a vacuum housing, together with appropriate support systems and control. The control system would regulate electrical power flow to and from the flywheel module in the form of kinetic energy in the spinning flywheel rotor.

SECTION 2

TECHNICAL DISCUSSION

2.1 Introduction

The goal of this section is to formulate the system models and discuss the analysis leading to the flywheel sizing and cost/benefit calculations. This is done in three stages: gathering of baseline data; formulation and discussion of the models; and analysis of the subway system, flywheel characteristics, and costs.

2.2 Baseline Data

In order to define the analytical models accurately, it was necessary to gather data on the trains, rail network, schedules, and ancillary equipment. Data on projected costs of flywheels, motors, rails, and other equipment were also gathered for use in the economic analysis. During this data gathering phase, it was decided that the MBTA Red Line would be the source of the most representative and complete data. Thus, the information-gathering effort related to rail networks and total energy usage were centered around the Red Line. While the conclusions will not necessarily be directly applicable to other MBTA lines or lines in other cities because of differences in loads, control strategies, and equipment, the models formulated using the Red Line data should have general applicability.

The data collection phase will be described in three parts. The first section involves physical characteristics of the rails and trains. Schedules and power consumption data are described in the second section. The third section discusses cost projections for flywheel systems and rails.

2.2.1 Rail System Characteristics

The section of rail line that was chosen for analysis was the MBTA Red Line from Harvard Square to Ashmont Station. This run is almost nine miles in length and services fourteen (14) stops. It is a third rail system using standard 150 lb/yd steel rail and fed by six (6) electrical substations spaced along the line delivering power at 600 VDC. The layout of the rail system is shown in Figure 1.

In the Red Line third-rail system, power is fed to the train through the 150 lb/yd power rail and is returned through the two running rails which are 115 lb/yd steel. The conductivities of the rails are important to the efficiency and receptivity of the system. In order to reduce system losses, a composite steel/aluminum third rail was developed which has much higher conductivity than the steel rail. For the purposes of the report, composite rail refers to Com-Tran-Rail, a product of H. K. Porter Co. This is a steel rail with an aluminum plate attached to the sides (see Figure 1). One goal of this study was to evaluate the effects of these high conductivity rails on regenerative braking. Therefore, conductivities for both standard steel and composite rails are shown in Table I.

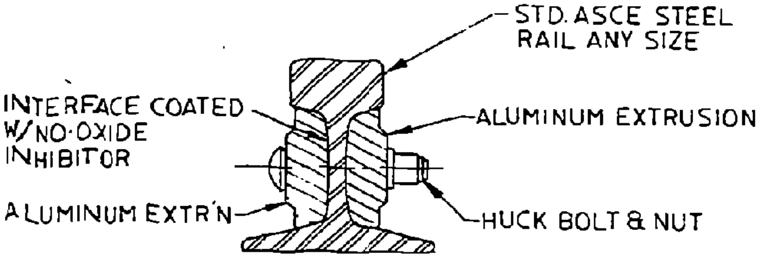


Figure 1: H.K. Porter (Composite) Rail

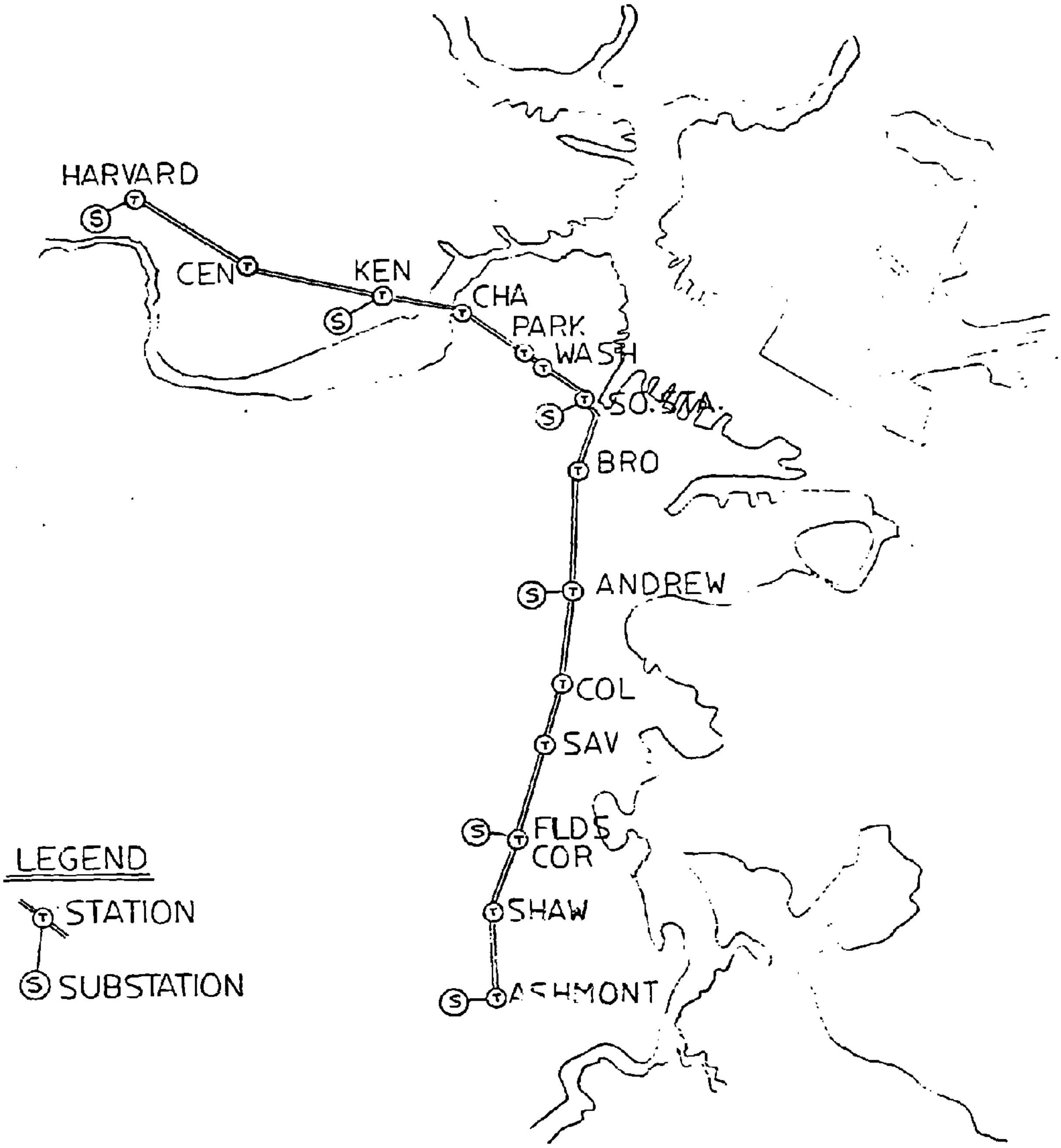


FIGURE 2. LAYOUT OF SECTION OF MBTA RED LINE

Table I - Resistances of Subway Rails

Material	Type	Resistance (Ω/1000 ft)
Steel	Power Return	.004 .0026
Aluminum	Power	.002

2.2.2 Train Characteristics

The data on the trains (speed, power, etc.) was taken from work done by Clarke.(5) The important parameters are given in Table II and are based on a four car train. More complete information is given in Appendix A.

Table II - Energy Requirements for Red Line Trains

Gross vehicle weight	280,000 lb
Energy required at wheels (over route studied)	11.05 kw-hr/mi
Peak velocity	50 mph
Peak acceleration	3.0 mph/sec
Peak deceleration	-3.0 mph/sec
Peak K.W. over 8 stop route	-2,750
Representative peak KW	2,000
Representative speed before stop	40 mph

Representative values for power dissipated in stopping and speed before stopping were determined for use in the study. During only one stop on the test run was the 2,750 KW peak achieved. On the other seven stops the peak power dissipated was 2,000 KW or less for the four car train. Similarly, the 50 mph peak speed overestimates the average energy available from a braking train. Thus, it was felt that a design based on 2,000 KW peak power and stops from 40 mph would be the best base for analysis.

2.2.3 Schedule and Loads

The Red Line carries about 382 cars per day per direction. These cars are organized into four car trains during rush hours (7:00 - 10:00 a.m. and 3:00 - 6:00 p.m.) and two car trains off peak. Table III lists these schedules.

Table III - Weekday Schedule for Red Line

Time	Headway	Train Length	Total Trips		Total Cars	
			to Ashmont	Quincy	Ashmont	Quincy
Peak	6 min	4 car	61	66	244	264
Off Peak	10 min	2 car	61	59	122	118
					366	382

By examining hourly data provided by the MBTA on substation power conversion, a representative daily load profile can be determined. This is important in calculating the energy required for daily load leveling. Figure 3 is a graph of power required versus time of day averaged over two Red Line substations. The power required lags behind the schedule by about the amount of time required to travel the length of the route. Another trend in power consumption is driven by the ambient temperature. For the Boston area system, the peak load occurs in the winter because of car and tunnel heating requirements as shown in

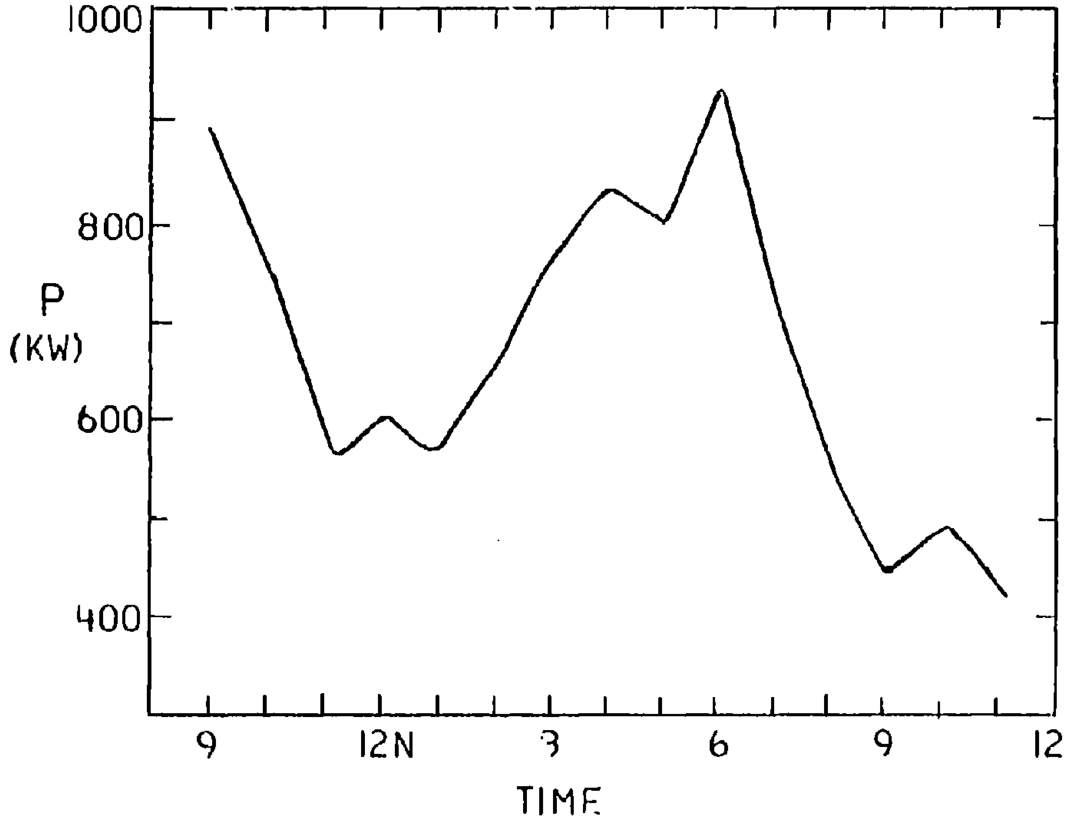


FIGURE 3. TYPICAL DAILY SUBSTATION POWER OUTPUT

Figure 4. Other systems that have been studied, such as Atlanta(1) have peaks in the summer caused by air conditioning. Since nonregenerative braking adds heat to tunnels, the addition of regeneration will have different effects in different geographic areas.

2.2.4 Rail and Flywheel Costs

Cost estimates gathered for composite rails and flywheel modules are described in the following two subsections.

2.2.4.1 Composite Rail Concepts

The first cost of a composite third rail system is made up of the rail and accessory costs and installation costs. The rail itself sells for $22 per foot. Because of its design using Huck bolts, the rail can be installed quickly. A team of six men and a crane can install at least fifty 39-foot sections each day. Steel rail of equivalent size sells for $10 per foot. However, this rail is more difficult to install. Thus a real comparison of composite and steel rails must include all installation and accessory costs. A study of Maryland Transit in 1974(4) found installed, ready-to-run costs to be $124,000 per mile for composite rail and $120,000 per mile for steel rail. This yields a total cost of $23.50 per foot for composite rail in 1974 dollars. No more recent information on costs is available, but extrapolating to today's dollars would give a cost of about $150,000 per mile.

2.2.4.2 Flywheel Module Costs

The cost projections for flywheels, motor/generators and supporting equipment were taken from "Economic and Technical Feasibility Study for Energy Storage Flywheels "(2)

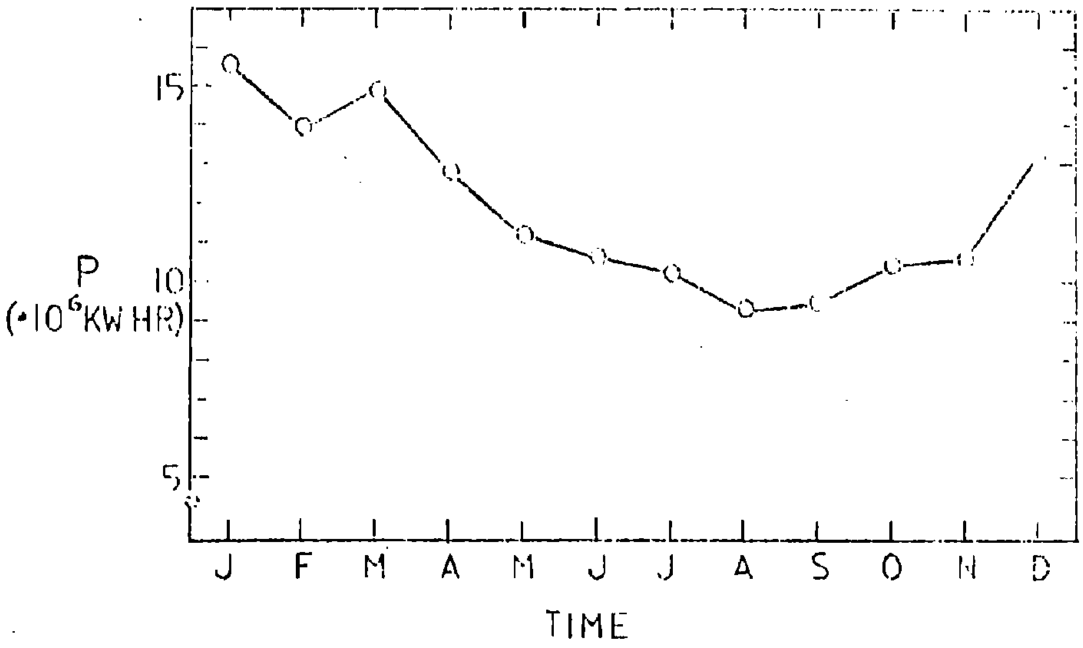


FIGURE 4. YEARLY SYSTEMWIDE POWER GENERATION

released by North American Rockwell in 1975.(2) The best currently available flywheel material in the sizes of interest is maraging steel. Such a flywheel is capable of storing 10 watt hours per pound of energy and costs $4.50 per pound. This gives a cost of $450 per kilowatt hour. The development of Kevlar or glass and epoxy composite flywheels is expected to reduce the cost of flywheel energy storage to about $150 per kilowatt hours by 1985. The rotating machine is expected to cost about $20 per kilowatt. The installation cost including excavation, site preparation, electrical lines, etc. is expected to cost about $10,000 based on scaling down the modules designed by Rockwell. A suitable vacuum system and housing would cost about $15,000. The maintenance cost is interpolated from the GE study(1) to be $2,500 per year.

2.3 System Modeling

With data described in the preceeding subsections, simple models of the trains, flywheels, and rails could be developed. A train and flywheel interaction model was developed first to examine the relationships among flywheel sizing, train characteristics and rail conductivities. With this model, the power flows between flywheels and trains could also be determined. A model of the rail network was then developed to study the number and location of flywheel modules. Finally, a statistical model of train movements and power flows is discussed.

2.3.1 Train and Flywheel Interaction Model

The basic elements included in the train/flywheel model are the power and return rails, one or two accelerating or decelerating trains, and the flywheel module, as drawn in Figure 5. The rails are modeled as pure resistors and the trains as variable voltage sources. The flywheel is assumed to maintain the power rail at 600 VDC. In considering

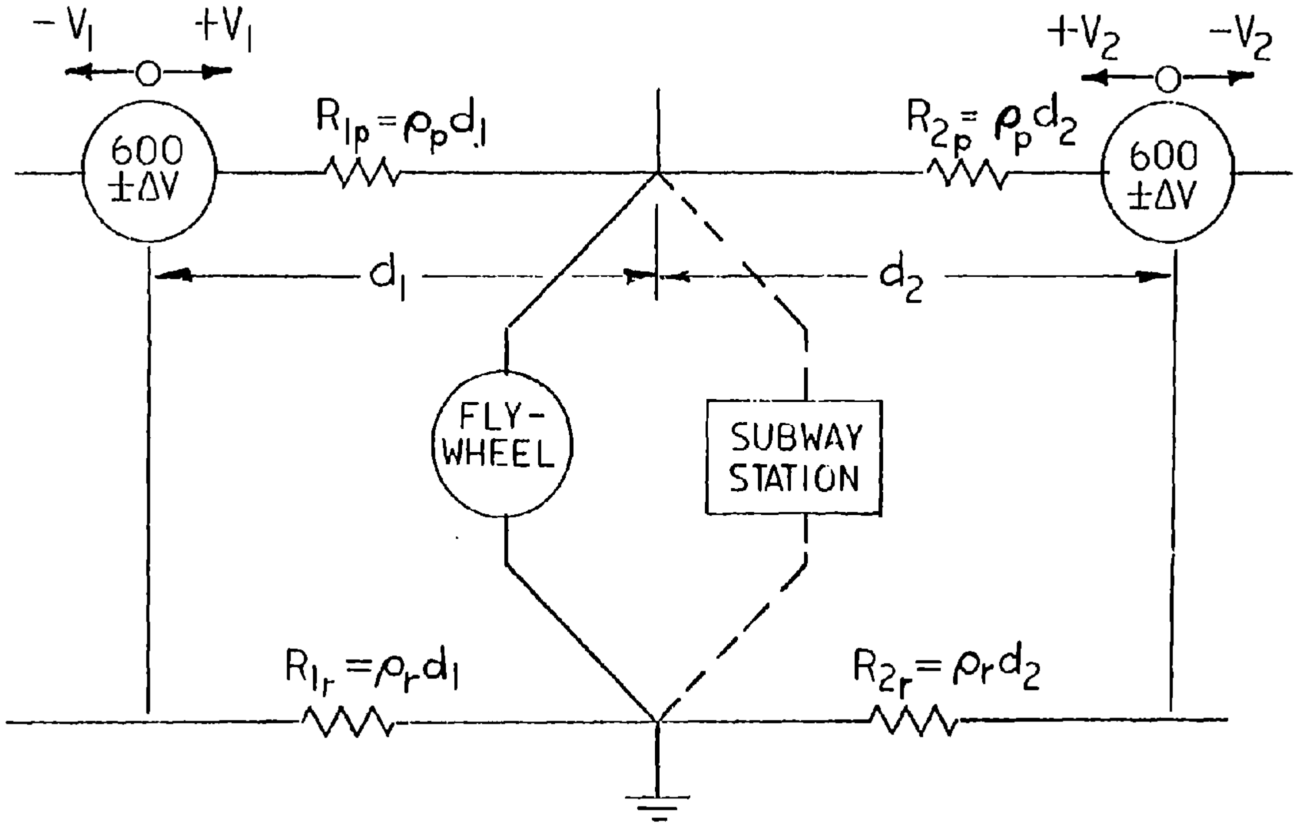


FIGURE 5. TRAIN FLYWHEEL MODEL.

the round-trip efficiency for power flow (from the train to the flywheel and back) only the regeneration efficiency of the traction motor, the rail losses back to the flywheel and the in and out efficiencies of the flywheel motor were included. The rail losses back to the train and the traction motor losses would be present whether or not regeneration is employed. The efficiencies used for the traction and flywheel motors were 85%. The losses in the rail depend on the rail conductivity, the distance the train travels while accelerating, and the voltage capabilities of the traction motors. If the deceleration from 40 mph at 3.0 ft/sec^2 is used for the analysis, the equations for regenerated power

$$P = Mav = VI \tag{1}$$

velocity $$v = 60 - \sqrt{2a(d-600)} \tag{2}$$

and loss $$I^2R = I^2(\rho p + \rho r)\,d \tag{3}$$

yield the average loss point, d = 500 ft. Combining this with the data in Table II and a regeneration voltage of 675V gives rail efficiencies of 97% for steel rail and 99% for composite rail. These are the values that will be used in the analysis section.

2.3.2 Rail Network Model

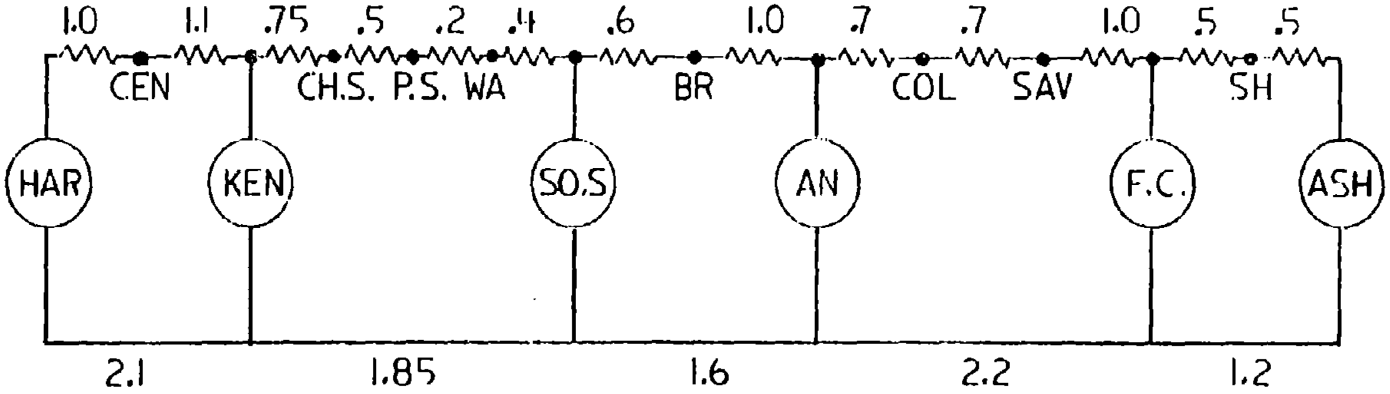
The network model was developed to determine the total number and location of storage nodes required for the line. Whether or not flywheels are needed in all stations depends primarily on the inter-station rail conductivities. Therefore, the model considers the stations to be connected by a simple resistive network with substations as voltage sources (see Figure 6). The distances in miles between the stops are written above the resistance symbols. Calculations of actual resistances between stations then can be performed for the different rail types and used in determining the locations of the flywheel modules.

2.3.3 Statistical Model

If the subway system had sufficient receptivity that a stopping train at one end of the line could send power to an accelerating train at the other end of the line, much less storage would be required. If enough trains could be linked together, the original program was outlined so that the train's running cycles would be statistically modeled, probably using either a Gaussian or lognormal distribution. That is, means and standard deviations of the numbers of cars accelerating, braking, and cruising would be calculated. However, once the study was underway, it became apparent that even with the highest conductivity rail available, only about three stations could be linked. Thus it was decided that the statistical approach was not appropriate.

2.4 Analysis

The analysis was done in three stages. First, the flywheel and motor/generator were sized and potential energy savings per station were calculated,using the train/flywheel interaction model. The determination of the number and location of modules and the effects of rail conductivity was the second stage. This analysis was performed on the network model. Finally, an economic analysis based on present value of costs and savings was performed.



ALL NUMBERS GIVEN ARE IN MILES

FIGURE 6. RED LINE NETWORK

2.4.1 Flywheel and Motor/Generator Sizing

The energy storage capacity of the flywheel is determined by the inertia of the train, the efficiency of the energy transfer process, and the number of train stops one wishes to store. Since the greatest amount of traffic is during the rush hour, the first calculations will be done assuming four-car trains with six minute headway. First, one must calculate the kinetic energy of the train

$$E_{ke} = 1/2\ MV^2 \qquad (4)$$

assuming a stop from 40 mph. This yields a kinetic energy of 6 kilowatt hours. Flywheels are generally not run below half speed. Since energy stored is proportional to the square of the rotational speed, three quarters of a flywheel's stored energy can be considered useful. Thus, for each stopping train, the theoretical energy storage, required E_{st} will be 1.33 times the energy of the moving train, or

$$E_s = 8 \text{ kilowatt hour/train}$$

However, not all this energy reaches the flywheel. One must first account for traction motor efficiency ($\eta_m = .85$), rail efficiency ($\eta_r = .97$ or $.99$) and flywheel motor/generator efficiency ($\eta_f = .85$). Thus, the actual storage requirement, E_{sa}, per four-car train is

$$E_{sa} = E_{st} \eta_m \eta_r \eta_f \qquad (5)$$

or

$$E_{sa} = 5.5 \text{ kilowatt hour, steel rail,}$$
$$= 5.7 \text{ kilowatt hour, alum rail.}$$

Next, the flywheel motor/generator must be sized. This is probably the most critical area since the cost of this motor obviously represents the largest single cost in the system (see Section 2.2.4). Since the probability of having two trains stopping at a station simultaneously is about 5%, it is clearly less economic to size the motor/generator for two stopping trains than for one train. The question then becomes whether the motor/generator should even be sized for the 2,000 kilowatt peak (see Section 2.2.2) minus, of course, the rail losses. However, given the scope and accuracy of this program, the motor/generator will be sized to the 2,000 kilowatt peak, minus the losses of 500 feet of rail.

For a train regenerating 2,000 kilowatts at 675 V, the current is 3,000 amps. This results in a 66 kilowatt loss for steel rails, or a 24 kilowatt, 8 V loss for aluminum rails. In either case, the rail losses are insignificant if a flywheel is in each station. Thus, the module will be considered to have the following capabilities:

E_s = 11 kilowatt hours

P = 2,000 kilowatts

Knowing the transmission and conversion efficiencies, one can calculate the gross energy saving per station. From earlier calculations it can be seen that each car has kinetic energy equivalent to 1.5 kilowatt hours. The schedule listed in Table III shows 382 cars travel each direction each weekday, or 764 stopping cars per station per day. Including the effects of losses, the gross amount of energy recoverable per day, E_r, is

$$E_r = (\text{number of cars})\ (\text{energy/car})\ \eta_m \eta_r \eta_f^2 \qquad (6)$$

$$= 680 \text{ kilowatt hours per day}$$

From this recoverable energy the standby losses of the flywheel must be subtracted. Typically, standby losses for a flywheel system are less than 5% of stored energy each hour.(2) If the average stored energy is 8 kilowatt hours, the losses are 400 watts, or 7 kilowatt hours per day. Weekends have about half the traffic, but the same losses. Thus, per week the net energy saved is 4,030 kilowatt hours, or the energy saved per station per year, E_{ts}, is

$$E_{ts} = 210{,}000 \text{ kilowatt hours}$$

2.4.2 Network Analysis

The purpose of this section is to determine where it is most economic to place storage modules with steel rails and how the addition of composite rail changes the number and location of these units. From Figure 6 one can see that the closest grouping of stations is Charles, Park, and Washington. If a storage module can be eliminated anywhere with the standard steel rail, it is at Park Street. Therefore, this will be the first station analyzed.

As a train approaches Park Street in the braking mode, energy flows to both Charles and Washington. Since the resistances between these stations are fixed by the rails, the distribution of this energy can be determined using the current divider relationship. The distance from Park to Washington is .2 miles ($R = .012\Omega$) and from Park to Charles is .5 miles ($R = .032\Omega$). Thus, the Washington modules receives 2,140 amps both at 649 V (675-26). This represents a 4% transmission energy loss which is quite acceptable. The 26-volt drop in the line, however, is about the upper limit for control purposes. The composite rail, while not saving much energy, would reduce the voltage drop to only 10 volts. This implies that with composite rails, flywheel modules could be eliminated in areas where the spacing between stations is substantially greater. In fact, with a voltage drop of 20 V, the Washington module could also be eliminated, leaving modules at Charles Street and South Station. This calculation performed for the Columbia and Shawmut Stations shows that they too could be eliminated. If a 27-volt drop is allowed, the Broadway Station could be eliminated also.

From the network model, it is concluded that using steel rail modules is required in all stations except Park Street; that is, a total of 13 modules. If composite rails were used, four additional modules could be eliminated.

2.4.3 Load Leveling Analysis

Once the system is sized to capture regeneration braking energy, one can ask whether this sizing can also be used for daily load leveling. To determine the requirements for load leveling, two calculations were performed at the substation and single station levels. At the substation level, a daily load profile (Figure 3) is examined. At the single station level, the schedules and average train motoring power are used. These answers are then compared to reduce the uncertainty.

The substation load profile shows a peak power requirement of about 900 kilowatts. The average power is about 650 kilowatts. Assuming the peak lasts three hours and the substation serves three stations, each flywheel module would have to store 250 kilowatt hours. For the three-hour rate, the module would need a motor/generator sized for at least 80 kilowatts.

During off peak hours, six two-car trains pass through each station each hour (12 cars/hr). During the peak, ten four-car trains pass each hour (40 cars/hr). Multiplying the average motoring power per car (2.5 kilowatt hour/mile), the amount of rail served by each flywheel module (1.3 miles) the difference in the number of cars per hour (28) and the length of the peak (3 hours), yields a required storage of 270 kilowatt hours of storage. This is in very close agreement with the first calculation. In either case, the storage required for load leveling is about a factor of twenty larger than the storage required to recover braking energy.

2.4.4 Economics

Knowing the specifications for the equipment required and amount of energy that can be saved, the dollar value of the costs and savings can be determined. For this analysis, all costs and benefits will be computed on a present value basis following the guidelines of OMB circular A-94. Electricity savings will be assumed to have a current value of \$.05 per kilowatt hour with the inflation rate of energy being 2.0 and 4% greater than the discount guideline. The recommended discount rate, r_d, is 10%. Using the present value method, the value, V_p, of a cost or savings, D, at some time in the future, t, is

$$V_p = D/(1 + r_d)^t \qquad (7)$$

If D is a yearly savings or cost expected over the life of an investment, T, then the present value of these costs or savings is

$$V_p = \sum_{t=1}^{T} D/(1 + r_d)^t \tag{8}$$

2.4.4.1 Flywheel Storage Modules

The cost of the storage modules is the initial cost plus the maintenance cost. The present value of the initial cost is simply that cost. The maintenance costs must be discounted according to equation (8) above. Using the cost data presented in Section 2.2.4 and assuming a life of 20 years, gives a present value cost of $92,000. Using a value of $.05/kilowatt hour, results in a savings of $10,500 in today's dollars. Over a 20-year period, this savings has a present value of $90,000. This savings would apply to modules placed between Ashmont and Andrew. Between Quincy and Andrew, the savings would be about $10,000. Between Andrew and Harvard, however, the traffic is the sum of the traffic to the southern branches. For a station in this section, the annual energy savings would have a value of about $20,500 or a twenty year present value of $175,000. For a module placed in Park Street and accepting power from trains at Park and Washington, 68% more energy could be saved. The other 32% is either dissipated in the rails or flows to Charles Street. Thus, the module at Park Street could save almost $35,000 a year worth of electricity, which would have a twenty year present value of $294,000. However, it is likely that the price of electricity will rise faster than costs in general. To quantify the effects of fuel price increases, the present value of the energy savings was also evaluated assuming energy prices rise 2% and 4% faster

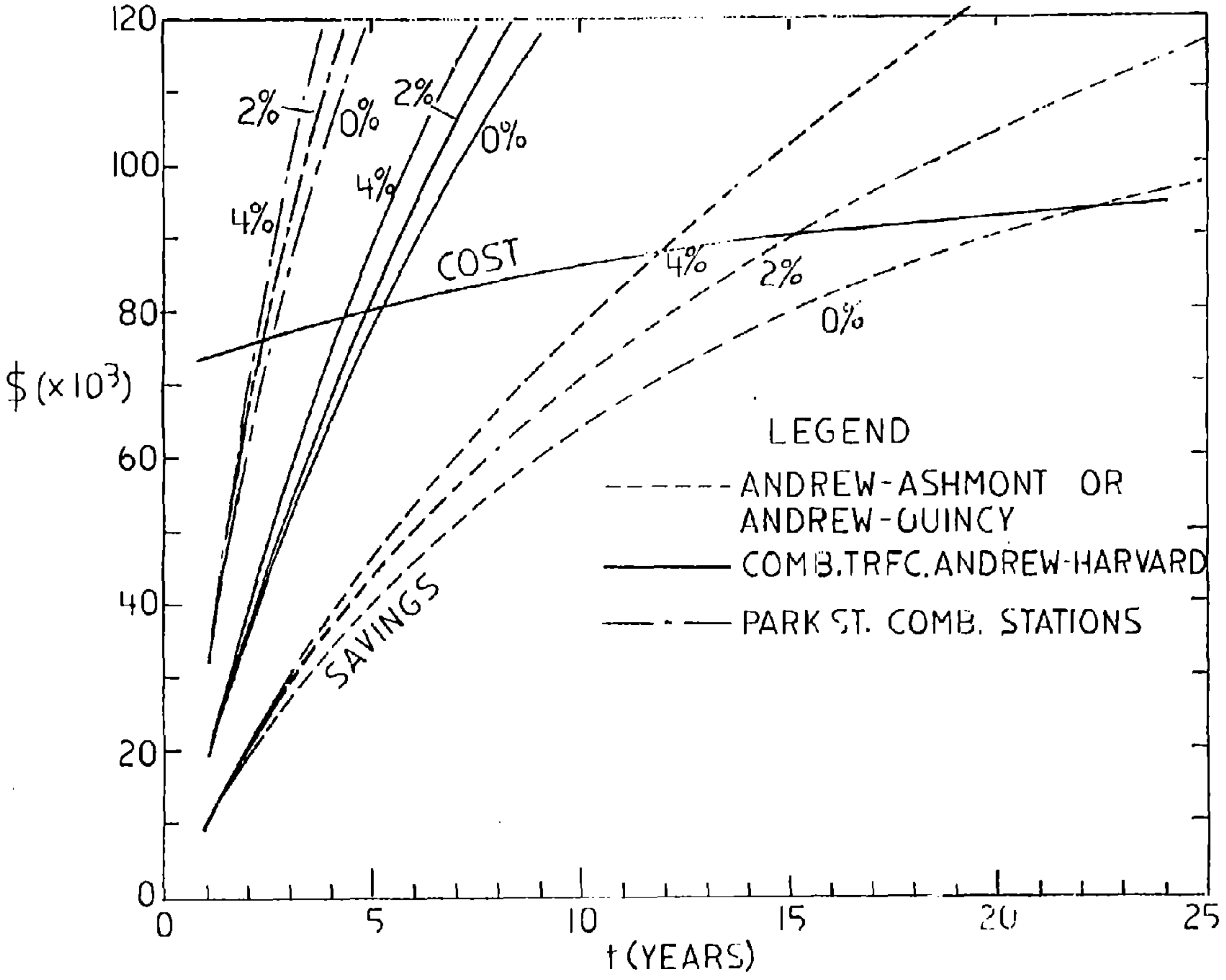


FIGURE 7 PRESENT VALUE COSTS AND SAVINGS AS A FUNCTION OF TIME

than the rest of the economy. These results are presented graphically in Figure 7, which shows the present values of the costs and savings as a function of time for three cases discussed above.

2.4.4.2 Composite Rails

It was seen in Section 2.4.2 that the use of composite rails would reduce by four the number of flywheel modules required and improve the rail efficiency about 40% thus improving overall efficiency about 5%. The important question is how the cost of the rails compares with the cost of a flywheel module. This analysis will be done on the section of rail between Charles Street and South Station, which are 1.1 miles apart. These four stations use about one million kilowatt hours of electricity yearly. The improved conductivity would save about $2,500 per year worth of power and the cost of one flywheel module ($70,000). The cost would be 2.2 miles of rail (11,600 ft.) and the labor required to install it. Given installed costs described in Section 2.2.4, it would cost $330,000 for rails and installation. Comparable steel rail would cost about $315,000 ready to run.

SECTION 3

RESULTS AND CONCLUSIONS

3.1 Results

3.1.1 Energy Savings

A single module on the Red Line has the potential of saving between 210,000 and 650,000 kilowatt hours of energy each year. The rail studied has fourteen stations, but the end point stations would only save half as much energy as other stations. However, eight stations handle the combined traffic of the two legs, and these stations could save over 400,000 kilowatts per year. The savings potential of the Red Line from Harvard to Ashmont is then about 4.2 million kilowatt hours. Since the end stations can only save half as much energy, but would cost the same, these stations probably should not be included. Thus, the most realistic estimate would be a savings of 4.0 million kilowatt hours per year. This amount of energy has a current value of about $200,000. Using steel rail, a total of eleven stations should then be built. The present value of these savings over a twenty-year period is 2.0 million, 2.1 million or 2.2 million dollars, depending upon the cost of energy.

3.1.2 Costs

The major cost is the flywheel storage module. Adding the various material and installation costs gives a first cost of $70,000 per module. Maintenance costs are expected to be $2,500 per year. The standby losses in the flywheel are small, and these are subtracted from the potential energy savings. Thus, the twenty-year present value cost of a module is $92,000. For eleven stations the expected cost is thus $1.0 million.

The greatest uncertainty in the costs is the cost of modifying the trains to return energy to the rails. Because of the cam control scheme used on the Red Line, the cost of modifying the trains would be prohibitive. In fact, the train modification problem is probably the greatest roadblock to demonstration of wayside flywheel storage modules. On the Red Line, for example, a peak of 80 cars can be found on line during rush hour. To modify the significant fraction of these trains to check the technical and economic feasibility of a single wayside storage module would be very expensive. Thus, a demonstration module would probably have to be placed in a system where a number of cars could be easily modified to give regenerative capability. The new LRV's of the MBTA Green Line are examples of trains that could be suitable.

3.1.3 High Conductivity Rails

To replace the power rails between Charles Street and South Station, the shortest section where composite rails would be desirable, would cost about $330,000. This is more expensive than the flywheel module and energy that could be saved. However, in the case where a new section is being built or rail is being replaced, the composite rails should be considered. This rail could allow the elimination of electrical substations and flywheel modules. If the system is air conditioned, the reduced ohmic losses with the composite rails could have a much greater impact on system costs than for the MBTA Red Line. Also the optimally cost effective configuration may be a combination of steel and composite for both the power and return rails. However, all of these trade-offs are beyond the scope of this program. A future study that could examine this question in depth is considered worthwhile.

3.1.4 Technical Feasibility

There are no obvious technical barriers to designing and building a flywheel module along the lines described above. However, a motor/generator that is capable of the required performance at $20 per kilowatt is not currently available. To eliminate a gearbox and keep the size of the machine small (to keep the materials cost low) would require a DC machine capable of operating in the 7,000 to 10,000 rev/min range. A steel flywheel could currently be built to store 10 kilowatt hours, but for reasons of safety and weight, a composite wheel would be more desirable. Composite wheels of this stage will probably not be available until the 1980's. Lastly, modification of existing trains to get regeneration capability is feasible, but to do so without interfering with passenger space and for a reasonable cost is unlikely for the Red Line trains. On more modern trains designed with regeneration or dynamic braking capability, this modification should present no problems.

3.1.5 Comparison With On-Board Storage

The study indicated that for many applications, depending on station spacing and traffic densities, the wayside flywheel implementation has a much lower system level first cost than on-board storage. For the MBTA Red Line, incorporating wayside modules in stations as previously described, have an estimated first cost of $980,000 while the incremental first cost of having on-board storage in all cars used on this line would be $5,480,000. Since the on-board system is moving and is in close proximity to passengers, safety must be a major concern. Thus, the on-board flywheel must be derated and also surrounded with a heavy protective shroud. The weight added to each car is

10,754 pounds, which will increase the power required by each car. Also, a unit must be installed in each car, and because of the non-constant nature of transit loads, many of these cars will sit idly on a siding much of the day. By contrast, in the wayside scheme, the expensive flywheel equipment is always on-line, even though it operates at half capacity most of the day. The total amount of storage and power capability per stop is similar for the two cases, but the wayside scheme uses larger but fewer components which should result in an economic savings. Since the wayside equipment is always on-line, a substantial net savings in the number of motor/generators is also realized. The on-board configuration has the advantage that there are no rail losses, but since the efficiency of the rails is over 95%, this does not represent a major savings. All these factors considered, the wayside storage configuration should be economically sound on its own and should also be more cost effective than the on-board configuration.

3.2 Study Conclusions

The study indicated that the inclusion of wayside flywheel modules in new subway systems can be justified on a purely economic basis. Their inclusion can be further justified by the long term social advantages of energy conservation, such as reduced environmental impact and less foreign dependence. The study also indicated that wayside flywheel storage has economic advantages over competitive regeneration schemes, in particular, on-board flywheel storage.

While the inclusion of wayside flywheel storage in new systems appears very promising, further study is needed regarding the feasibility of retrofits into existing systems.

There are significant differences in requirements within the MBTA system itself and in comparison with other transit systems. These differences include such factors as number and type of cars, voltages, station spacing, and traffic densities.

Further efforts in this area should include more detailed specifications and development of system components, as well as studies of capital equipment in existing transit systems. The studies of existing transit systems should be directed toward determining the most economical common denominator in transit systems to provide one or a class of wayside storage systems for general use.

SECTION 4

RECOMMENDATIONS FOR FUTURE STUDY

4.1 Introduction

Wayside flywheel energy storage shows a potential for significant energy and cost savings, particularly if a mass transit system were designed from the begining to use regenerative braking and energy storage. However, in an existing system where equipment has to be replaced gradually because of capital limitations, substantial questions still exist. While the design, construction and testing of a wayside flywheel energy storage prototype seems to be a desirable goal, questions regarding more detailed cost projections and actual implementation must be answered first. The following sections discuss the most immediate questions and propose a program to answer these questions and to ultimately lead to prototype construction and testing. This program is described in three phases, which are then broken down into tasks. Figure 8 presents an overview of this program. Phase I, the reduction of uncertainties, will be discussed in detail in Section 4.2. Phases II and III, detailed design and prototype construction, would be based on the results of Phase I, and will be discussed in Section 4.3.

4.2 Recommendations for Phase I

Three key questions that were unearthed are:

1) How suitable are current train propulsion motors and controls for regeneration or for modification to allow for regeneration?
2) Are there any subway lines, either in Boston or another part of the country, where installation and testing of wayside flywheel energy storage modules make sense?

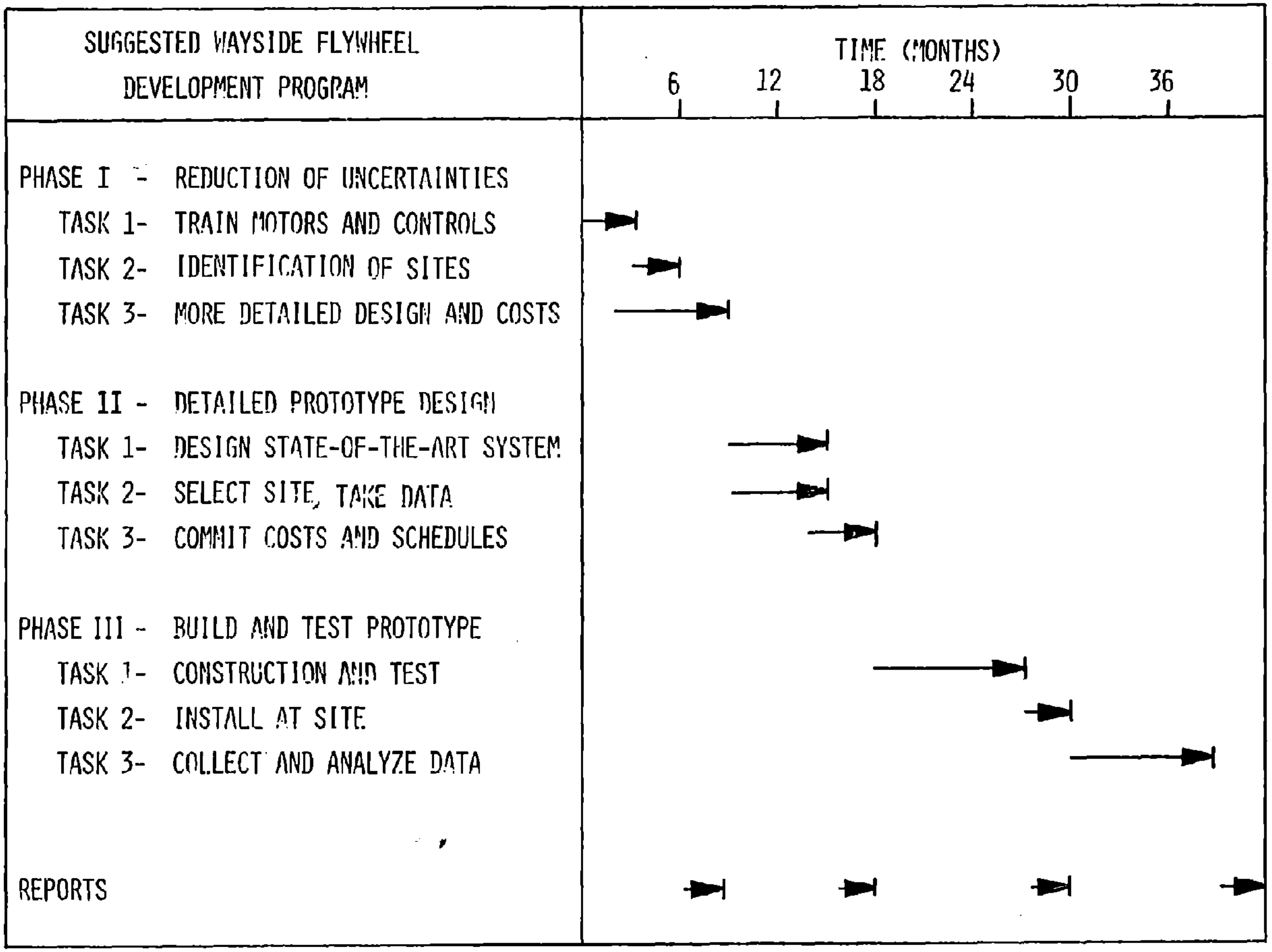


FIGURE 8 OUTLINE OF FUTURE PROGRAM

3) What would the flywheel module really look like in detail and would the cost projections change?

A research objective and plan that would lead to the answers to these questions are discussed in the following two subsections.

4.2.1 Phase I Research Objectives

The basic objective of Phase I is to address issues whose importance became known during the study just completed and evaluate the effects of these issues on the cost estimates. First, the availability of trains with regenerative braking capability or the suitability of existing trains for modification to regenerative braking must be determined. Since a meaningful prototype demonstration would require several trains with regenerative braking capability, any required modifications may end up being a significant cost factor. Second, a transit system where a prototype could be installed must be identified. Ideally, the transit system would have space to install a demonstration module, trains capable of regenerative braking, complete data on schedules and power consumption, and be located in the Northeast. Finally, given constraints likely to be uncovered regarding controls, space requirements, and voltage levels, a more detailed design must be outlined. With the more detailed design, cost estimates would be reevaluated. At the end of Phase I, enough information will be available to make a decision on the role of regenerative braking and wayside flywheel energy storage for mass transit systems.

4.2.2 Phase I Research Plan

Phase I will be broken down into three tasks as shown in Figure 8. These tasks will be discussed separately, although there is significant overlap.

Task 1 - Suitability and/or modifications of train propulsion motors and controls

This task will first attempt to identify trains that have regenerative braking capability or that can be readily modified. If such trains are not available, other trains that could be modified, but at significant cost, will be identified and the cost of the modifications determined. The impact of the train control system on the flywheel module design will be detailed.

Task 2- Identification of suitable subway system(s), either in Boston or nationwide, for regenerative braking and wayside storage demonstration.

The major subway systems will be contacted, starting with the New England area and expanding as necessary. In addition to having appropriate trains and controls, the system must have space, want a demonstration module, and should have good data on loads, etc.

Task 3- More detailed design and cost estimates of the flywheel module

The outputs from Tasks 1 and 2 will probably constrain the design of the flywheel module in terms of voltage, size, control implementation, and power and energy levels. A more detailed 'straw man' flywheel module design will be determined which will allow more accurate cost projections.

4.3 Outline of Phases II and III

If Phase I concludes that wayside flywheel energy storage modules are technically and economically feasible, the program should move into the final design and demonstration phases as shown in Figure 8. These phases are discussed briefly below.

4.3.1 Phase II - Final Design

The final design phase would involve selection of components, selection of a site for testing, measurements of actual voltage fluctuations, etc. at the site, detailed design of the module, and determination of subcontractors, costs, and schedules. The output of this phase would be detailed engineering drawings, materials lists, and commitments of costs and schedules from subcontractors and the selected transit system.

4.3.2 Phase III - Build and Test Prototype

The flywheel module would be built and performance tested. Any problems arising in the lab tests would be corrected and the module would be installed at the test site. Once on line, data would be collected and analyzed to determine power flows, efficiencies, energy savings, standby flywheel losses, and maintenance costs. The outputs of this phase would be an interim report following installation at the site and a final report summarizing the data collection and analysis and projecting accurate costs and performance of future storage modules.

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APPENDIX A

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VEHICLE ENERGY REQUIREMENTS FOR
ONE TRANSIT OF MISSION PROFILE :

MBTA RED LINE - (4 CARS)

ENERGY REQ. AT WHEELS :    MOTORING    BRAKING
               FT-LBS =  200779206. -137419374.
               HP-HRS =      98.670     -72.022
               KW-HRS =      73.579     -53.708
TOTAL TRAVELING TIME IN SECONDS =   756.
TOTAL TRAVELING TIME IN HOURS =  0.210
TOTAL DIST. TRAVELED =    6.29 MI.
ELEC. EFF. = 1.00000
MECH. EFF. = 1.00000
RESISTANCE COEFFICIENTS :
    A = .003000
    B = .000015
    C = .793000
HEADWIND IN MPH = 30.00
FRONTAL AREA IN SQ-FT =  90.000
VEHICLE GROSS WEIGHT IN LBS =  280000.
PEAK VEL. =  50.00 MPH
PEAK ACCEL. =   3.00 MPH/SEC
PEAK DECEL. =  -3.00 MPH/SEC
PEAK GRADE =  -0.0313 RAD
PEAK THRUST = 42173. LBS
PEAK H.P. =  -3624.5
PEAK K.W. =  -2702.9
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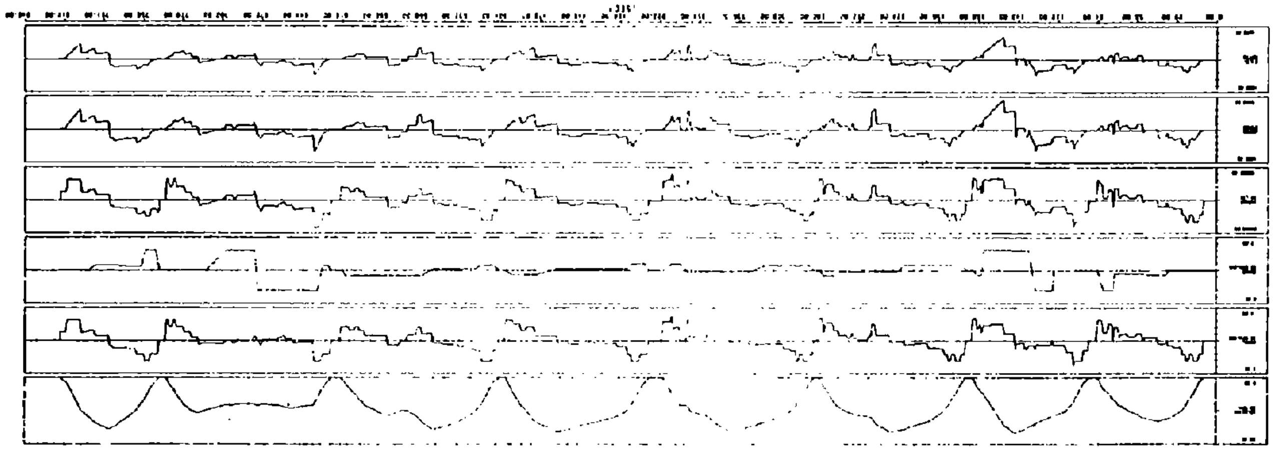
APPENDIX A



APPENDIX B

REPORT OF INVENTIONS

This study was performed with very limited funding and, therefore, was directed primarily toward system level studies instead of detailed component level research. There does appear to exist, however, significant areas for innovation on the component level which would lead to novel and/or patentable items.

The program goals and accomplishments were, however, quite significant. For instance, wayside storage does have a very attractive potential economic and energy payoff. The payoff rises dramatically with volume of traffic, shortness of runs, and close proximity of stations. Wayside storage offers economic advantages over onboard flywheels since energy recovery is accomplished throughout the entire operating day without the necessity for outfitting all trains with flywheels. If all trains are equipped for peak periods, then much of the time the investment will sit idle. Partially equipped fleets would also sacrifice energy recovery potential.

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