UMTA Report No. PA-06-0059-81-1

Final Report

# COST-EFFECTIVENESS MODEL DEVELOPMENT
# for
# ENERGY STORAGE DEVICES IN RAPID TRANSIT SYSTEMS

September 1980

U. S. DEPARTMENT OF TRANSPORTATION
Urban Mass Transportation Administration
Washington, D. C. 20590

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# COST-EFFECTIVENESS MODEL DEVELOPMENT
# for
# ENERGY STORAGE DEVICES IN RAPID TRANSIT SYSTEMS

Prepared by

Rail Systems Center
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16. Abstract

Results of the return on investment model (ROI) performed on on-board and wayside flywheel and battery energy storage systems and regenerative substations are presented. The model takes into account: the initial cost of the system, savings per year, costs incurred, energy and inflation escalators and the life of the asset. User and programmer instructions, including input data formats, program computation methods and program output descriptions and examples are provided. A description of the costs and methodology employed is included.

17. Key Words

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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 |

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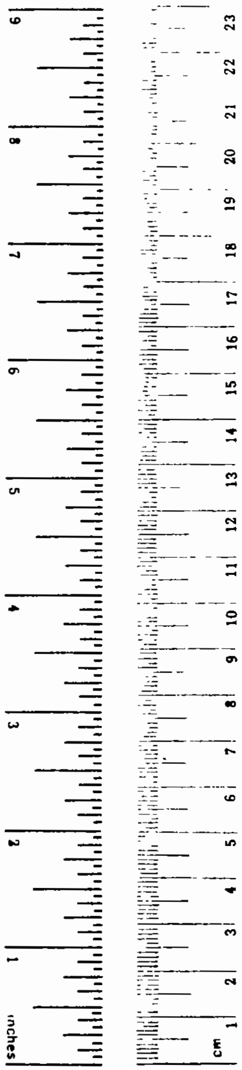
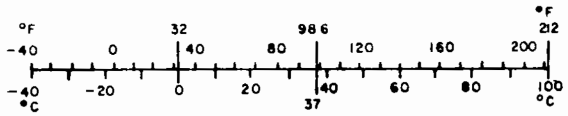
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



## Approximate Conversions from Metric Measures

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



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## 1.0 EXECUTIVE SUMMARY

This report is the result of an effort to develop a computer model which is capable of estimating the return on investment (ROI) for any energy-storage system. To complete development of this model, an analysis of the range of capital and operating costs for various energy-storage systems was conducted.

The various systems analyzed were flywheels and batteries, placed on-board and off-board, and regenerative substations.

Summaries of the capital and operating costs for all systems analyzed in this report are illustrated in Tables 1-1 and 1-2. Table 1-1 lists the capital and operating costs based on the highest range of estimates, while Table 1-2 lists the costs on the lowest range basis.

When determining the costs for on-board battery systems, off-board flywheel, off-board battery and regenerative substations, kilowatts (KW) should be used as the basis of cost analysis. The reasoning for this is that the major electrical components of each of these systems is a function of KW. Therefore, these systems are costed on the basis of kilowatts. On the other hand, on-board flywheels should be costed on the kilowatt hours (KWH) basis due to the fact that the flywheel is the primary costing element of an on-board flywheel system. The electronic components of this on-board system do not play as crucial a role in determining the costs of the system as they do with the four other systems. In determining the costs of all of these energy-storage systems, there should be a combination KW and KWH cost figures in the calculation process. This was not possible in the study due to the limited amount of information available to us. Additional studies should be conducted in the future regarding this problem.

After the required KW or KWH is determined for the transit property to be analyzed, a costing process is performed using the cost figures developed in this study. The next step is to plug these figures into the return on investment model.

A return on investment model was developed for this study. It determines a return on investment based on the following input factors: capital investment, annual operating costs, annual savings, inflation rate, energy inflation rate and number of operating periods. This model is able to accept more than one type of operating cost, i.e. costs can be accepted on a yearly basis, every second year, etc.

An actual test of a transit system was conducted based on the PATCO Lindenwold Line. Following the process mentioned previously, return on investments ranging from -1.00 to .35 were calculated for the five energy-storage systems.

The following conclusions have been reached as a result of this study:

1. Of the five energy-storage systems studied, all are technologically feasible. The technology exists today to implement any of these systems immediately.

2. With advances in technology, new energy-storage systems may be developed. They should be analyzed in the same manner as these systems were, including an ROI analysis using the computer model developed in this study.

TABLE 1-1 RANGE OF CAPITAL COSTS

| SYSTEM | $/KW<br>HIGH | <br>LOW | $/KWH<br>HIGH | <br>LOW |
|---|---|---|---|---|
| ON-BOARD FLYWHEEL | 271 | 41 | 41,656 | 8,454 |
| ON-BOARD BATTERY | 307 | 307 | 370,666 | 370,666 |
| OFF-BOARD FLYWHEEL | 227 | 173 | 403 | 256 |
| OFF-BOARD BATTERY | 470 | 470 | 235 | 235 |
| REGENERATIVE SUBSTATION | 154 | 102 | - | - |

TABLE 1-2 RANGE OF OPERATING COSTS

| SYSTEM | $/KW /YEAR |  | $/KWH /YEAR |  |
|---|---|---|---|---|
|  | HIGH | LOW | HIGH | LOW |
| ON-BOARD FLYWHEEL | 2.77 | 2.36 | 565.40 | 143.99 |
| ON-BOARD BATTERY | 61.00 | 61.00 | 73,281. | 73,281. |
| OFF-BOARD FLYWHEEL | 5.20 | 2.70 | 14.40 | 12.38 |
| OFF-BOARD BATTERY | 3.31 | 3.31 | 1.66 | 1.66 |
| REGENERATIVE SUBSTATION | .98 | .98 | - | - |

## 2.0 INTRODUCTION

Reusing the kinetic energy of trains in light and rapid rail transit systems through the use of regenerative energy storage systems is an old idea that has recently been revived.

An opportunity exists for effective savings in total energy expended, and in reducing heat generated during braking, if the train's kinetic energy can be utilized in some useful form of braking. Energy savings possible are especially important for train systems in which interstation distances are small.

Aside from the energy savings, the reduction in heat generated reduces tunnel heating and the ventilation and air-conditioning requirements in terminals and underground stations.

The simplest method of utilizing the kinetic energy of trains, while braking, is to allow an energy exchange between them. However, there are practical limitations involved in achieving this objective. There is the problem of synchronizing all trains on a system. For optional energy exchange, another train must be accelerating and consuming energy at the very instant when another train is braking and generating energy and must be in close proximity.

Since it would be too restrictive to synchronize the operation of trains for energy exchange, an energy storage system is the one practical alternative.

Several methods have been considered for storing energy for transit application - as kinetic energy of a rotating flywheel, or as chemical energy in a battery.

Each alternative has its advantages and limitations. A further option is to feed the regenerated energy into the supply line, where a load exists at all times to receive the energy. The location of the storage device is another factor. It can be located on each car of the train, or on the wayside at substations or tie stations. Each of these alternatives will be described and evaluated.

## 2.1 PURPOSE

The purpose of the work reported here was to develop a cost-effectiveness model which could assess the return on investment (ROI) obtained when energy storage devices or regenerative substations are applied to real transit properties with regenerating trains. The storage devices can either be flywheel or batteries and can be placed off-board or on-board.

Computations of the ROI model consists of three basic steps:

1. Determine the capital and operating costs of the storage devices which will be used on the property.
2. Estimate the operating savings in energy obtained by installing the devices.
3. Using the present value equation, estimate the ROI.

Step 2 is accomplished using the energy management model which was previously developed at the Rail Systems Center. A brief description of it is presented in Appendix C.

This work concentrated on steps 1 and 3. Capital and operating costs were developed using previous studies which were completed in this area and are documented in the bibliography. An ROI model was developed and computerized.

## 2.2 BACKGROUND ON ENERGY STORAGE

Flywheels have long ago made their mark in history with their energy storage characteristics. During the last 200 years, large shaft-mounted flywheels have been used to stabilize the output of steam engines used in the mills and factories of the industrial revolution period. Other flywheel applications have emerged over the last 200 years, the most notable of which was the Howell Torpedo built in 1884.

The most extensive use of flywheels in the transportation field during the last 25 years was the vehicle propulsion system used by the Oerlikon Engineering Company of Switzerland.[1] The possibility of using flywheels in public transportation was realized in developing a small flywheel powered railroad engine for switchyard work. This led to the development of the electrogyro bus in the early 1950's. This 35 passenger bus, with about 3 kilowatt-hours of stored energy operated between electrical charging sites located about one-half mile apart. It went into service in 1953 and remained in service for ten years. Routing limitations, the 1-2 minute spin-up charge period at each stop, and the economics of diesel buses limited more widespread acceptance of this bus.

Renewed interest in this type of vehicle stems from the dual concern with reducing pollution from fuel-burning vehicles and, following the 1974 oil embargo, with developing alternative energy sources.

Flywheel energy-storage systems are now under consideration for use not only in buses but also in subway cars, trolleys and other vehicles. For example, an energy-storage unit was built by Garrett Corporation and evaluated in-service on New York City Transit Authority (NYCTA) R-32 subway cars. Also, the Urban Mass Transportation Administration (UMTA) proposed the design of a flywheel-electric drive system to propel trackless trolley coaches for the San Francisco Municipal Railway (MUNI).

### 2.2.1 General Discussion

Regenerative braking is a form of dynamic braking in which part of the kinetic energy of the vehicle can be used to drive other vehicles. In terms of a system of trains running on a transit property, regeneration with natural receptivity means that only the vehicles or trains on the line can accept the regenerated energy, while regeneration with assured receptivity means that some assurance is provided that all of the regenerated energy is accepted either by on-board or off-board storage devices, other trains and/or regenerative substations by which the energy is returned to the utility.

Regeneration of braking energy has a large potential for energy savings. With natural receptivity, traction energy savings of 5-25% may be realized, while with assured receptivity, savings can range from 20-50%. The exact value of the energy savings depend upon a complex set of physical and operational characteristics of the transit system. As a consequence, it is necessary and desirable to perform site-specific studies using simulation models to reach sound rather than general conclusions when planning regeneration capability for new or existing systems.

# 3.0 COSTS OF STORAGE DEVICES AND REGENERATIVE SUBSTATIONS

## 3.1 ENERGY AND POWER REQUIREMENTS

Table 3-1 illustrates an approximation of the ranges of KW of maximum power input and KWH of energy for on-board and off-board systems and regenerative substations for various rapid transit systems.

The figures for KW and KWH were determined as follows:

$$KW_{wheel} = 9.95 \times 10^{-5} \times a \times v \times w$$

$$KWH_{wheel} = 1.258 \times 10^{-8} \times w \times v^2$$

where

a = deceleration (MPHPS)
v = maximum speed (MPH)
w = weight of loaded car (lbs.)

The previous equations only give the KW and KWH at the wheel. There is a loss of energy from the wheels to the traction gears, from the traction gears to the traction motor and from the traction motor through the chopper to the line. This amounts to about a 24 percent loss on the average. Thus the conversion efficiency is 76 percent. This phenomena is common to both the on-board and off-board systems.

The maximum power entering the on-board flywheel system is

$$KW_{on\text{-}board} = 0.76 \times KW_{wheel}$$

but the requirement for stored energy is

$$KWH_{on\text{-}board} = 0.76 \times 0.87 \times KWH_{wheel}$$

since 13 percent of the power is lost in the flywheel motor, control and gears. This process is illustrated in Figure 3-1.

## TABLE 3-1 GENERAL TRANSPORTATION SYSTEM DESIGN CHARACTERISTICS AND ENERGY RELATED STATISTICS

| PROPERTY | CARS PER TRAIN | CAR WEIGHT LOADED | MAXIMUM SPEED | BRAKE RATE | BRAKING EFFORT AT WHEEL | PER/CAR KW AT WHEEL | PER/CAR KW RETURNED TO LINE 76% EFFICIENCY | PER/ TRAIN KW AT WHEEL | PER/TRAIN KW RETURNED TO LINE 76% EFFICIENCY | PER/ CAR KWH AT WHEEL | PER/CAR KWH RETURNED TO LINE 76% EFFICIENCY | PER/ TRAIN KWH AT WHEEL | PER/TRAIN KWH RETURNED TO LINE 76% EFFICIENCY | ON-BOARD STORAGE REQUIREMENTS | | OFF-BOARD STORAGE REQUIREMENTS | | REGENERATIVE REQUIREMENTS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | MAX. KW | MAX. KWH | MAX. KW | MAX. KWH | MAX. KW |
| NYCTA | 12 | 127,000 | 80 | 2.5 | 15,875 | 2,527 | 1,921 | 30,324 | 23,046 | 10.22 | 7.77 | 122.64 | 93.21 | 1,921 | 6.78 | 1,787 | 75.04 | 1,787 |
| WMATA | 8 | 98,250 | 75 | 3.0 | 14,737 | 2,200 | 1,672 | 17,600 | 13,376 | 6.95 | 5.28 | 55.60 | 42.26 | 1,672 | 4.61 | 1,555 | 34.02 | 1,555 |
| MARTA | 10 | 89,500 | 75 | 3.0 | 13,425 | 2,004 | 1,523 | 20,040 | 15,230 | 6.33 | 4.81 | 63.30 | 48.10 | 1,523 | 4.20 | 1,416 | 38.72 | 1,416 |
| BART | 10 | 73,800 | 80 | 3.0 | 11,070 | 1,762 | 1,339 | 17,620 | 13,391 | 5.94 | 4.51 | 59.40 | 45.10 | 1,339 | 3.94 | 1,245 | 36.31 | 1,245 |
| PATCO | 6 | 93,250 | 75 | 2.5 | 11,656 | 1,740 | 1,322 | 10,440 | 7,934 | 6.60 | 5.02 | 39.60 | 30.10 | 1,322 | 4.38 | 1,229 | 24.23 | 1,229 |
| CTA | 10 | 58,900 | 70 | 3.2 | 9,424 | 1,313 | 998 | 13,130 | 9,979 | 3.63 | 2.76 | 36.30 | 27.60 | 998 | 2.41 | 928 | 22.22 | 928 |
| PCC | 1 | 51,750 | 50 | 3.2 | 8,280 | 824 | 626 | 824 | 626 | 1.63 | 1.24 | 1.63 | 1.24 | 626 | 1.08 | 582 | 1.00 | 582 |

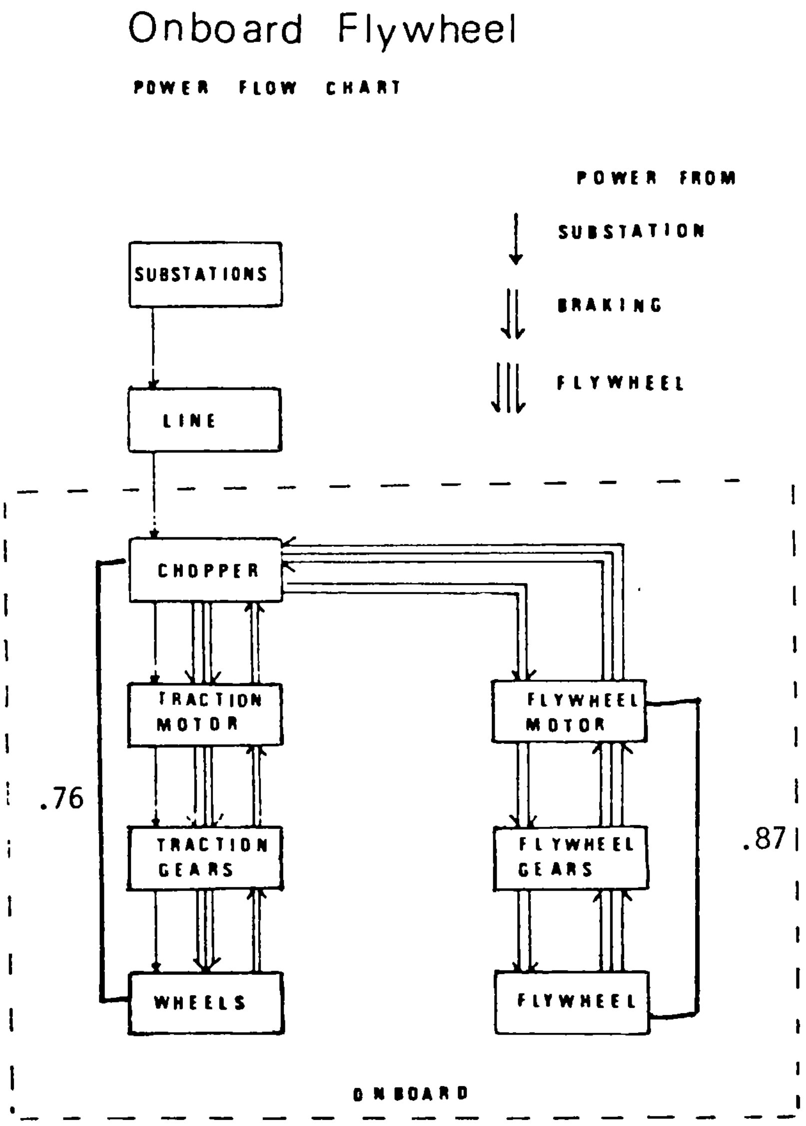


FIGURE 3-1 ON-BOARD FLYWHEEL

The maximum power entering the off-board flywheel is

$$KW_{off\text{-}board} = 0.76 \times 0.93 \times KW_{wheel} \times n$$

where n = number of cars per train

since line losses from the train to substation represent another 7 percent loss.

The off-board energy requirement is

$$KWH_{off\text{-}board} = 0.76 \times 0.93 \times 0.87 \times KWH_{wheel} \times n$$

This process is illustrated in Figure 3-2.

The regenerative substation incurs power losses from the wheels to the chopper as well as in the transmission of the power over the lines. There is less energy loss associated with the regenerative substation than with either of the other two systems.

$$KW_{at\ substation} = 0.76 \times 0.93 \times KW_{wheel} \times n$$

The numbers calculated in Table 3-1 are based on operation over level tangent track. Further studies will have to be conducted for operations involving curves and grades.

The table only represents an approximation to the actural power and energy requirements. In the case of on-board storage, a train performance simulation using the TPS will determine the maximum values, while running the total energy management model (EMM) with off-board storage or regenerative substations will determine these requirements. In the case of off-board storage or regenerative substations, some of the power will go to other trains on the line thus reducing the energy and power requirements of the substation storage.

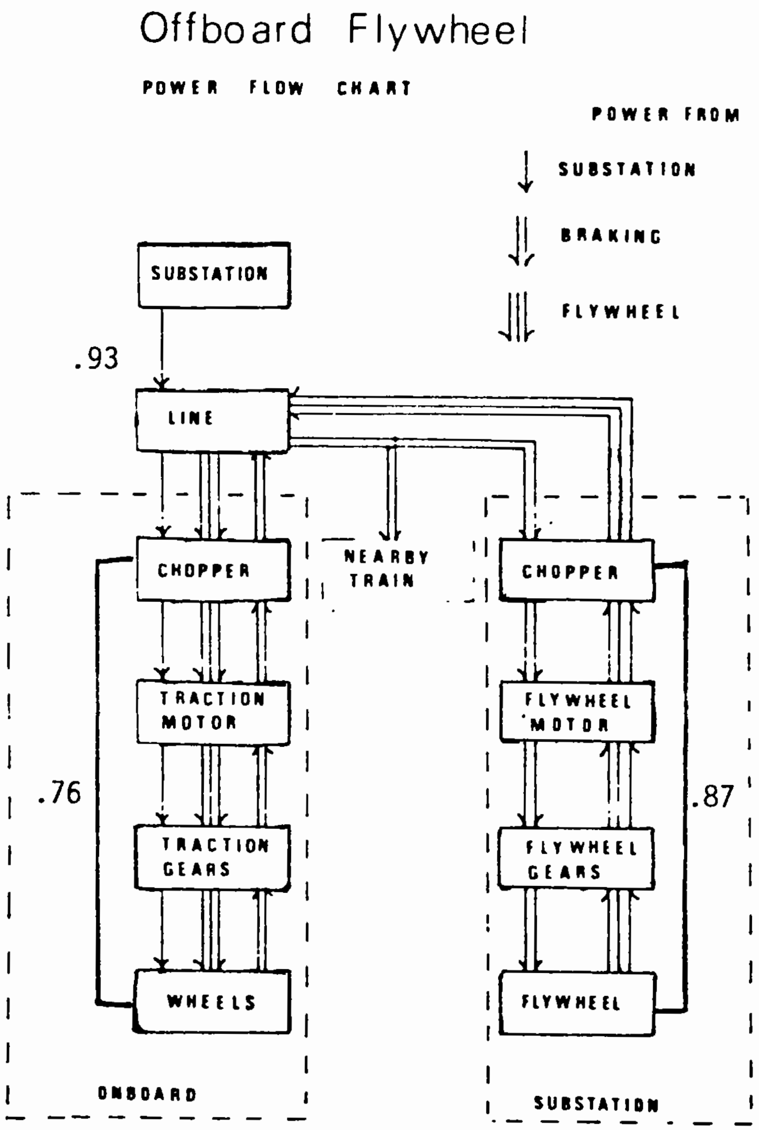


FIGURE 3-2 OFF-BOARD FLYWHEEL

### 3.1.1 On-board Systems

There are two alternative methods for on-board storage, flywheels or batteries. The requirements for an on-board energy-storage device are that it be fairly compact, lightweight and suitable for under-car mounting. Energy must be stored and supplied rapidly, efficiently, safely and in a flexible manner at low cost. Although batteries can supply power rapidly during acceleration, those that can recharge and accept power rapidly during braking are not currently available at reasonable cost and weight. At the present time, the use of a battery as an energy-storage device is more costly than a flywheel. Figure 3-3 provides a block diagram of procedures for on-board energy-storage systems.

### 3.1.2 On-board Flywheels

#### 1. Conceptual Design

Since there is only one revenue tested on-board flywheel system in a light or rapid rail vehicle, the following dicsussion will be based on the results of the Garrett AiResearch Study[2] of flywheel energy-storage systems (FESS) on New York City Transit Authority (NYCTA) R-32 subway cars. These cars were demonstrated on all lines in the NYCTA system, where they provided energy savings of 20 to 40 percent.

As can be seen from Figure 3-4, when a train leaves a station, the power demand reaches a peak. This peak remains, until the maximum speed of the train is reached, after which the power demand falls to a level required to overcome the drag on the train due to friction and wind resistance. Before the train comes to a stop at a station, the kinetic energy of the train must be absorbed in a short time span. If the kinetic energy lost during braking can be utilized, then the average power consumption for the typical station-to-station run will be appreciably reduced.

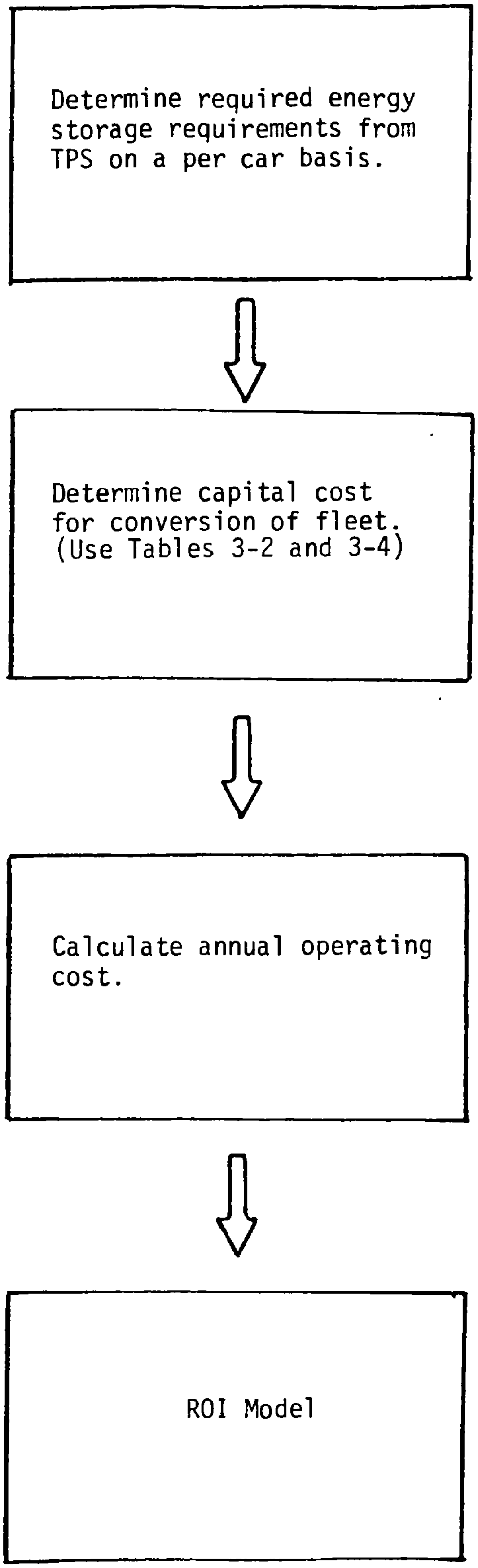
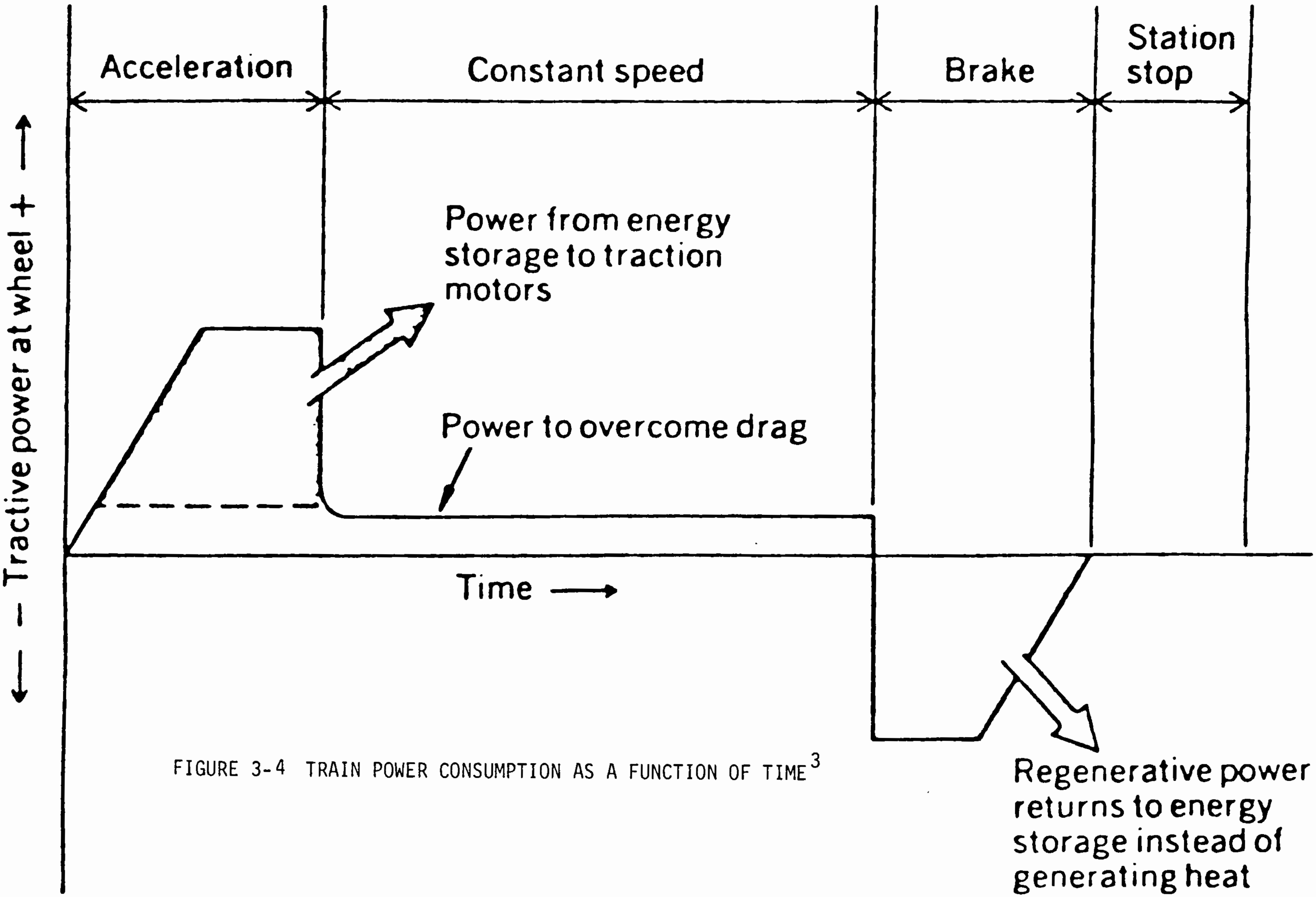


FIGURE 3-3 BLOCK DIAGRAM OF PROCEDURE FOR FINDING COST/EFFECTIVENESS OF ON-BOARD ENERGY-STORAGE SYSTEMS



Typical train power consumption as a function of time, for a station-to-station run.

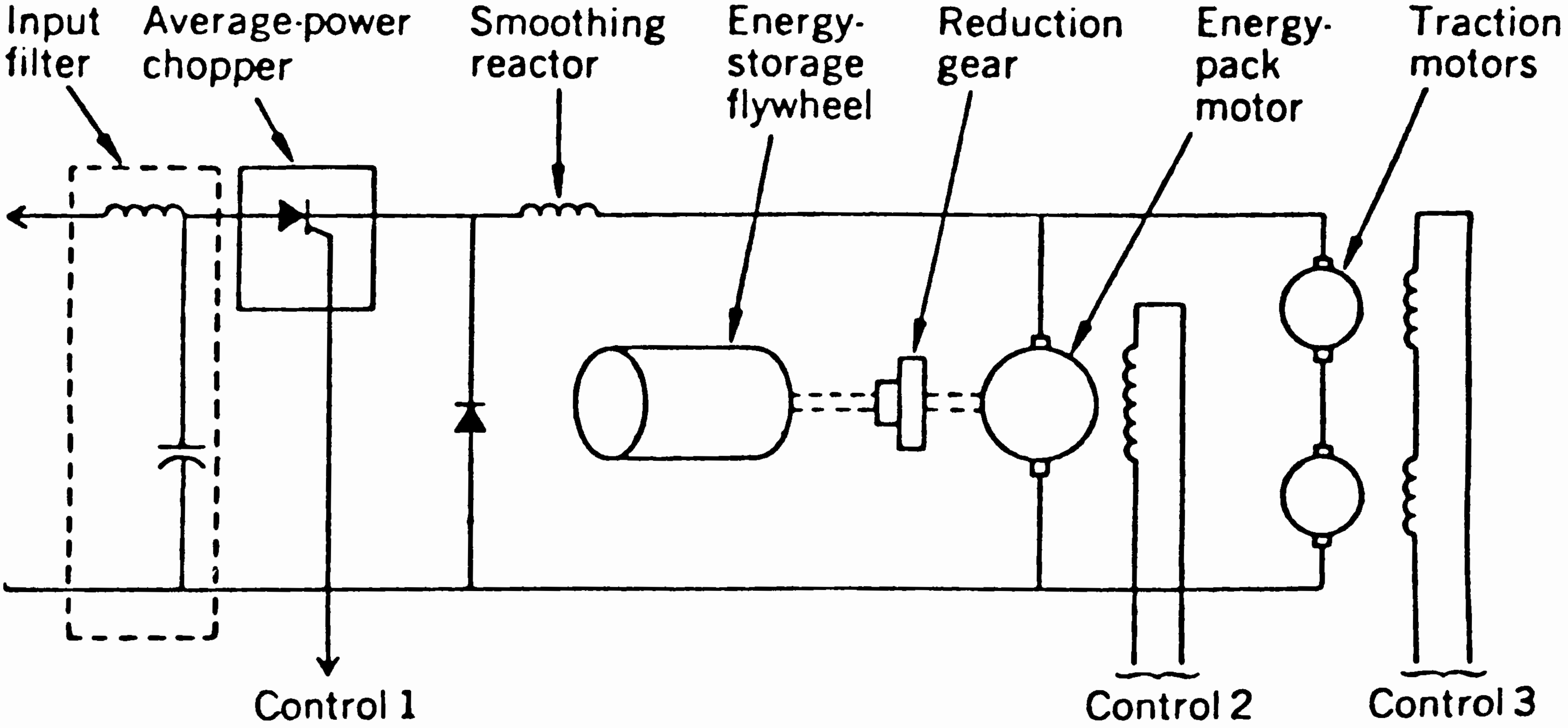
FIGURE 3-4 TRAIN POWER CONSUMPTION AS A FUNCTION OF TIME[3]

During the braking of the transit car, its kinetic energy must be removed. For most operations during braking, the DC traction motor is connected to operate as a generator, and its electrical output is dissipated in a brake resistor grid. This technique is called dynamic braking. Dynamic braking is augmented by friction brakes for lower speeds and emergency conditions.

Instead of dissipating the braking energy, it can be stored in a flywheel device and used to start the car from the station.

Figure 3-5 shows the block diagram for the on-board FESS as used by Garrett AiResearch. The flywheel consists of four 20 inch diameter, 2 inch wide disks rotated at speeds ranging from 9,800 to 14,000 RPM. The flywheel housing was evacuated until it was at a pressure of one inch of mercury, to reduce windage losses and associated heating of the flywheel disk. A reduction gear with a ratio of 3.33:1 is used to connect the flywheel to the rotating machine. Two flywheels per car are required. The energy-storage units add a weight of approximately 9,920 pounds. Figures 3-6 and 3-7 describe the system and its performance.

When a vehicle is at zero speed, the flywheel operates at its maximum speed. When the vehicle speeds up, the flywheel will slow down so that at the maximum car speed the flywheel will operate at 70 percent of its maximum speed. This means that 50 percent of the energy stored in the flywheel is supplied to the car because energy stored is a function of the square of the speed. If the flywheel tries to operate at a speed above its minimum permitted speed, the power taken from the third rail is reduced to zero, so that all power requirements of the car are taken from the flywheel. If the flywheel tries to operate below its minimum permitted speed, all energy



**The on-board flywheel energy storage system (FESS), as used by Garrett Airesearch, in experimentation, on the New York City Transit System.**

FIGURE 3-5 ON-BOARD FLYWHEEL ENERGY STORAGE SYSTEM (FESS)[4]

# ENERGY PACK
# Onboard Energy Storage for Rapid Transit Vehicles

## AN IMMEDIATE ANSWER TO INTRA-CITY RAPID TRANSIT

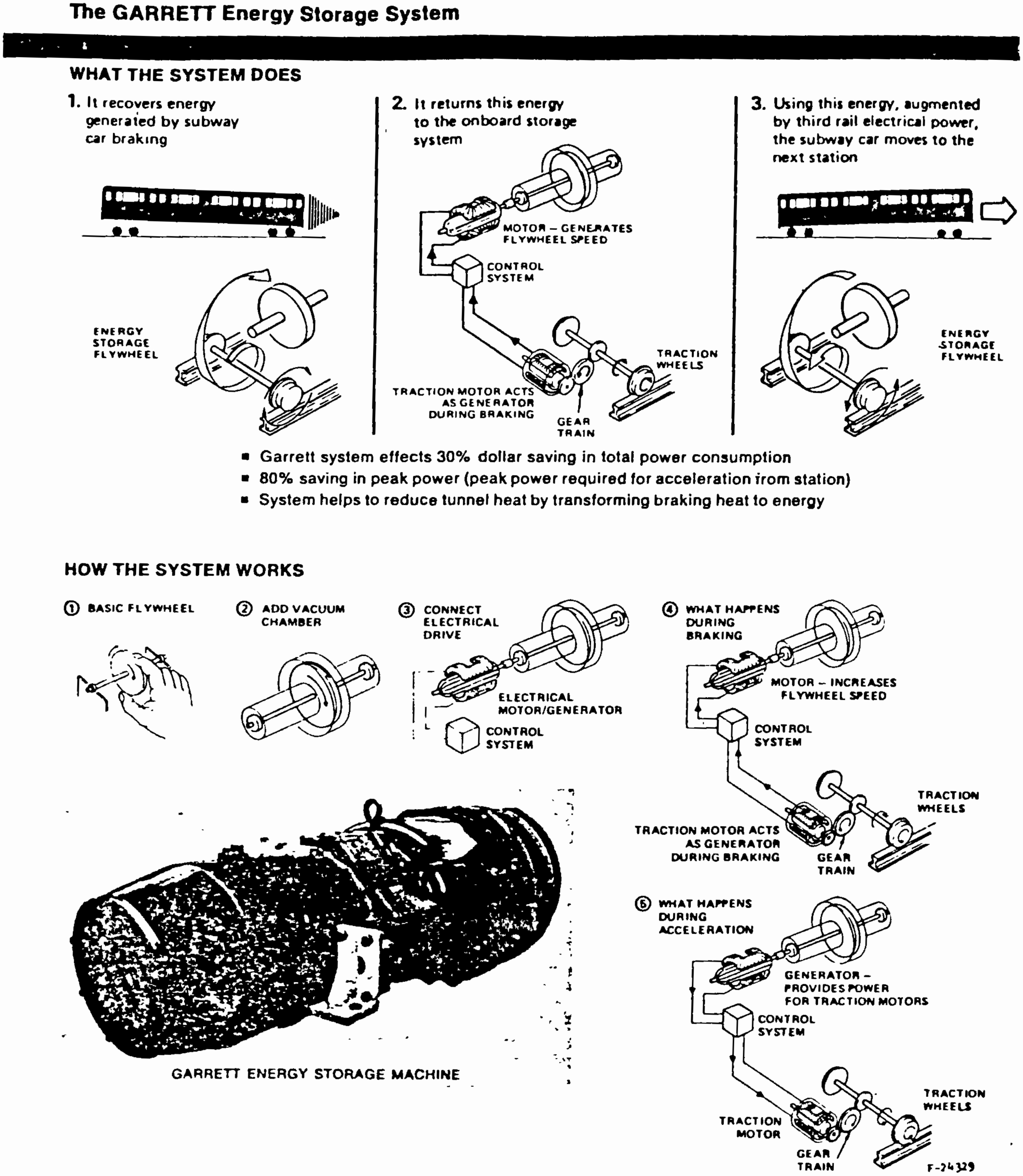
The Garrett Energy Storage System incorporates an onboard flywheel device to provide peak power to drive traction motors during car acceleration. The energy is recovered during car braking by converting the kinetic energy of a moving car into stored mechanical energy in the flywheel device rather than losing it through heat in the brake resistors. Recovered energy is then used for subsequent car acceleration.

The Garrett Onboard Energy Storage System sponsored by the U.S. Department of Transportation's Urban Mass Transportation Administration (UMTA) and the New York Metropolitan Transportation Authority (MTA) is another step toward the goal of energy conservation.

**FEATURES**

- Self-contained regenerative braking on car
- Significant energy savings
- Increased utilization of facility
  - Reduction of substation
  - Reduction of headway — more cars
- Increased passenger comfort
  - Jerk free
  - Elimination of jerks and lighting flicker
  - Substantial reduction of subway tunnel heat normally generated by braking
- Safer
  - Car moves without third rail in maintenance yard, and can move to next station in case of power blackout

FIGURE 3-6 ENERGY STORAGE SYSTEM [5]



**The GARRETT Energy Storage System**

**WHAT THE SYSTEM DOES**

1. It recovers energy generated by subway car braking
2. It returns this energy to the onboard storage system
3. Using this energy, augmented by third rail electrical power, the subway car moves to the next station

- Garrett system effects 30% dollar saving in total power consumption
- 80% saving in peak power (peak power required for acceleration from station)
- System helps to reduce tunnel heat by transforming braking heat to energy

**HOW THE SYSTEM WORKS**

FIGURE 3-7 THE GARRETT ENERGY STORAGE SYSTEM[6] requirements are obtained from the third rail, so that the flywheel maintains its proper operating speed. Dynamic-brake resistor grids are provided for dissipation of energy, if necessary, to keep the flywheel speed below its maximum value, due to dead-car inertia loads or steep down grades.

An advantage of the on-board FESS is that only a chopper rated for average power is required, instead of a chopper rated for peak power, which would be necessary if the energy was stored on the wayside. On the other hand, because of space limitations on-board the vehicle, low weight, high-speed flywheels are required. This means that the use of reduction gears may be required, which would result in energy losses between 5 and 10 percent. The safety of the high-speed flywheels also has to be considered, during derailments or accidents, along with the gyroscopic effects. The on-board FESS adds 10 percent to the weight of the car, resulting in increased power requirements.

## 2. On-board Flywheels - Capital Costs

The capital costs or, more generally, initial investment costs, were based on three primary sources. These sources were a study done by Garrett AiResearch Manufacturing Company of California[7] or the Jet Propulsion Laboratory, a report by the Charles Stark Draper Laboratory, Inc.[8] and a study performed by General Electric Corporate Research and Development.[9] The Draper Laboratory and General Electric reports are of a more theoretical nature, i.e., not based on the results of an actual operating system. However, the study conducted by Garrett AiResearch for the Jet Propulsion Laboratory, is based on the results obtained from actual operations conducted on New York City Transit Authority R-32 transit cars. For this reason, more credence should be placed on the figures obtained by Garrett for $/KW and $/KWH. This is also true for the figures which appear in the next section - Flywheel Operating Costs.

Table 3-2 lists the cost per KW and KWH for each of the three studies involved.

TABLE 3-2 CAPITAL COST PER KW AND KWH FOR ON-BOARD FLYWHEELS

| | (April 1980 $'s)<br>$/KW | $/KWH |
|---|---|---|
| 1. Draper Laboratory | $ 41 | $ 8,454 |
| 2. Garrett AiResearch | $130 | $41,656 |
| 3. General Electric | $271 | $16,552 |

It should be noted that the figures in the General Electric study are for a flywheel operated bus. Therefore, they may not be acceptable for cost comparison usage.

In our opinion, cost per KWH should be used as the basis for cost analysis for on-board flywheel systems. The motor and chopper unit, which are costed on a KW basis, are less critical in ascertaining the costs, due to the fact that the motor and control unit make up a small percentage of the cost of an on-board flywheel system. The flywheel size is the governing factor in determining the cost, therefore, KWH is the appropriate basis for costing.

3. <u>On-board Flywheels - Operating Costs</u>

The operating costs in Table 3-3 are based on the three studies referred to in the previous section.

TABLE 3-3 OPERATING COST PER KW AND KWH FOR ON-BOARD FLYWHEELS

| | (April 1980 $'s)<br>$/KW | <br>$/KWH |
|---|---|---|
| 1. Draper Laboratory | $2.77 | $565.40 |
| 2. Garrett AiResearch | * | * |
| 3. General Electric | $2.36 | $143.99 |

*We were unable to determine an annual operating cost for the Garrett AiResearch study. However, they do state that maintenance costs for on-board flywheel units is equivalent to the maintenance requirements of 2.5 traction motors.

### 3.1.3 On-board Batteries

1. Conceptual Design

There are several reasons why an on-board battery energy-storage system has never been put into operation on a rapid transit system. First, a battery energy-storage system is extremely heavy. There is a substantial difference in weight between an on-board flywheel system and an on-board battery system, with the battery system weighing approximately 8,300 pounds more. This additional weight increases vehicle train resistance and increases energy consumption. The second factor is the inability of the battery system to accept a rapid influx of energy. Batteries are only able to accept energy at a relatively slow charge rate. The problem is that the energy that is produced during the braking process comes in very short and rapid periods. This is exactly the opposite of how a battery operates. For these reasons, a battery system has not been actively considered as a viable energy-storage system. However, it may be acceptable as an off-board energy-storage system where these two factors are not considered as critically as they would be on-board.

Figure 3-8 provides a block diagram of the all battery energy-storage system.

## 2. On-board Battery System - Capital Costs

The capital costs for the on-board battery energy-storage system as shown in Table 3-4 were based on one source. This was the study performed by General Electric Corporate Research and Development Center.[10] It should be noted that the figures in this study are for a battery storage system on a bus. Therefore, they may not be acceptable for cost comparison usage.

TABLE 3-4 CAPITAL COST PER KW AND KWH FOR ON-BOARD BATTERIES

|  | (April 1980 $'s) |  |
|---|---|---|
|  | $/KW | $/KWH |
| 1. General Electric | $307 | $370,666 |

## 3. On-board Battery System - Operating Costs

The operating costs in Table 3-5 are based on the General Electric study referred to in the previous section.

TABLE 3-5 OPERATING COSTS PER KW AND KWH FOR ON-BOARD BATTERIES

|  | (April 1980 $'s) |  |
|---|---|---|
|  | $/KW | $/KWH |
| 1. General Electric | $61 | $73,281 |

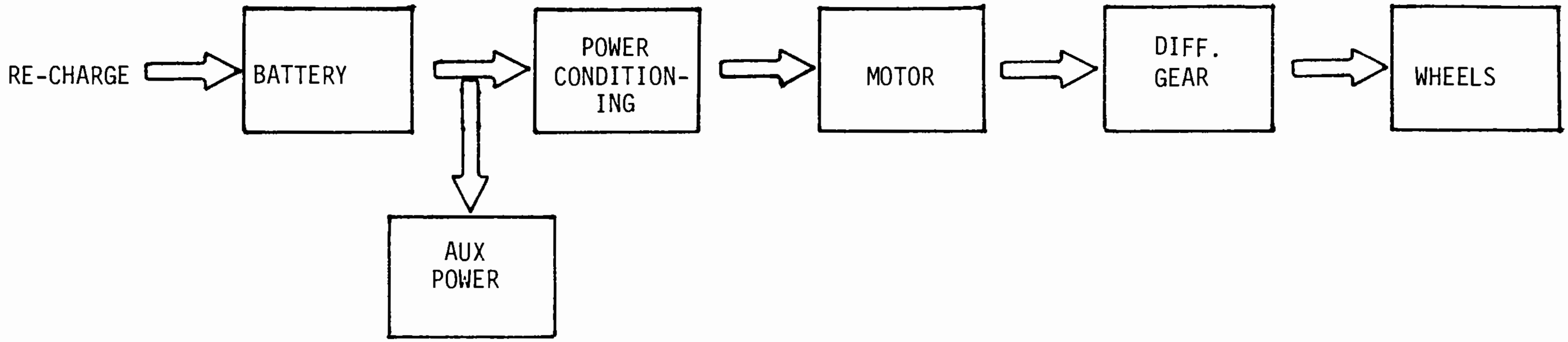


FIGURE 3-8 SCHEMATIC FOR AN ALL BATTERY SYSTEM

### 3.1.4 Comparison of On-Board Flywheel vs. On-Board Battery

It is quite apparent that the on-board flywheel system is much more economical than an on-board battery system for both capital and operating costs. An on-board flywheel system can be acquired for approximately one-tenth the cost ($/KWH) of a comparable on-board battery energy-storage system. The same holds true for yearly operating costs. On-board flywheel operating costs ($/KWH) are <u>less than</u> one percent of those incurred in operating a comparably sized on-board battery system.

On-board battery energy-storage systems may become more competative in the future with advances in battery technology. When compared with on-board flywheel systems, battery systems are much quieter and waste less energy at idle. However, they currently are not a viable alternative due to their heavy weight and their inability to accept energy at a rapid charge rate.

Since the on-board battery energy-storage system is not considered a practical alternative, only the on-board flywheel system will be used in future comparisons.

## 3.2 OFF-BOARD SYSTEMS

### 3.2.1 Off-board Flywheels

#### 1. <u>Conceptual Design</u>

Off-board flywheel energy-storage systems (FESS) operate on the same principle as on-board FESS except for changes in scale. Some of the limitations of the on-board storage concept are eliminated while additional savings in cost can be achieved. In an off-board FESS, a separately excited DC motor can be directly connected to the flywheel. This is possible because size, space and weight are less important on the wayside. Lower flywheel speed of up to 3,000 RPM, for example, can be used. Therefore, losses in reduction gears are eliminated. However, it becomes necessary to transport the energy from the braking train to the off-board FESS, and from the FESS to an accelerating train. Transmission losses in this case partly offset the savings from the elimination of reduction gears.

The most significant advantage of an off-board FESS is that the installed capacity of rotating machinery and flywheels is reduced, compared to an on-board FESS. This is because the installed capacity on the off-board system can be reduced by the amount of direct energy exchange between trains (natural receptivity). The reduction in installed capacity due to this factor alone can be expected to be about 20 to 30 percent. Further savings in cost may be possible due to economies of scale. A ten car train with an on-board storage system requires 20 flywheels (2 per car). It is likely that one large FESS in the station would cost less than 40 FESS's on-board the train due to economies of scale. The acquisition and maintenance costs per KW and KWH will be lower than for an on-board storage system. The car weight will be reduced also.

Off-board energy storage, however, has several undesireable characteristics. Because of its off-board location, for car regenerated energy to be absorbed, the line voltage must be allowed to rise substantially. This line receptivity problem can be minimized by installing an energy-storage unit at each substation, but this increases the acquisition cost. As a result, off-board energy storage is much more suitable for new transit system or transit systems which already have regeneration. Figure 3-9 provides a block diagram of procedures for off-board energy-storage systems.

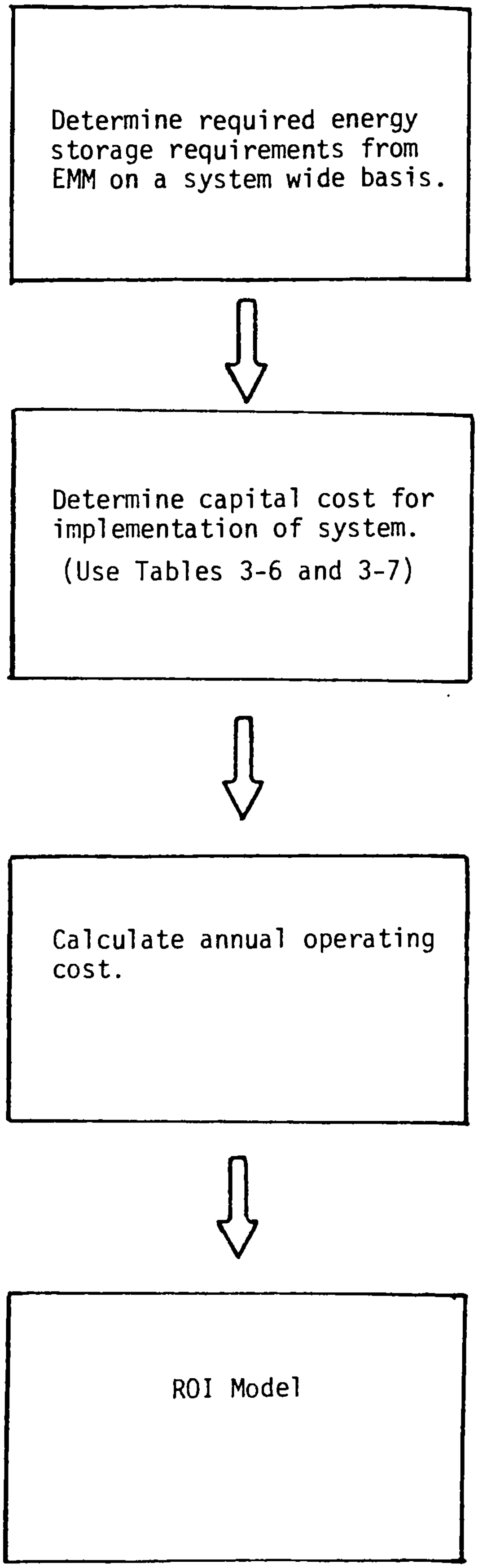


FIGURE 3-9 BLOCK DIAGRAM OF PROCEDURE FOR DETERMINING COST/EFFECTIVENESS OF OFF-BOARD ENERGY-STORAGE SYSTEMS

## 2a. Off-board Flywheels - Capital Costs per KW

Captial costs per KW were based on two principle sources, a study on assured receptivity performed by General Electric[11] and a study of the economic feasibility of energy storage flywheels by Rockwell International,[12] Space Division. Both studies give $/KW over a wide range of KW. It should be noticed that the cost per KW drops sharply as the KW capability increases. This is due to the economies of scale associated with the larger units. These decreasing costs/KW are illustrated in Table 3-6 for both studies.

## 2b. Off-board Flywheels - Capital Costs per KWH

Capital costs per KWH were based on four primary sources. These sources were the Rockwell International/Space Division[13] study referred to in the previous section, a report by the Charles Stark Draper Laboratory, Inc.[14] and a study by AiResearch Manufacturing Company of California.[15] In comparing the figures for $/KWH in the three studies, it should be noted that the cost per KWH continually drops as the amount of KWH increases. This is due to the economies of scale associated with the larger units. The decreasing costs per KWH are illustrated in Table 3-7 for each of the studies.

TABLE 3-6 CAPITAL COST PER KW FOR OFF-BOARD FLYWHEELS

1. GENERAL ELECTRIC

| | (April 1980 $'s) |
|---|---|
| 1250 KW | $660.65 |
| 2500 KW | 367.03 |
| 3750 KW | 271.87 |
| 5000 KW | 226.56 |
| 6250 KW | 201.39 |
| 7500 KW | 186.47 |
| 8750 KW | 177.59 |
| 10000 KW | 172.66 |

2. ROCKWELL INTERNATIONAL/SPACE DIVISION

| | (April 1980 $'s) |
|---|---|
| 1000 KW | $1,437.14 |
| 10000 KW | 256.88 |
| 15000 KW | 212.45 |

## TABLE 3-7 CAPITAL COST PER KWH FOR OFF-BOARD FLYWHEELS

| | | (April 1980 $'s) |
|---|---|---|
| 1. ROCKWELL INTERNATIONAL/SPACE DIVISION | | |
| | 2400 KWH | $303.74 |
| | 8450 KWH | 258.81 |
| | 18600 KWH | 256.06 |
| | 37200 KWH | 255.69 |
| 2. CHARLES DRAPER LABORATORY | | |
| | 250 KWH | 402.87 |
| 3. AiRESEARCH MANUFACTURING COMPANY | | |
| | 7330 KWH | 288.02 |

Figure 3-10 displays a plotting of the various $/KW amounts calculated in Table 3-6. From the curve drawn on this graph, a capital cost per KW can be determined for any number of KW's up to 15,000 KW by finding the appropriate point along the curve.

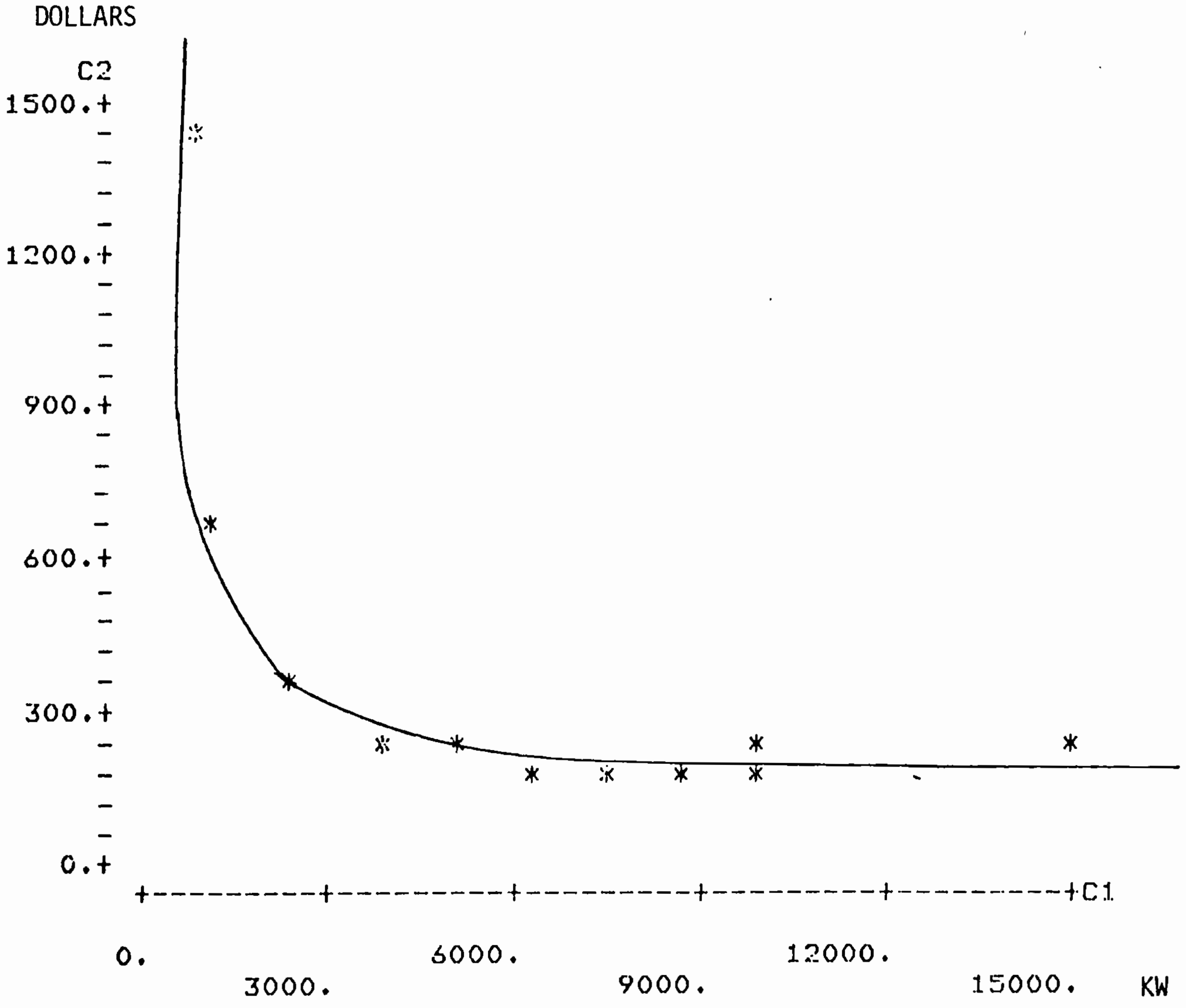


FIGURE 3-10 CAPITAL COST PER KW FOR OFF-BOARD FLYWHEELS

Figure 3-11 illustrates the various $/KWH calculated in Table 3-7 plotted as a function of KWH. From the curve, a capital cost per KWH can be determined for any number of KWH's up to 50,000 KWH by locating the appropriate point along the curve. Most of this curve is way out of the range of the transit application.

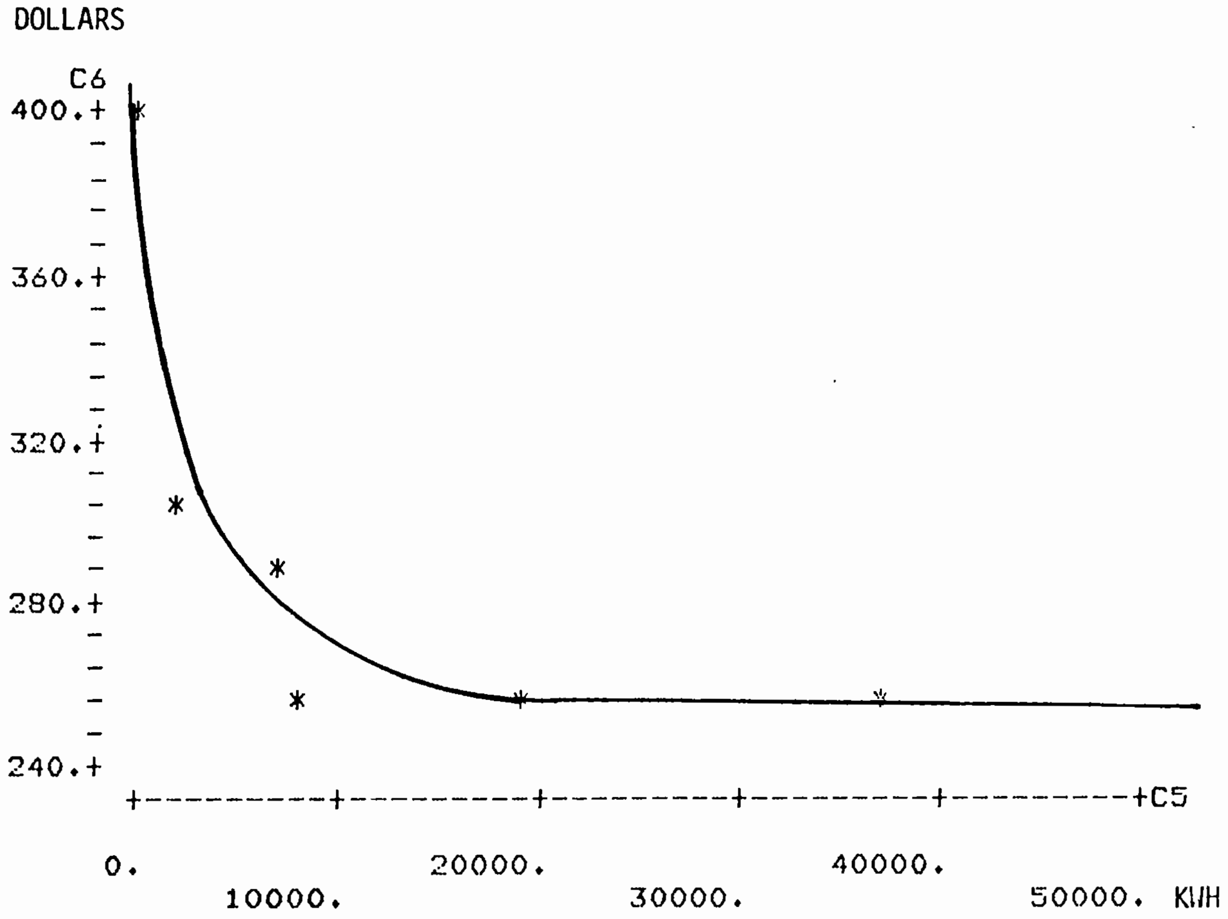


FIGURE 3-11 CAPITAL COST PER KWH FOR OFF-BOARD FLYWHEELS

3. Off-board Flywheels - Operating Costs per KW and KWH

The operating costs in Table 3-8 are based on the four studies referred to in the previous section.

TABLE 3-8 OPERATING COST PER KW AND KWH FOR OFF-BOARD FLYWHEELS

| | (April 1980 $'s)<br>$/KW | <br>$/KWH |
|---|---|---|
| 1. Rockwell International/Space Division | $2.78 | - |
| 2. General Electric | 5.20 | - |
| 3. Draper Laboratory | - | $12.38 |
| 4. Garrett AiResearch | - | 14.40 |

### 3.2.2 Off-board Batteries

1. Conceptual Design

This discussion of an off-board battery system is based on a study conducted by Westinghouse Electric Corporation[16] for the New York City Transit Authority (NYCTA). There are several reasons why an off-board battery energy-storage system has never been put into operation on a rapid transit system. First, a battery energy-storage system is incapable of accepting a rapid influx of energy. Batteries are only able to accept energy at a relatively slow charge rate. The system proposed by Westinghouse for the New York subway system was to have been recharged during the periods from 9 a.m. to 4 p.m. and from 6 p.m. until 7 a.m. as illustrated in Figure 3-12. The purpose of this system was for reduction of peak loads and not to accept regeneration. However, costing procedures for an energy storage system based on cost per KW would be appropriate.

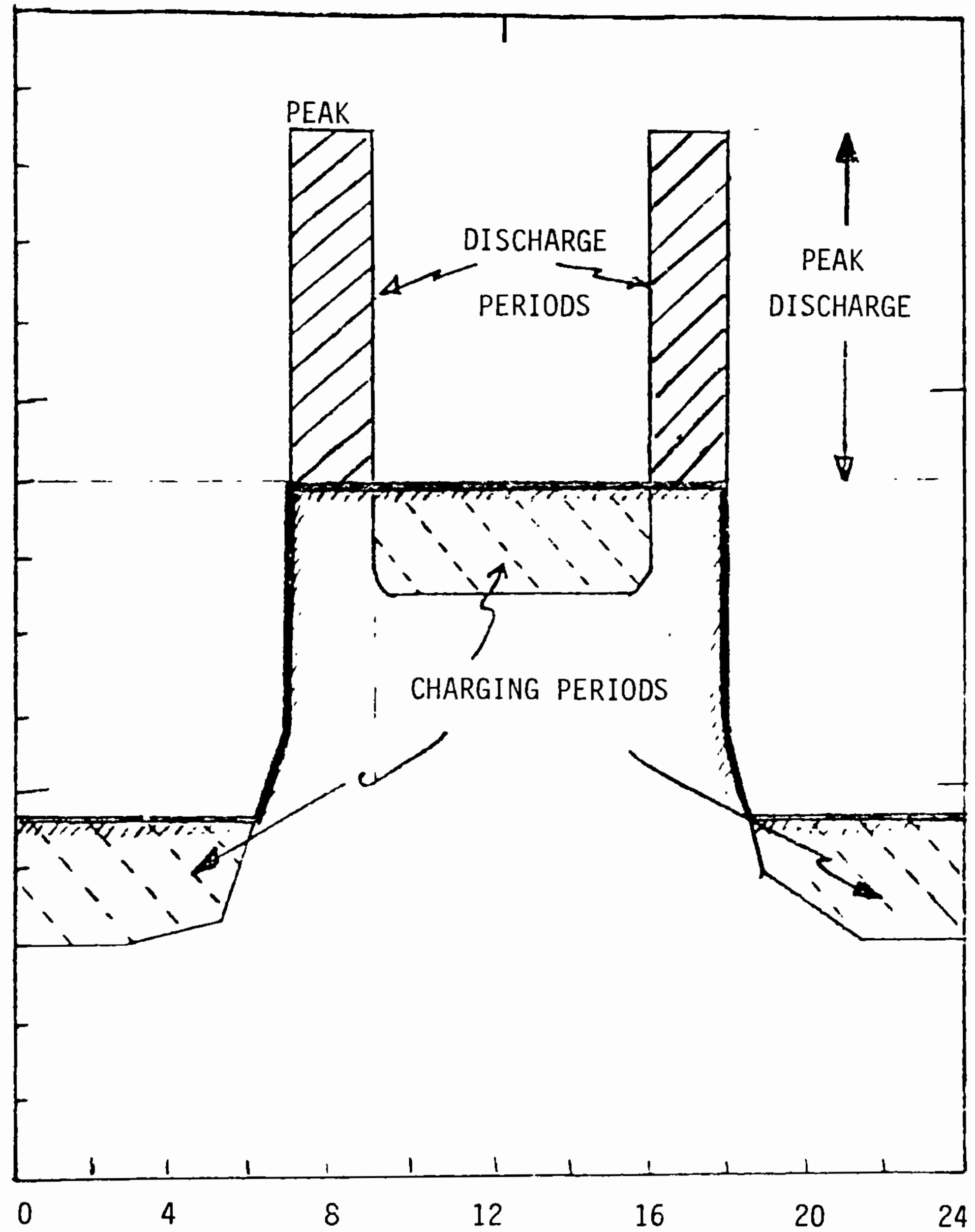


FIGURE 3-12 CHARGING VS. TIME OF DAY AT TYPICAL SUBWAY SUBSTATION

A second factor is the life of a battery. In an energy-storage system, battery life would be expected to be low because of high discharge and charge rates. A conservative estimate, based on the experience of industrial truck batteries, is a battery life-time of approximately three years. In most cases, the cost of replacing the batteries over a life-time comparable to that of a flywheel system, would be the equivalent of purchasing the original system a second time. A functional diagram of the Westinghouse system is shown in Figure 3-13. When determining the costs of an off-board battery system, KW should be used as the basis of costing. The number of batteries required for a system is determined by KW.

### 2. Off-board Battery System - Capital Costs

The capital costs in Table 3-9 are based on the Westinghouse Electric study referred to in the previous section.

TABLE 3-9 CAPITAL COSTS PER KW AND KWH FOR OFF-BOARD BATTERIES

| | (April 1980 $'s) | |
|---|---|---|
| | $/KW | $/KWH |
| 1. Westinghouse | $470 | $235 |

### 3. Off-board Battery System - Operating Costs

The operating costs in Table 3-10 are based on the Westinghouse Electric study. However, these operating costs do not include the cost of replacing the batteries every three years. This expenditure was not included in the Westinghouse study.

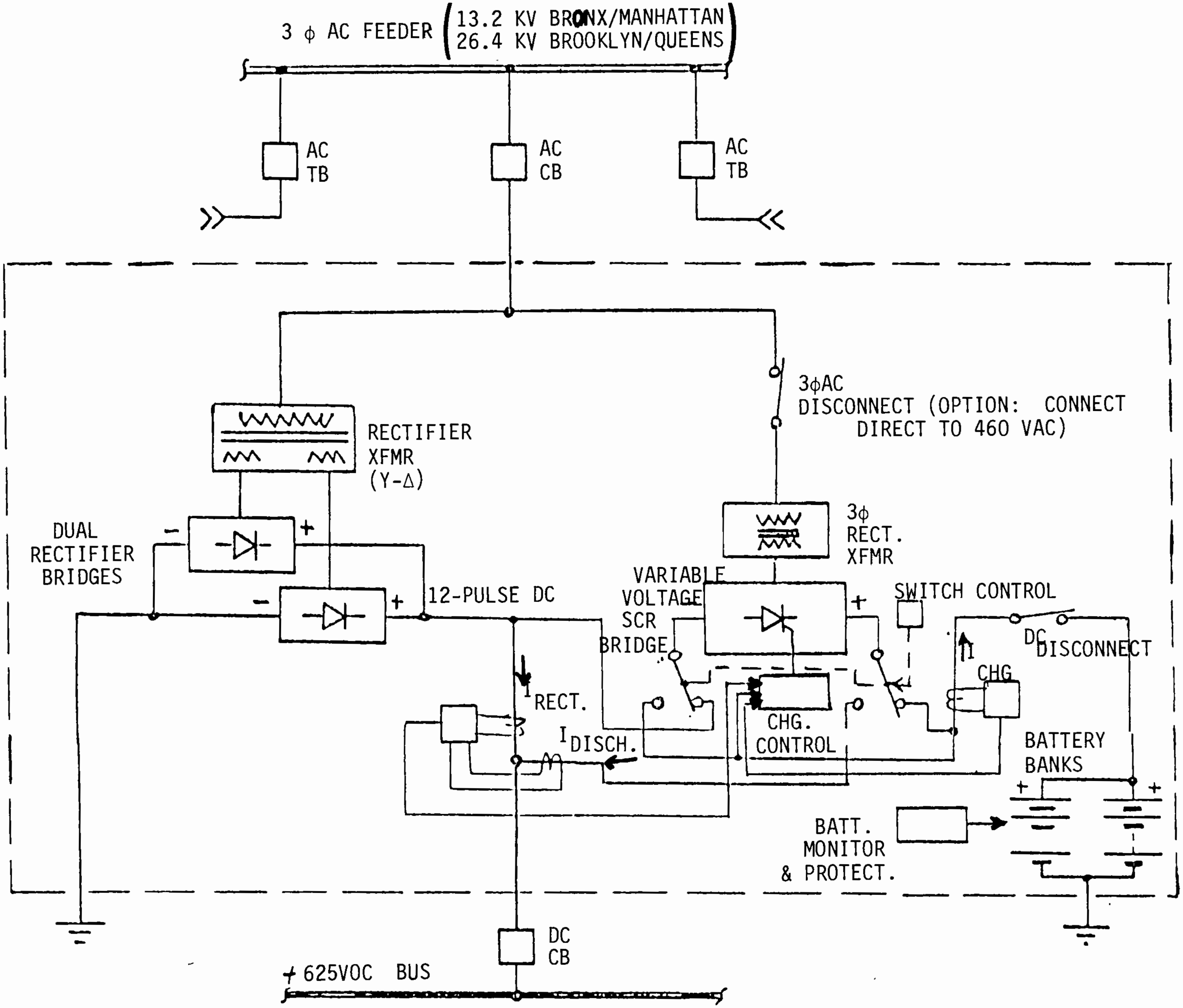


FIGURE 3-13 PROPOSED MODIFIED SUBWAY SUBSTATION [17]

TABLE 3-10 OPERATING COSTS PER KW AND KWH FOR OFF-BOARD BATTERIES

| | (April 1980 $'s) | |
|---|---|---|
| | $/KW | $/KWH |
| 1. Westinghouse Electric | $3.31 | $1.66 |

### 3.2.3 Comparison of Off-Board Flywheel Vs. Off-Board Battery

A comparison of the capital costs per KWH do not readily tell which of these two systems is more economical. However, a comparison of capital costs per KW show a tremendous difference. The capital cost per KW of an off-board flywheel system are approximately one-third of those of a comparable off-board battery energy-storage system. The operating costs for off-board batteries do not represent the true costs incurred every year. Replacement battery costs were not included in either operating costs per KW or KWH. Capital and operating costs for each of the systems are not the only factors in determining which is the better of the two systems. Two factors which weigh very heavily against the off-board battery system are its inability to accept energy at a rapid charge rate (and the resulting loss of recoverable energy) and its relatively short life-time. The cost of replacing the batteries every three years results in a total battery replacement expenditure equivalent to the cost of the original system. This factor alone makes the off-board battery system unacceptable.

An off-board battery energy-storage system may become more competitive in the future with advances in battery technology.

## 3.3 REGENERATIVE SUBSTATIONS

### 1. Conceptual Design

Regenerative substations achieve a substantially higher effective receptivity by allowing regenerated energy to flow through the substations back to the electrical utility grid. The utility is an essentially infinite sink for receiving regenerated energy.

Energy regeneration to the utility requires a reversible substation that allows the reverse flow of energy. The reversible substation employs somewhat more thyristor circuitry than a modern unidirectional substation adding approximately ten percent to the cost of a standard substation. Additional maintenance costs of the reversible substation relative to the unidirectional substation are not expected to be significant.

Using reversible substations,combined with a high conductivity third rail, provides an effective receptivity approaching 100 percent that is independent of the number of trains operating.

In a regenerative substation, the low voltage DC power from the third rail is converted into high-voltage three-phase power, and fed into the three-phase high-voltage distribution system. There are two advantages to this system. First, energy can be shared by all trains on the system. Second, if the energy generated by all the braking trains on the system exceeds the energy requirements of the rest of the operating trains, then the energy can be fed back to the utility to help meet their energy requirements. This means that there always will be a load present to accept energy from braking. Also, energy can be exchanged between trains through the low-voltage distribution system.

A regenerative substation was being considered for the Sao Paulo, Brazil, Metro Project. A schematic of the system is illustrated in Figure 3-14. The low-voltage DC supply is connected through a circuit breaker and a choke to two series-connected thyristor assemblies. Each thyristor assembly is a three-phase full-wave bridge configuration, individually providing six-phase DC operation. The outputs of the thyristor assemblies feed into separate low-voltage windings of a three-phase transformer. One of the low-voltage windings is connected in a wye configuration, while the other is connected in a delta configuration. The third winding is connected in a wye configuration to the high-voltage line. This arrangement results in a $30^\circ$ phase displacement between the outputs of thyristor assemblies, allowing a combined 12-pulse operation for the inverter. Forced-air cooling is provided through the thyristor heat-sinks.

Two modes of control-constant current and constant voltage are available. While the DC supply is below the nominal voltage, a constant current of approximately 100 amperes is fed into the AC system to maintain synchronism. If the voltage of the DC supply tries to rise above the level of the nominal voltage, then the constant voltage mode overrides. Under the constant-voltage mode, if the DC voltage tries to increase due to a braking train in the regenerative mode, the control allows DC current to increase, this allowing excess energy to be transformed to the AC network. In this way, the DC rail voltage is prevented from rising to unacceptable levels.

Regeneration to the utility is a relatively new concept that has not been adopted in the United States. It requires a cooperative effort between the transit operator and the utility. The utilities in the past have been wary of accepting energy from regeneration due to its harmonic content.

**Equipment needed for an inverter-recuperative system.**

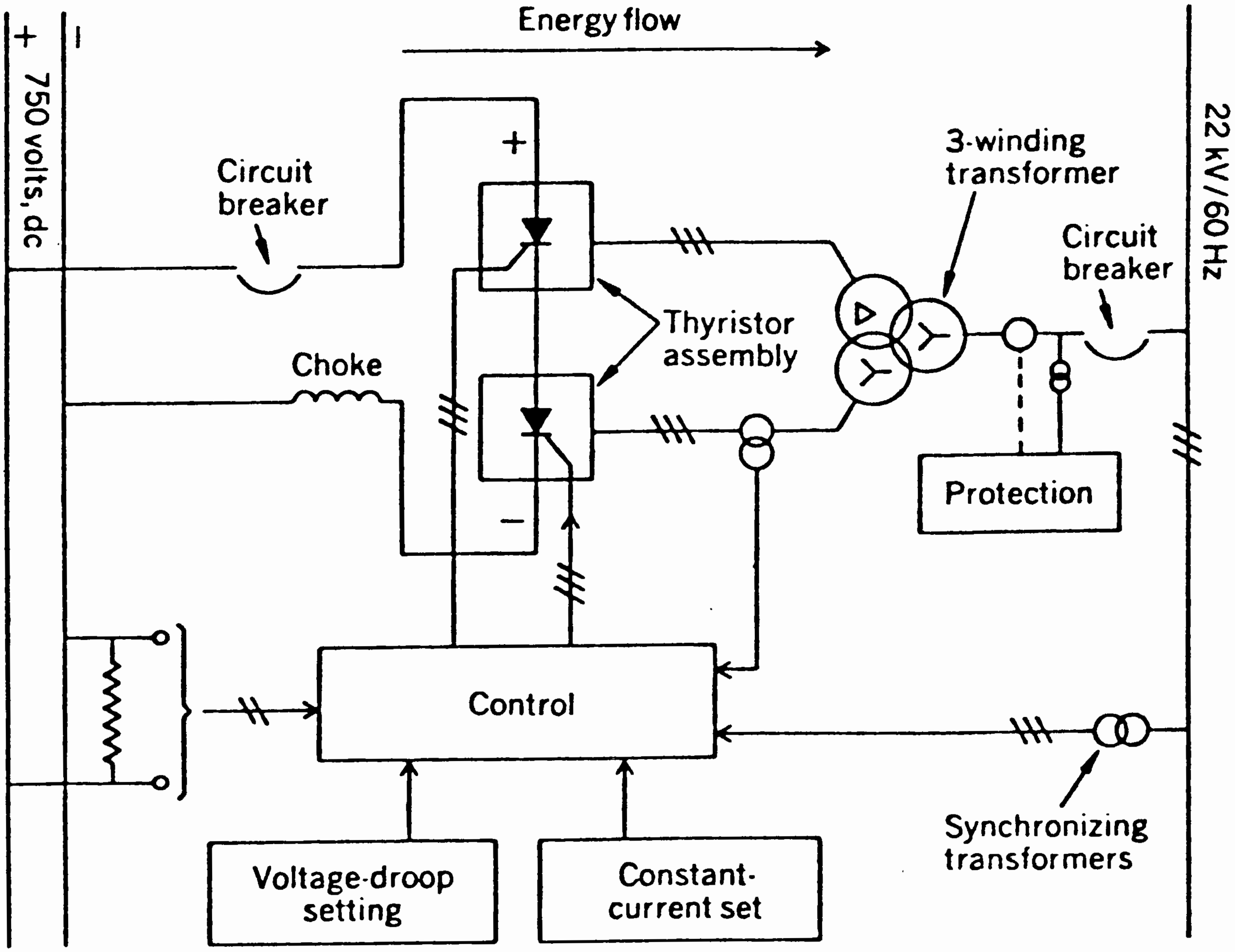


FIGURE 3-14 SCHEMATIC OF INVERTER-RECUPERATIVE SYSTEM[18]

This problem of harmonics can be mitigated by using forced commutated inverters. This has alleviated the concern expressed by the utilities. Another matter which must be taken into consideration is the cost rebates to be allowed for returned energy. In most cases, these rebates may be subject to state public utility commission jurisdiction. Figure 3-15 provides a block diagram of cost/effectiveness procedures for regenerative substation energy-storage systems.

### 2. Regenerative Substations - Capital Costs

The capital costs for regenerative substations are based on two primary sources. These sources were a study done by the Transportation Research Institute, Carnegie-Mellon University[19] and a report by Westinghouse Electric Corporation[20] for the U.S. Department of Transportation. Since there are no regenerative substations in operation on a transit property today, inverter-recuperative systems developed for other applications were used as the basis of cost analysis. The results of the Transportation Research Institute report are based on studies of foreign transit properties.

Several problems were encountered in the costing process. First, the data being used as the basis of analysis was not current. A rare phenomena has occurred in the electronics field, prices are going down instead of up. Since regenerative substations are basically made up of thyristors and diodes, this occurence has had a marked effect on the cost of regenerative substations. In updating the costs to April 1980 dollars, adjustments had to be made to decrease the costs instead of raising them as had to be done for other systems. A second problem encountered in this analysis was that some of the components of the regenerative substation were not consistently indexed by the Department of Commerce/Bureau of Economic Analysis throughout the entire analysis period. This situation was resolved with the cooperation of the Department of Labor/ Bureau of Labor Statistics when they furnished us with revised indexes. These are illustrated in Tables 3-11[21] and 3-12.[22]

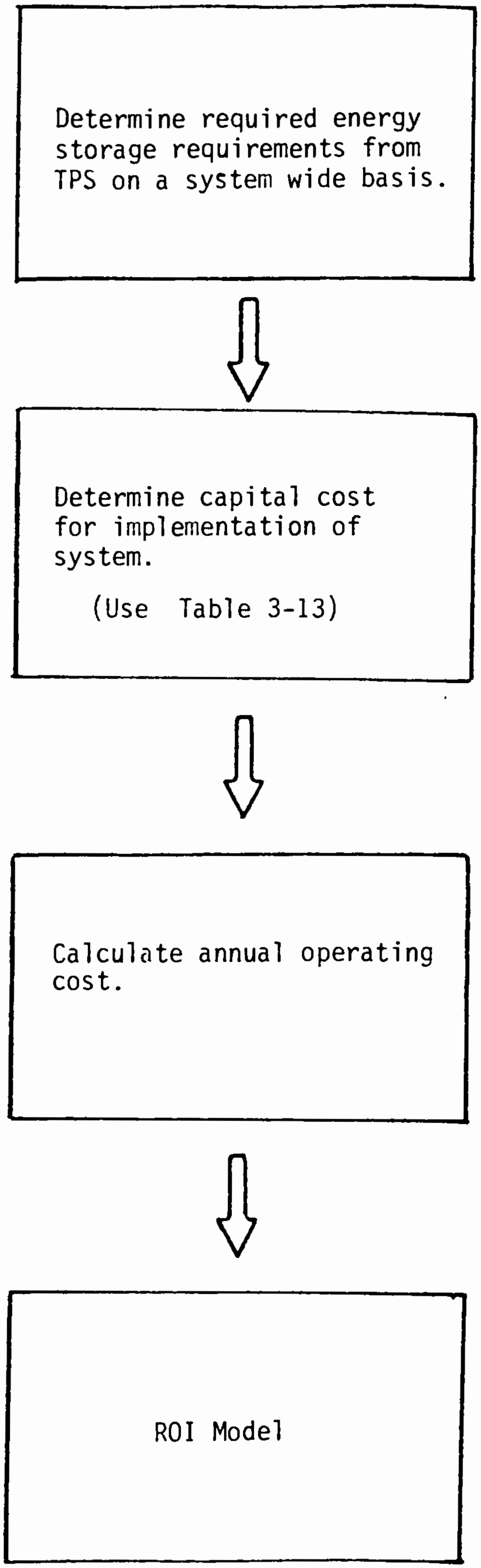


FIGURE 3-15 BLOCK DIAGRAM OF PROCEDURE FOR DETERMINING COST/EFFECTIVENESS OF REGENERATIVE SUBSTATION ENERGY-STORAGE SYSTEMS

## TABLE 3-11 CONVERSION INDEX FOR THYRISTORS

PPI 11780447 Silicon controlled rectifier ea. BASE 1967 = 10

| YR | ANN AVG | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1965 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 159.7 |
| 1966 | 127.3 | 156.5 | 149.4 | 149.4 | 149.4 | 123.2 | 123.2 | 123.0 | 123.0 | 108.1 | 108.1 | 107.3 | 106.7 |
| 1967 | 100.0 | 106.7 | 106.7 | 106.7 | 106.4 | 104.8 | 103.7 | 103.7 | 103.7 | 89.3 | 89.3 | 89.3 | 89.3 |
| 1968 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 |
| 1969 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 | 89.3 |
| 1970 | 90.4 | 89.3 | 89.3 | 89.3 | 90.7 | 90.7 | 90.7 | 90.7 | 90.7 | 90.7 | 90.7 | 90.7 | 90.7 |
| 1971 | 83.7 | 90.8 | 90.8 | 90.8 | 90.1 | 89.4 | 88.7 | 82.7 | 82.0 | 75.2 | 74.7 | 74.4 | 74.4 |
| 1972 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 |
| 1973 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 | 74.4 |
| 1974 | 78.0 | 76.1 | 76.1 | 76.1 | 76.1 | 76.1 | 78.6 | 78.6 | 78.6 | 78.6 | 80.2 | 80.2 | 80.2 |

NA NOT AVAILABLE

PPI 11783104 Rectifier diode, silicon ea. BASE 7412 = 10

| YR | ANN AVG | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1974 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 100.0 |
| 1975 | 98.1 | 100.0 | 100.0 | 100.0 | NA | 100.0 | 100.0 | 100.0 | 100.0 | 93.7 | 93.7 | 93.7 | NA |
| 1976 | 0.0 | 94.3 | 94.3 | 94.3 | 94.3 | 93.7 | 93.7 | 93.7 | 93.7 | 100.2 | 100.2 | 100.2 | 100.6 |
| 1977 | 97.5 | 100.6 | 100.6 | 94.1 | 100.6 | 100.6 | 100.6 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 |
| 1978 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 |
| 1979 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 | 95.5 |
| 1980 | NA | 95.5 | 98.1 | 98.1 | 98.1 | 98.1 | 98.1 | NA | NA | NA | NA | NA | NA |

NA NOT AVAILABLE

When updating costs for years prior to 1974, use the following process:

1. Take original cost back to base year (January 1967).
2. Update base year cost to last available index figure in top half of table.
3. Multiply index (from 2) times index of desired year in bottom half of table to get new index.

Example:

Base 1967 (100) $79.15

Jan. 1969 (89.3) $70.68

Dec. 1974 (80.2) $63.48

April 1980 (80.2 x 98.1= 78.8) $62.29

# TABLE 3-12 CONVERSION INDEX FOR DIODES

PPI 11700442 Silicon diode ea. BASE 1967

| YR | ANN AVG | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1965 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 158.5 |
| 1966 | 153.4 | 158.5 | 158.0 | 158.0 | 158.5 | 158.5 | 158.2 | 157.5 | 157.1 | 157.1 | 157.1 | 156.4 | 103.6 |
| 1967 | 100.0 | 103.6 | 101.4 | 101.5 | 100.5 | 100.5 | 100.5 | 100.5 | 100.5 | 100.5 | 100.5 | 96.0 | 94.0 |
| 1968 | 91.6 | 92.4 | 92.4 | 92.4 | 92.4 | 91.8 | 91.8 | 91.8 | 91.8 | 90.5 | 90.5 | 90.5 | 90.5 |
| 1969 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 90.5 | 88.5 |
| 1970 | 84.9 | 90.5 | 90.5 | 90.5 | 88.1 | 85.7 | 85.1 | 82.6 | 82.6 | 81.5 | 81.5 | 81.5 | 78.4 |
| 1971 | 79.4 | 78.5 | 77.5 | 76.5 | 76.5 | 76.5 | 76.5 | 75.5 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 |
| 1972 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 |
| 1973 | NA | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | 83.1 | NA | NA | NA |
| 1974 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA |

NA NOT AVAILABLE

PPI 11783102 Signal diode, silicon ea. BASE 7412 = 1

| YR | ANN AVG | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEPT | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1974 | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 100.0 |
| 1975 | NA | 99.5 | 99.5 | 99.5 | NA | NA | NA | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 | 99.0 |
| 1976 | 99.9 | 99.9 | 99.9 | 99.9 | 99.9 | 98.5 | 98.5 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 |
| 1977 | 100.1 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 | 100.4 | 99.5 | 99.5 | 99.5 | 99.5 |
| 1978 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | NA | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 |
| 1979 | 98.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 99.5 | 93.6 | 93.6 |
| 1980 | NA | 93.6 | 94.3 | 94.3 | 94.3 | NA | 94.3 | NA | NA | NA | NA | NA | NA |

NA NOT AVAILABLE

When updating costs for years prior to 1974, the following process:

1. Take original cost back to base year (January 1967).
2. Update base year cost to last available index figure in top half of table.
3. Multiply index (from 2) times index of desired year in bottom half of table to get new index.

Example:

| | | | |
|---|---|---|---|
| Base | 1967 | (100) | $5.31 |
| Jan. | 1969 | (90.5) | $4.81 |
| Sept. | 1973 | (83.1) | $4.42 |
| April | 1980 | (94.3 x 83.1 = 78.4) | $4.16 |

A different method was used in bringing the costs up to date for the regenerative substation than was used for any of the other systems. Instead of bringing the costs of the entire system as a whole up-to-date, the components of the substation were updated individually. It was determined from the Westinghouse Electric report that the three primary components of an inverter substation were thyristors, diodes and commutating components. The thyristors and diodes are made up of 65 percent thyristor or diode material and the remaining 35 percent electronic components. There was a breakdown in this manner because of the declining costs of the thyristors and diodes but a continuing rise in the costs of the other materials. A detailed example of the Westinghouse Electric costs follows:

| | (April 1980 $'s) |
|---|---|
| THYRISTORS | |
| 65% Silicon controlled rectifier | $ 62.29 |
| 35% Electronic components | 74.00 |
| Total Thyristor Cost | $136.29 |
| DIODES | |
| 65% Rectifier diode, silicon | $ 4.16 |
| 35% Electronic components | 5.00 |
| Total diode cost | $ 9.16 |
| COMMUTATING COMPONENTS | |
| Components | $ 8.30 |
| Inverter Substation Total | $153.75/KW |

Table 3-13 lists costs per KW for both studies.

TABLE 3-13 CAPITAL COST PER KW FOR REGENERATIVE SUBSTATIONS

| | (April 1980 $'s) |
|---|---|
| 1. Transportation Research Institute Report* | $102.04 |
| 2. Westinghouse Electric | 153.75 |

3. Regenerative Substations - Operating Costs

The operating costs in Table 3-14 are based on a study performed by General Electric Company.[23] However, these costs were for a resistor substation. It was felt that the operating costs for a regenerative substation would be very similar to those incurred by the resistor substation.

TABLE 3-14 OPERATING COSTS PER KW FOR REGENERATIVE SUBSTATIONS

| | (April 1980 $'s) |
|---|---|
| 1. General Electric | $ .98/KW |

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*"Energy Conservation in Three Electric Powered Transportation Systems", R.A. Uher, S.N. Talukdar and D. Ghahraman, Transportation Research Institute, Carnegie-Mellon University, January 1979.

## 4.0 DESCRIPTION OF RETURN ON INVESTMENT MODEL (ROI)

A return on investment (ROI) model was developed to be used as a basis of cost comparison between various energy storage methods. This model can be used for flywheel (on-board or wayside), battery (on-board or wayside), regenerative substations or any other energy storage system that may become feasible in the future.

The return on investment is found by solving the following equation:

$$F(x)=(1+R)-S/P\left[\frac{1-\left[\frac{(1+X2)\ (1+X1)}{1+R}\right]^{N}}{1-\left[\frac{(1+X2)\ (1+X1)}{1+R}\right]}\right]+$$

$$C(J)/P\ *\ \left[\frac{1-\left[\frac{(1+X2)}{(1+R)}\right]^{J*INT\ (N/J)}}{1-\left[\frac{(1+X2)}{(1+R)}\right]^{J}}\right]*\left[\frac{(1+X2)}{(1+R)}\right]^{J-1}$$

where

P= Initial Cost of System
S= Savings Per Year
R= Return on Investment (ROI)
C(J)= Cost Incurred in "J'th" Year
X1= Energy Escalator
X2= Inflation Escalator
N= Life of Investment
J= Year Cost Occurs
F(x)= 0
INT(N/J)= Integer Part of N/J

This is a very flexible model, since any or all of the parameters can be changed without having to structurally change the model. Factors that must be watched carefully are the initial costs and savings. They must be brought up to current, i.e. present day, cost figures so as to permit the comparison of like dollars. This process is fully described in Appendix B.

This model can accommodate changes in economic conditions through adjustments in the inflation (X2) and energy (X1) escalator factors. A sensitivity analysis can be performed through this adjusting process. The feasibility of an energy storage system may be drastically affected by changes in the energy escalator which would be demonstrated by this model.

Another feature of this model is its capability to handle more than one cost. The equation will take into account costs which occur every year as well as those which occur every "J'th" ($0<J<=N$) Year. These costs may be such things as yearly maintenance, a five year overhaul or a coat of paint every 10'th year. It can accommodate any number of costs occurring any number of years apart.

# 5.0 ANALYSIS OF PATCO PROPERTY[24]

## 5.1 DESCRIPTION OF THE SYSTEM

The characteristics associated with the PATCO line were used to test the cost/effectiveness model. The PATCO Lindenwold transit line operates from 16th Street Center City, Philadelphia to Lindenwold, New Jersey, a distance of 14.5 miles with 11 intermediate station stops with an average speed of 35 mph and a terminal to terminal run time of 25 minutes. This line was the first automated transit system in revenue operation in the United States. Figure 5-1 shows the path of the system and the station locations superimposed on a map of the area.

The PATCO rail line is a two track system. The elevation and grade profile is shown in Figure 5-2. The station locations are also shown for reference. Maximum grades of up to 5% occur mostly in sections from the underground portions in Philadelphia and Camden, New Jersey to the approaches of the Benjamin Franklin bridge over the Delaware River.

The speed restrictions on the system are also shown in the plots of Figure 5-2. The maximum speed is 75 mph. Most of the sharp curves in the alignment occur on the approaches to the Benjamin Franklin bridge.

Table 5-1 summarizes the vehicle characteristics which were used for the Train Performance Simulator (TPS). Although the vehicles are of two different types; namely, a single car with an empty weight of 39.7 tons and a married pair of A and B-cars each with an empty weight of 37.45 tons, an average empty weight of 38.4 tons was used as shown in the table. The full weight of the vehicle with 145 passengers each weighing 160 lbs. was taken at 50.0 tons. This was the assumed 100%

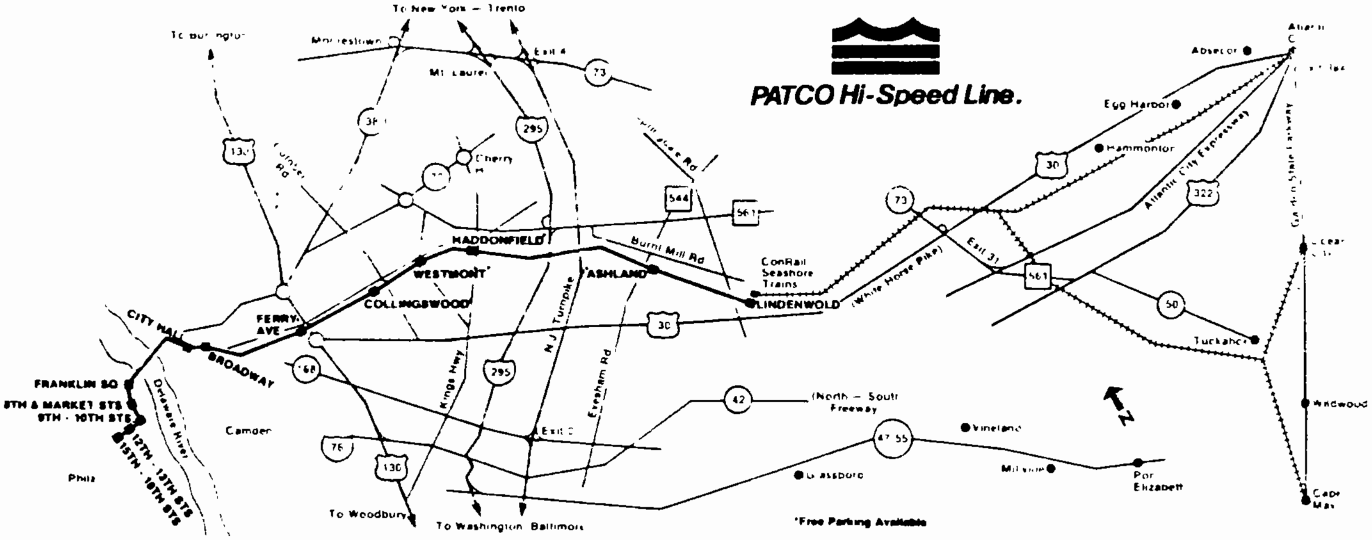


FIGURE 5-1 PATCO HI-SPEED LINE

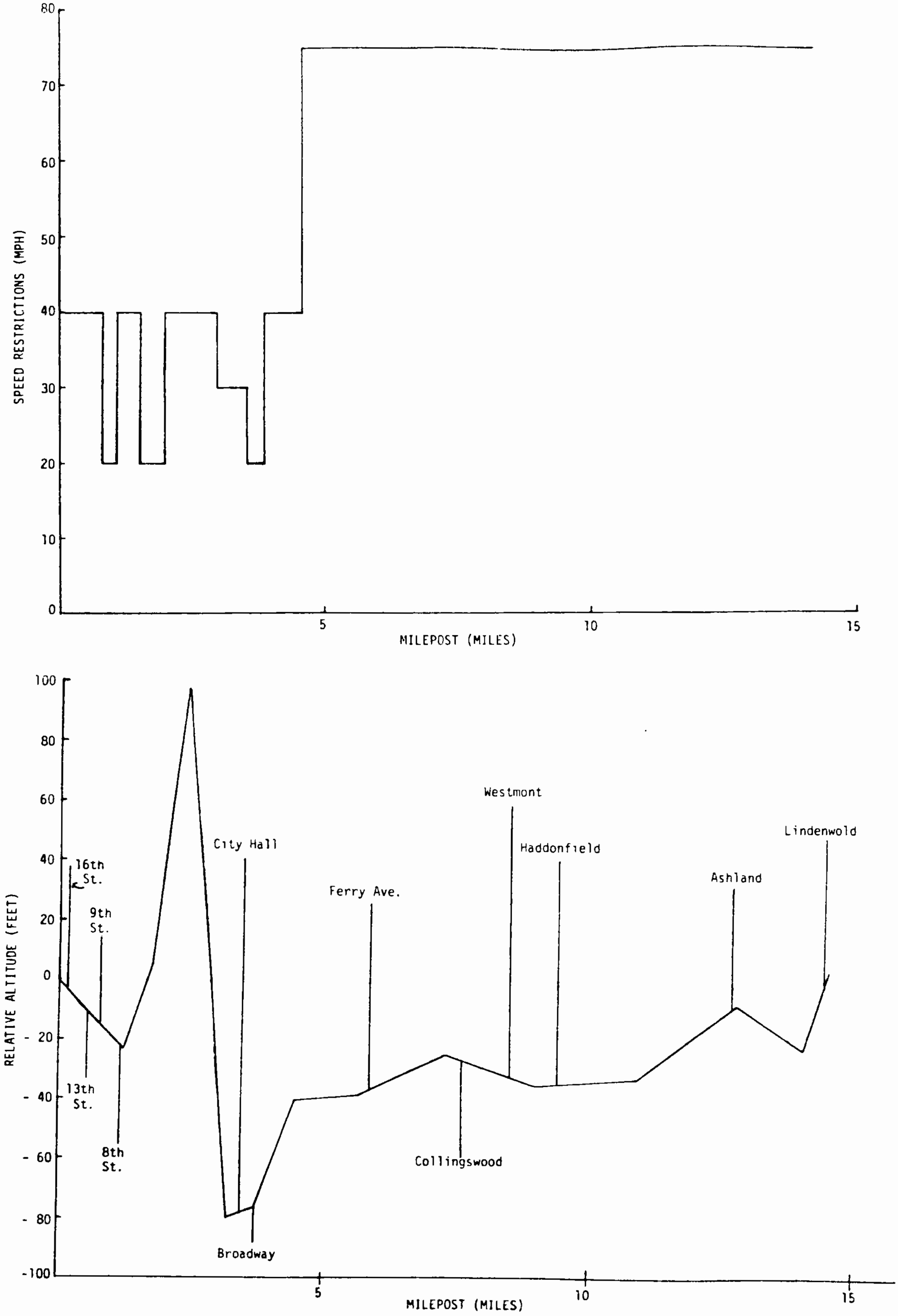


FIGURE 5-2 SPEED RESTRICTIONS AND ELEVATION VS DISTANCE FOR PATCO (WESTBOUND TRACK)

## TABLE 5-1

## PATCO VEHICLE CHARACTERISTICS USED IN TRAIN PERFORMANCE ESTIMATES

| | |
|---|---|
| Vehicle Empty Weight (tons) | 38.4 |
| Vehicle Full Weight (tons) | 50.0 |
| Vehicle Length (feet) | 68.0 |
| Cross Sectional Area (sq.ft.) | 125.0 |
| Number of Axles (all powered) | 4 |
| Auxiliary Power Requirements (KW) | 40.0 |

passenger load factor. This is slightly higher than the quoted "fully loaded" value of 125 passengers.

Table 5-2 shows the propulsion characteristics for the PATCO vehicle which is self-propelled with all axles powered. Motor curves for the GE-1255-A1 motor are shown in Figure 5-3.

Because of the inefficiency which would be experienced using the present cam-control resistor switching for regeneration, a hypothetical chopper control was modelled instead. Efficiency curves using this model were calculated and these are shown in Figure 5-4. The model used kept the motors permanently connected in two series/two parallel and incorporated the same type of field weakening as in the present PATCO propulsion system. The control philosophy depicted schematically in Figure 5-5 can be described as follows:

Power Operation

1. As the speed increases, the chopper increases the voltage applied to the motor circuit.

2. When the voltage to the motor circuit reaches line voltage, the motor field strength is weakened by field shunting steps until 33% field strength is obtained.

3. As speed further increases, the tractive effort developed will follow the 33% field strength motor curve.

4. Constant speed running is obtained by using the field strength such that tractive effort matches the train resistance for the given speed and profile conditions or if this is not possible, by reducing the motor circuit voltage using the chopper until the match is obtained.

### TABLE 5-2

### PATCO PROPULSION CHARACTERISTICS USED IN TRAIN PERFORMANCE ESTIMATES

Motors per Vehicle - 4

Motor Characteristic - (GE) Type 1255 A1

Power Conditioner - Chopper (For Regeneration)

Maximum Accelerating Rate - 3.0 MPHPS

Wheel Diameter - 28 in.

Gear Ratio - 4.79

Maximum Speed - 75 MPH

GE-1255-A1 300/600 VOLT MOTOP
CHARACTERISTICS ON 300 VOLTS
GEAR RATIO: 4.79:1
WHEEL DIAMETER: 28"
Includes GA-56-B1 Gear Loss
CALCULATED FROM TEST
GENERAL ELECTRIC CO. (RY)
F. C. Kreitler (CTH)

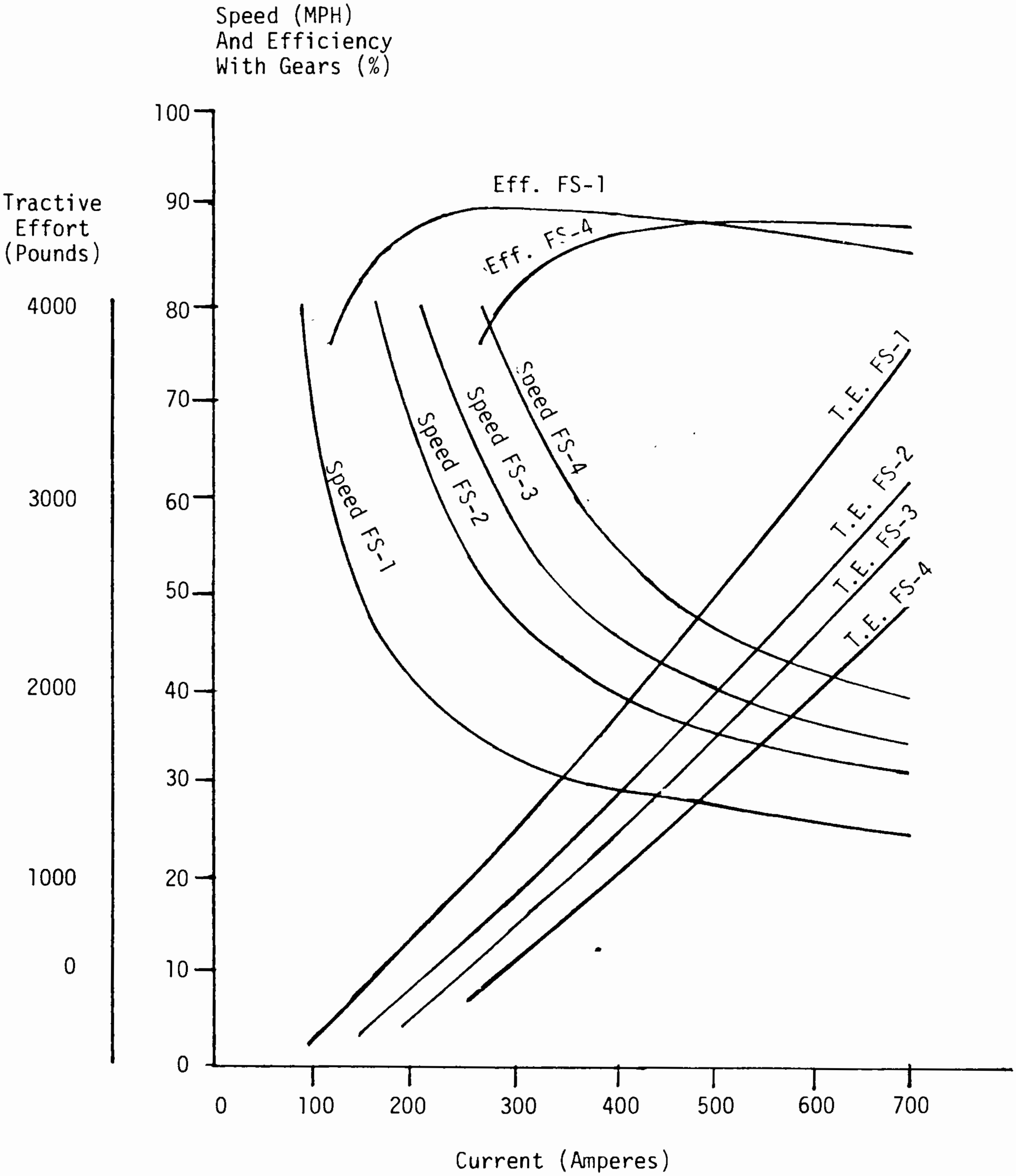


FIGURE 5-3 GE 1255-A1 MOTOR CURVES

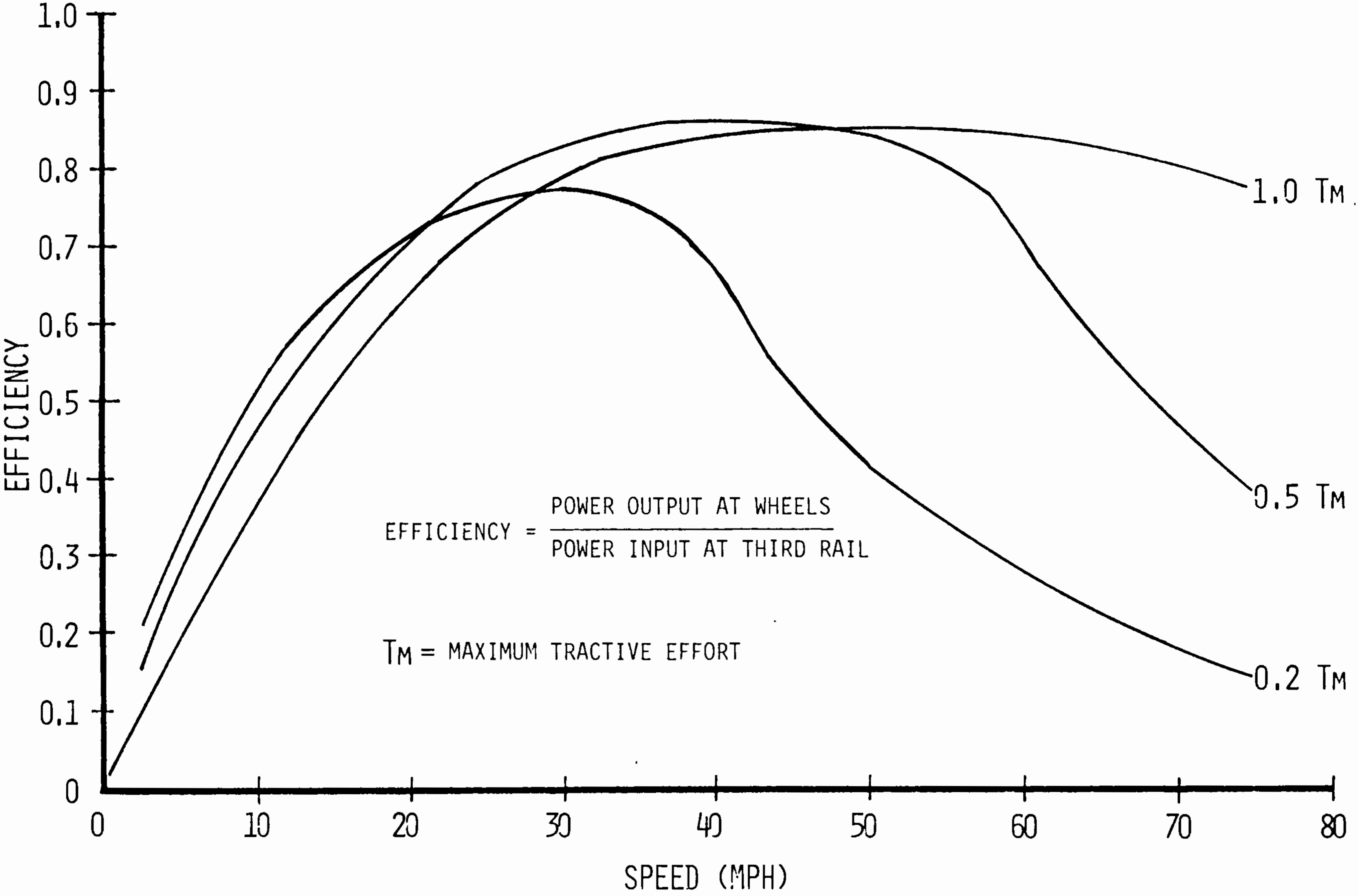


FIGURE 5-4 PROPULSION EFFICIENCY VS SPEED AND TRACTIVE EFFORT FOR PATCO CAR -- CHOPPER CONTROL

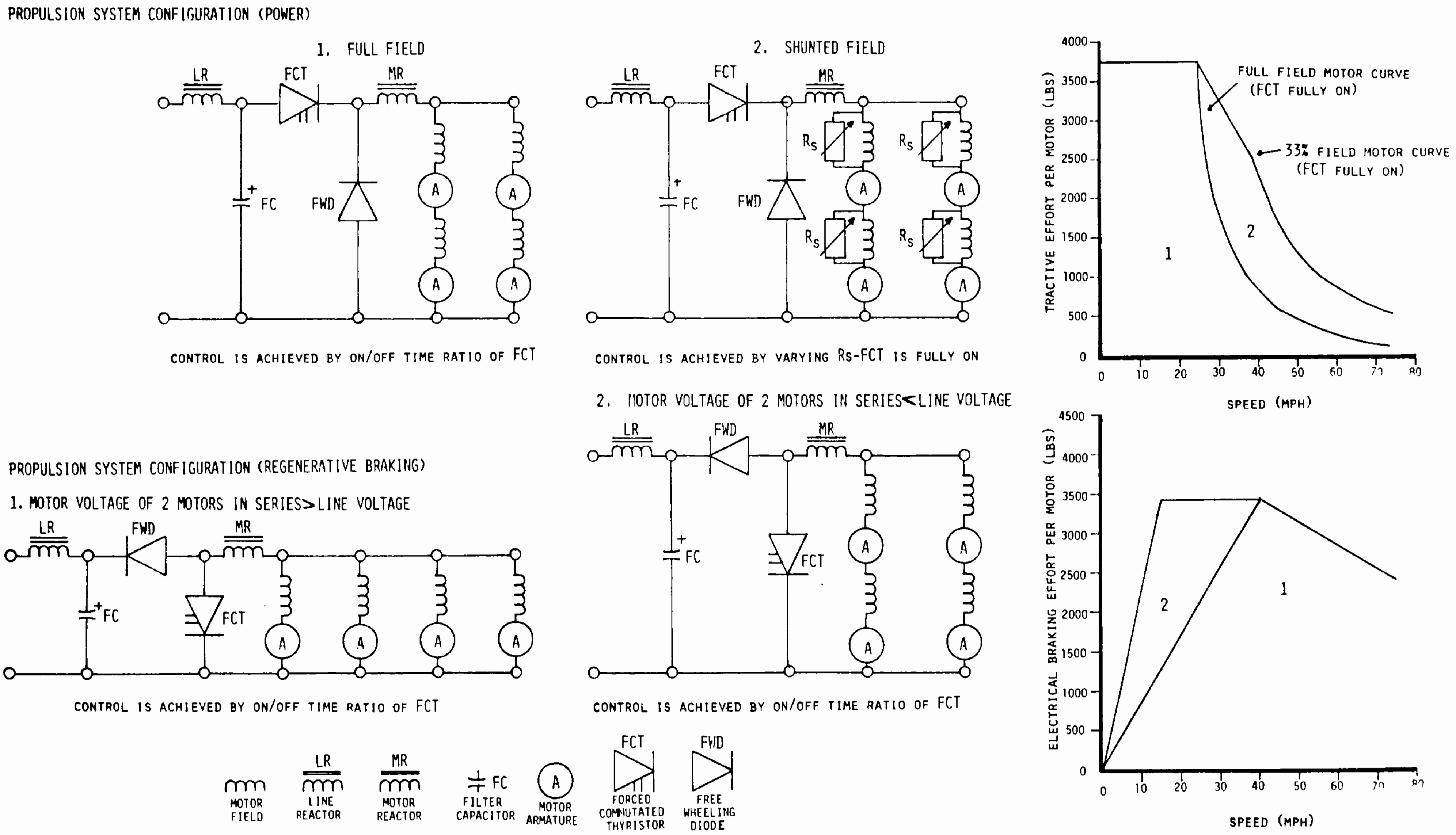


FIGURE 5-5 CHOPPER CONTROL PHILOSOPHY

## Braking Operation

1. At high speed when the combined voltage of the two series motors is higher than line voltage, the motors are reconnected in four parallel and the chopper is used to "chop up" the voltage from motor voltage to slightly above line voltage.

2. When the chopper can no longer maintain required margin above line voltage, the motors are reconnected in two series/two parallel to maintain the higher voltage. The chopper is again used to "chop up" the voltage marginally above line voltage.

3. When line voltage can no longer be maintained by chopper action, fadeout of the regenerative brake occurs and friction brake is applied blending with the decreasing dynamic brake in such a way as to keep a 3.0 MPHPS deceleration.

4. In the above braking operation (1-4), full motor field is used and the motor reactor provides the inductance necessary to "chop up" from a low motor circuit voltage to a higher than line voltage.

The milepost locations and the dwell times of the various trains at each station are listed in Table 5-3.

A diagram of the PATCO electrical network used in this study is shown in Figure 5-6 . The nominal DC distribution voltage on the third rail is 700 volts.

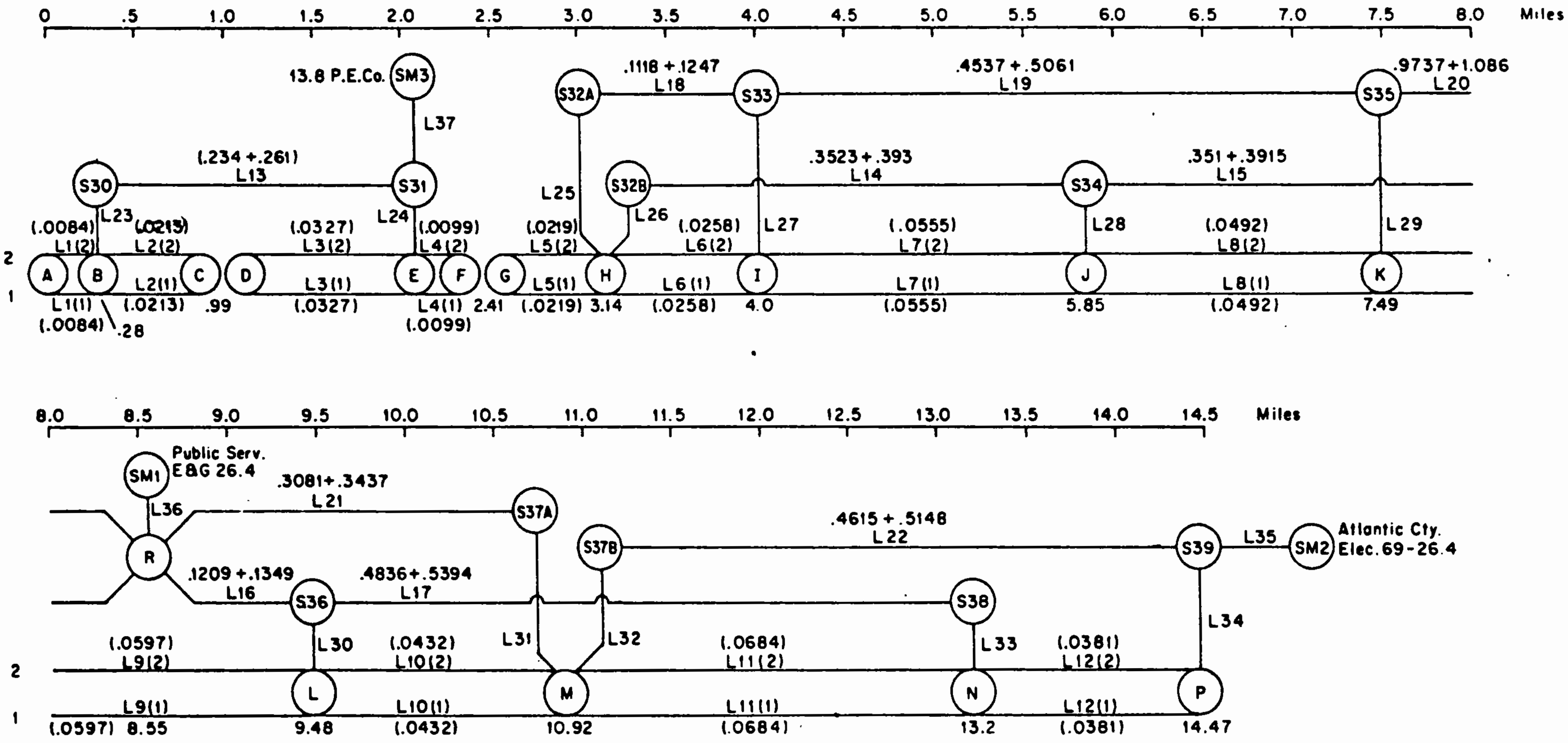
Power is purchased from three utilities at high voltage, three phase AC. The metering points are:

1. Philadelphia Electric Co. at the Front Street Substation (13.8kV).
2. Public Service Electric and Gas Co. at Westmont Substation (26.4kV).
3. Atlantic Electric Co. at Lindenwold Substation (26.4kV).

## TABLE 5-3

## STATION LOCATION AND DWELL TIMES

| STATION | MILEPOST | DWELL TIMES (seconds) |
|---|---|---|
| 16 St. | 0.19 | 0. |
| 13 St. | 0.47 | 20. |
| 9 St. | 0.76 | 20. |
| 8 St. | 1.12 | 20. |
| City Hall | 3.47 | 20. |
| Broadway | 3.72 | 20. |
| Ferry Ave. | 5.88 | 20. |
| Collingswood | 7.49 | 20. |
| Westmont | 8.54 | 20. |
| Haddonfield | 9.41 | 20. |
| Ashland | 12.60 | 20. |
| Lindenwold | 14.39 | 0. |



( ) = per unit impedances

FIGURE 5-6 DIAGRAM OF PATCO ELECTRICAL NETWORK USED IN SIMULATOR

There is a DC tie to the SEPTA facilities at Locust Street in Philadelphia; however, for the purposes of this study the tie breakers are assumed to be open. On the nodal diagram of Figure 5-6, the metering points described are shown by SM3, SM1 and SM2 in respective order.

There are ten rectifier substations in the distribution system, designated by (S30-S39) in the nodal diagram with 2 - 1500KW rectifiers in each station, which feed the third rail.

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

The PATCO timetable was analyzed along with PATCO's quotation of peak, daily and yearly estimate of passengers. Although there was no data available on actual passenger flow rates between stations, an estimate was made on a configuration of trains and passenger load factors which might typically represent the "average" train and load factor makeup during the week. These trains and associated load factors are shown in Table 5-4. These were the basis for the energy management study on regeneration which is discussed in the next section.

## 5.2 ENERGY SAVINGS BY REGENERATION

### 5.2.1 Regeneration Configurations

It would be neither easy nor inexpensive to equip the present PATCO cars, which have cam-controlled resistor switching, for regeneration using that cam-control method. Even if it were possible, there is a limit to the amount of energy which can be saved using this propulsion scheme. All regeneration configurations were run using the hypothetical chopper control described in Section 5.1.

# TABLE 5-4

# TYPICAL POINTS USED IN SIMULATION OF PATCO OPERATION

| | | | Hours of Operation in Mode | |
|---|---|---|---|---|
| Number of Cars in Consist | Passenger Load Factor (%) | Train Headway (Minutes) | Weekdays (Hours) | Saturdays & Sundays |
| 6 | 95 | 5 | 4 | -- |
| 6 | 95 | 7.5 | 4 | -- |
| 2 | 30 | 10 | 8 | 12 |
| 1 | 50 | 10 | 8 | 12 |

The four operating modes defined in Table 5-5 are analyzed with various regeneration configurations:

1. No Regeneration

   This is the base case operation. The cam-control resistor switching propulsion system has been replaced by a chopper control propulsion system. Regeneration was turned off.

2. Regeneration with Natural Receptivity - Regeneration Attempted Every Snapshot

   The regeneration on a given train is shut down if the line voltage at that train exceeds 10% above nominal. Once regeneration is shut down, there is a delay of five seconds until the next snapshot and the train once more attempts regeneration.

3. Regeneration with Natural Receptivity - Regeneration Attempted Every Brake Cycle

   Regeneration on a given train is shut down if the line voltage at the train is 10% above nominal. Regeneration is not attempted again until the next braking cycle. This is typical of the operation of the BART rail system.

4. Regeneration with Assured Receptivity - Wayside Energy Storage Devices

   Receptivity of regenerated energy is assured by providing wayside storage devices in each substation rather than aboard the cars. The input and output efficiencies of the storage device were set at 0.87.

5. Regeneration with Assured Receptivity - Regenerative Substations

   Assured receptivity is provided by allowing all energy to be fed back through the substation and metering points back to the utility. It is assumed that the utility can accept the energy and will give PATCO credit.

## TABLE 5-5

## SUMMARY OF RESULTS OF NORMAL OPERATION FOR PATCO

| Case | Consist | % Load Factor | Headway (Minutes) | Schedule Time (Minutes) | Energy Consumption at Vehicle (KWHPCM) | Metered Energy Consumption (KWHPCM) |
|---|---|---|---|---|---|---|
| 1 | 6 | 95 | 5 | 24.4 | 6.62 | 7.56 |
| 2 | 6 | 95 | 7.5 | 24.4 | 6.62 | 7.55 |
| 3 | 2 | 30 | 10 | 24.0 | 6.39 | 6.63 |
| 4 | 1 | 50 | 10 | 24.4 | 7.03 | 7.20 |

Average over one year's operation = 7.17 KWHPCM

Estimate of Actual Consumption = 6.94 KWHPCM

6. Regeneration with Assured Receptivity - Onboard Energy Storage

Receptivity is assured by placing generic storage devices onboard each vehicle. The input and output efficiencies of the storage devices and its control equipment were both set at 0.87. It is assumed to weigh 10% of the empty car. This is the effective weight of the flywheel storage devices and control placed on the R32 car prototypes at NYCTA. This weight has been added to the PATCO cars for these simulations.

### 5.2.2 Analysis of Regeneration Configurations

A summary of the simulations which were completed using the energy management model appears in Table 5-6. One computer simulation was made for each of the modes of operation which approximated the timetable (see Table 5-4) and for each of the six configurations described in the previous section. The following remarks refer to Table 5-6:

1. Each energy network simulator had a snapshot interval of 5 seconds. The simulation was run for a time interval of one headway. Thus, for a 5 minute headway, 60 snapshots were taken and for the 10 minute headway, 120 snapshots were taken.

2. Except for the case of on-board and off-board storage, the system as set up repeats itself, so that only the headway time interval need be simulated.

3. In the case of on-board and off-board storage, if the storage devices are precharged with energy such that

a. For the on-board storage case the eastbound train initially has the stored energy of the westbound train after its run is complete and visa-versa, and

b. For the off-board storage case the storage devices are initially charged with the energy they would have at the end of the loadflow simulation of one headway time interval

## TABLE 5-6 RESULTS OF COMPUTER SIMULATION RUNS ON THE PATCO LINDENWOLD LINE USING REGENERATION

| | | | | | ENERGY CONSUMPTION (KWHPCM) | | | |
|---|---|---|---|---|---|---|---|---|
| | | Cars/ Train | Headway (min) | Load Factor | Metered | Deli-vered | Regen-erated | Losses |
| 1 | No Regeneration | 6 | 5 | 95 | 7.61 | 6.67 | - | 0.94 |
| 2 | Regeneration-Natural Receptivity-Try on Each Snapshot | 6 | 5 | 95 | 6.70 | 6.67 | 1.19 | 1.22 |
| 3 | Regeneration-Natural Receptivity-Try Each Brake Cycle | 6 | 5 | 95 | 6.96 | 6.67 | 0.93 | 1.22 |
| 4 | Regeneration-Assured Receptivity-Offboard Storage | 6 | 5 | 95 | 5.40 | 6.67 | 2.58 | 1.31 |
| 5 | Regeneration-Assured Receptivity-Regener. Substations | 6 | 5 | 95 | 5.19 | 6.67 | 2.58 | 1.10 |
| 6 | Regeneration-Onboard Storage | 6 | 5 | 95 | 5.66 | 4.95 | - | 0.71 |
| 7 | No Regeneration | 6 | 7.5 | 95 | 7.60 | 6.67 | - | 0.93 |
| 8 | Regeneration-Natural Receptivity-Try Each Snapshot | 6 | 7.5 | 95 | 7.21 | 6.67 | 0.71 | 1.25 |
| 9 | Regeneration-Natural Receptivity-Try Each Brake Cycle | 6 | 7.5 | 95 | 7.57 | 6.67 | 0.33 | 1.23 |
| 10 | Regeneration-Assured Receptivity-Offboard Storage | 6 | 7.5 | 95 | 5.41 | 6.67 | 2.57 | 1.31 |
| 11 | Regeneration-Assured Receptivity-Regener. Substations | 6 | 7.5 | 95 | 5.27 | 6.67 | 2.58 | 1.18 |
| 12 | Regeneration-Onboard Storage | 6 | 7.5 | 95 | 5.67 | 4.95 | - | 0.72 |
| 13 | No Regeneration | 2 | 10 | 30 | 6.66 | 6.43 | - | 0.23 |
| 14 | Regeneration-Natural Receptivity-Try Each Snapshot | 2 | 10 | 30 | 6.16 | 6.43 | 0.54 | 0.27 |
| 15 | Regeneration-Natural Receptivity-Try Each Brake Cycle | 2 | 10 | 30 | 5.49 | 6.43 | 0.20 | 0.26 |
| 16 | Regeneration-Assured Receptivity-Offboard Storage | 2 | 10 | 30 | 4.79 | 6.43 | 2.34 | 0.70 |
| 17 | Regeneration-Assured Receptivity-Regener. Substations | 2 | 10 | 30 | 4.39 | 6.43 | 2.34 | 0.30 |
| 18 | Regeneration-Onboard Storage | 2 | 10 | 30 | 4.93 | 4.77 | - | 0.16 |
| 19 | No Regeneration | 1 | 10 | 50 | 7.19 | 7.07 | - | 0.12 |
| 20 | Regeneration-Natural Receptivity-Try Each Snapshot | 1 | 10 | 50 | 6.61 | 7.07 | 0.60 | 0.14 |
| 21 | Regeneration-Natural Receptivity-Try Each Brake Cycle | 1 | 10 | 50 | 6.82 | 7.07 | 0.39 | 0.14 |
| 22 | Regeneration-Assured Receptivity-Offboard Storage | 1 | 10 | 50 | 5.36 | 7.07 | 2.30 | 0.59 |
| 23 | Regeneration-Assured Receptivity-Regener. Substations | 1 | 10 | 50 | 4.93 | 7.07 | 2.30 | 0.16 |
| 24 | Regeneration-Onboard Storage | 1 | 10 | 50 | 5.54 | 5.45 | - | 0.09 |

then the system is again cyclic and only one headway time interval need be considered. (Two train performance and loadflow runs must be made; however, the first of which is to determine the initial storage energy.)

4. The metered energy consumption is the summation of all energy at all of the three metering points on the network. This energy contains third rail, running rail, substation and transmission losses. The sum of these losses is also shown. Because of the convergence used for the loadflow calculation, the losses are expected to be accurate to within 10%.

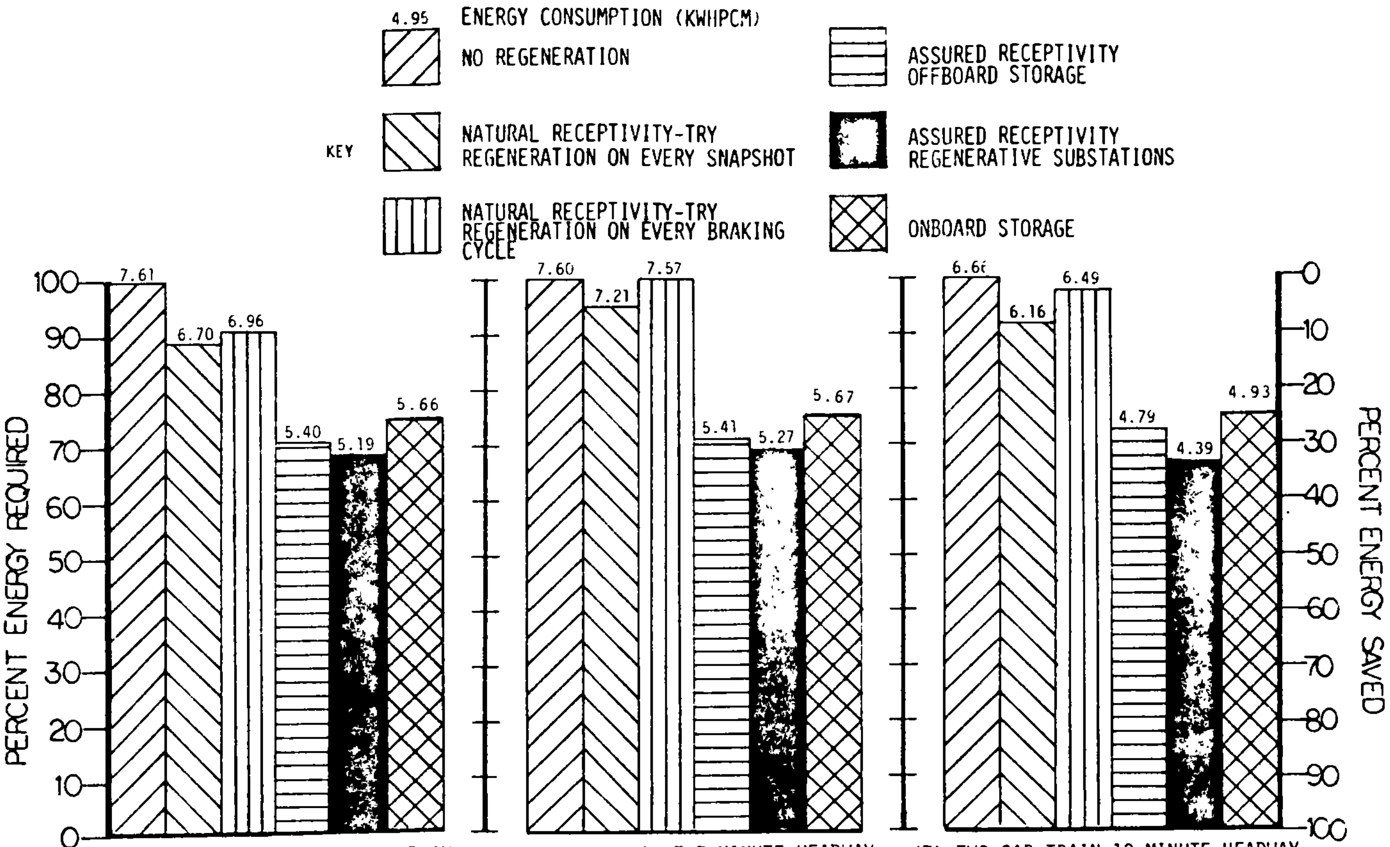
5. Delivered energy is that energy used by the vehicles for traction and auxiliaries. These remain the same unless the weight of the car or train consist size changes.

6. The regenerated energy is the energy delivered to the third rail by the train at the third rail. If as in the case of natural receptivity conditions, the DC network cannot accept the energy regeneration will be shut down. This is determined by placing an upper limit on the third rail voltage of 10% above nominal.

Figure 5-7 provides a summary of the results of the analysis of all regeneration strategies in the four modes of operation plus the "average" operation. The "average" is obtained by determining how many car-miles are accumulated in each mode and by using these as a weighting factor to sum the KWHPCM shown in the figure.

The following remarks refer to Figure 5-7:

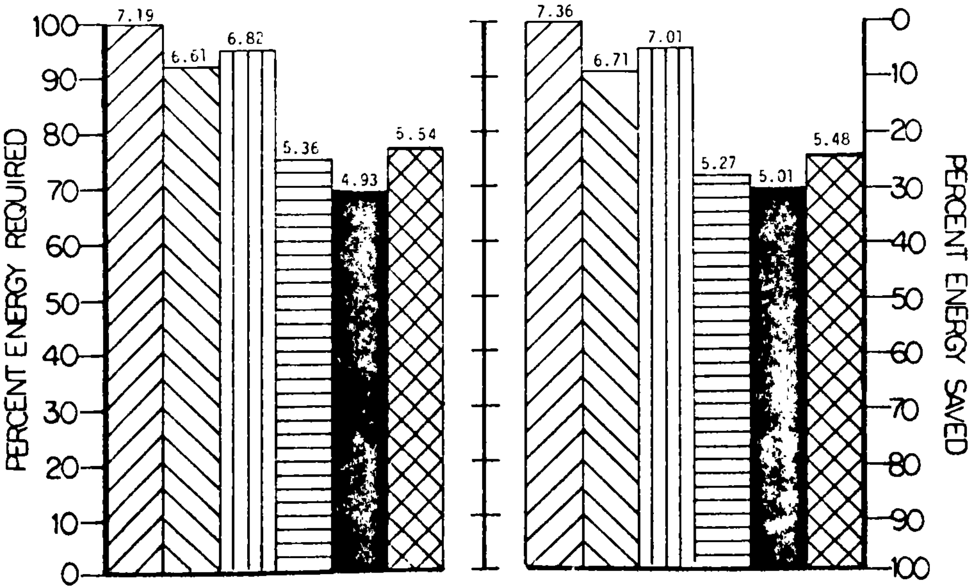
1. Energy savings obtained by natural receptivity whether regeneration attempts are made on each snapshot or on each brake cycle are small, typically



(1) SIX CAR TRAIN-5 MINUTE HEADWAY-95% PASSENGER LOAD FACTOR

(2) SIX CAR TRAIN-7.5 MINUTE HEADWAY-95% PASSENGER LOAD FACTOR

(3) TWO CAR TRAIN-10 MINUTE HEADWAY-30% PASSENGER LOAD FACTOR



(4) ONE CAR TRAIN-10 MINUTE HEADWAY-50% PASSENGER LOAD FACTOR

(5) TIMETABLE AVERAGE

FIGURE 5-7 REGENERATION ANALYSES SUMMARY FOR PATCO LINDENWOLD LINE of the order of ten percent. The reason for this is easily seen since even with a five-minute headway, the intertrain spacing would be twice the average substation spacing.

2. Assured receptivity can save from 28-32% of the total energy for the traction vehicles. Off-board storage will range closer to 28% while regeneration substations will be nearly 32%. The difference of 4% represent the additional in/out losses of that energy going into storage vs. that passing through the substation.

3. On-board storage of energy is not as good as off-board assured receptivity under these conditions since a savings of only about 25% would be realized. Increasing the weight of the vehicle to accomodate storage works agains the energy savings.

Table 5-7 shows the energy and power requirements of the off-board storage devices if all energy sent to the devices were to be accepted and stored by them.

Energy and power requirements of an on-board energy storage device for a PATCO car are as follows: maximum power input of 1060 KW/car and maximum energy storage of 3.34 KWH/car.

## 5.3 TEST RUN OF RETURN ON INVESTMENT MODEL USING PATCO

A test run of the Return on Investment (ROI) model was conducted using the PATCO Lindenwold Line to compare the five energy-storage methods studies in this report. The results of these tests are illustrated in Tables 5-8 and 5-9. Appendix D describes the procedure for obtaining capital investment, annual operating costs and annual savings. Two tables were constructed, one based on the highest capital and operating costs, Table 5-8, and the other based on the lowest capital and operating costs, Table 5-9. When performing a cost analysis, the highest costs should be included so as to abide by

TABLE 5-7 ENERGY AND POWER REQUIREMENTS FOR OFF-BOARD STORAGE DEVICES ON PATCO

| Substation* | Maximum Energy Stored (KWH) | Maximum Power Input (KW) | Maximum Power Output (KW) |
|---|---|---|---|
| B | 19.8(2) | 6890(2) | 5580(2) |
| E | 19.1(1) | 5510(1) | 6060(1) |
| H | 24.9(2) | 4110(2) | 3940(2) |
| I | 9.6(1) | 3380(2) | 3860(1) |
| J | 15.5(2) | 3970(2) | 3010(2) |
| K | 24.9(2) | 6270(2) | 5830(2) |
| L | 22.0(2) | 4980(2) | 5120(2) |
| M | 6.3(1) | 1630(1) | 1590(1) |
| N | 14.3(2) | 3860(2) | 4560(2) |
| P | 4.0(1) | 3280(1) | 1370(1) |

( ) Indicates the run which determines maximum energy or power conditions:

(1) Six car trains- 95% load factor - 5 minute headway

(2) Six car trains- 95% load factor - 7.5 minute headway

*Refer to Network Nodal Diagram of Figure 5-6.

## TABLE 5-8 HIGH RANGE CAPITAL AND OPERATING COSTS

| ENERGY STORAGE SYSTEM | CAPITAL INVESTMENT | ANNUAL OPERATING COSTS | ANNUAL SAVINGS | ENERGY ESCALATOR | INFLATION ESCALATOR | 30 YEAR ROI | 20 YEAR ROI |
|---|---|---|---|---|---|---|---|
| ON-BOARD FLYWHEEL | $10,435,000 | $142,000 | $274,000 | .13 | .10 | .20 | .14 |
| ON-BOARD BATTERY | $24,407,000 | $4,850,000 | $321,000 | .13 | .10 | -.04 | * |
| OFF-BOARD FLYWHEEL | $ 9,941,000 | $228,000 | $321,000 | .13 | .10 | .20 | .15 |
| OFF-BOARD BATTERY | $20,624,000 | $145,000 | $321,000 | .13 | .10 | .17 | .10 |
| REGENERATIVE SUBSTATION | $ 6,746,000 | $ 43,000 | $379,000 | .13 | .10 | .27 | .23 |

## TABLE 5-9 LOW RANGE CAPITAL AND OPERATING COSTS

| ENERGY STORAGE SYSTEM | CAPITAL INVESTMENT | ANNUAL OPERATING COSTS | ANNUAL SAVINGS | ENERGY ESCALATOR | INFLATION ESCALATOR | 30 YEAR ROI | 20 YEAR ROI |
|---|---|---|---|---|---|---|---|
| ON-BOARD FLYWHEEL | $ 2,118,000 | $36,000 | $274,000 | .13 | .10 | .35 | .33 |
| ON-BOARD BATTERY | $24,407,000 | $4,850,000 | $274,000 | .13 | .10 | -.04 | * |
| OFF-BOARD FLYWHEEL | $ 7,576,000 | $122,000 | $321,000 | .13 | .10 | .24 | .19 |
| OFF-BOARD BATTERY | $20,624,000 | $145,000 | $321,000 | .13 | .10 | .17 | .10 |
| REGENERATIVE SUBSTATION | $ 4,477,000 | $ 43,000 | $379,000 | .13 | .10 | .30 | .27 |

conservative accounting practices. All conclusions of this analysis are based on the higher, more conservative figures. Also, each table reports a ROI for both thirty and twenty year operating periods, with the twenty year figure being the more conservative of the two.

An energy escalator of thirteen percent and a general inflation escalator of ten percent are used in cost analysis for all five of the energy-storage systems.

On the basis of Table 5-8, and a twenty year ROI, the on-board and off-board energy-storage systems are eliminated as potential alternatives for PATCO. Of the three remaining alternatives, the regenerative substation produces the highest return on investment, 23 percent. This is a very respectable ROI inspite of the fact that very conservative figures were used. The same holds true for the off-board flywheel which had a ROI of approximately 15 percent.

If the most optimistic figures were used (Table 5-9 and a thirty year ROI), the on-board flywheel system would provide a ROI of over 35 percent. This should not be considered an unobtainable figure. It is quite likely a ROI of over 35 percent could be achieved; however, it should not be used in the decision and analysis process due to the rule of conservatism.

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# 8.0 APPENDICES

# APPENDIX A

## ROI COMPUTER MODEL

```
      DIMENSION C(100)
   10 FORMAT ('    ENTER CAPITAL INVESTMENT:')
   20 FORMAT ('    ENTER SAVINGS/YEAR:')
   30 FORMAT ('    ENTER ENERGY ESCALATOR:')
   40 FORMAT ('    ENTER INFLATION ESCALATOR:')
   50 FORMAT ('    ENTER INVESTMENT PERIODS:')
   60 FORMAT ('    ENTER COST INCURRED EVERY JTH YEAR; TYPE J:')
   70 FORMAT ('    RETURN ON INVESTMENT =',F10.4)
   90 FORMAT ('    ENTER COST FOR EVERY ',I2,' TH YEAR:')
  100 FORMAT (F10.0)
  110 FORMAT(I2)
      WRITE (2,50)
      READ (5,110)N
      WRITE (2,10)
      READ (5,100)P
      WRITE (2,20)
      READ (5,100)S
      WRITE (2,30)
      READ (5,100)X1
      WRITE (2,40)
      READ (5,100)X2
  300 WRITE (2,60)
      READ (5,110)J
      IF (J.EQ.0) GO TO 310
      WRITE (2,90)J
      READ (5,100)D
      C(J)=D
      GO TO 300
  310 CALL NWTN(P,S,C,X1,X2,N,R)
      WRITE (2,70)R
      STOP
      END
      SUBROUTINE NWTN(P,S,C,X1,X2,N,R)
      DIMENSION C(100)
      I1=1
      X=.001
      DX=.5
      CALL PVF(X,Y,S,P,C,X1,X2,N)
      IF(Y.GT.0.) DX=-.5
  200 X=X+DX
      CALL PVF(X,Y1,S,P,C,X1,X2,N)
      Y2=Y1*Y
      Y=Y1
      I1=I1+1
      IF (I1.GT.300) GO TO 270
      IF (Y2.GT.0.) GO TO 200
      DX=-DX/2.00001
      IF (ABS(DX).LE..00001) GO TO 260
      GOTO 200
  270 STOP 'LACK OF CONVERGENCE'
  260 R=X
      RETURN
      END
      SUBROUTINE PVF(X,Y,S,P,C,X1,X2,N)
      DIMENSION C(100)
      F=(1+X)-(S/P)*(1-((1+X1)*(1+X2)/(1+X))**N)/(1-
     *(1+X1)*(1+X2)/(1+X))
      G=0.
      DO 180 J=1,N
      IF(C(J).EQ.0.) GO TO 180

      G=G+(C(J)/P)*(1-((1+X2)/(1+X))**(J*INT(N/J+.001
     *)))/(1-(((1+X2)/(1+X))**J))
     **((1+X2)/(1+X)**(J-1))
  180 CONTINUE
      Y=G+F
      RETURN
      END
```

# APPENDIX B

## COST UPDATING

The updating process is relatively easy to accomplish. The first step of this process is to determine the year to which the costs are applicable. For costs prior to January 1979, a biennial publication of the United States Department of Commerce/Bureau of Economic Analysis, Business Statistics 1979, should be used as the pricing index. Dates from January 1979 should be referenced from Survey of Current Business, published monthly by the United States Department of Commerce. The next step is to determine the appropriate category which the energy storage system falls under, such as: "Electrical Machinery and Equipment" for flywheel systems or "Storage Batteries" for a battery type system, etc.

Each commodity has an index which corresponds to the appropriate year and month of the cost to be updated. The function of the index is to bring the "old" initial cost back to 1967 prices (the base year) and then to current prices. The following example of a flywheel system, in January 1975 dollars, being brought up to date, shows the actual process:

| | |
|---|---|
| Flywheel System (January 1975 dollars) | $972,000 |
| Index for Electrical Machinery & Equipment (Jan. 1975) | 1.381 |

$972,000 ÷ 1.381 = $703,838

This step has brought the cost back to 1967 (Base 100) figures, to bring it up to April 1980 dollars.

$703,838 ÷ 1.987 = $1,398,526

By following this process, a fair comparison can be made regarding the costs and savings of each system.

# COMMODITY PRICES--WHOLESALE PRICES--Con.

ELECTRICAL
MACHINERY

U S DEPARTMENT OF LABOR INDEXES [1] 1947-1976

| YEAR AND MONTH | Industrial commodities [2] | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Lumber and wood products | | Machinery and equipment [3] | | | | | Metals and metal products | | | | Nonmetallic mineral products | | | | |
| | Total [4] | Lumber | Total [4] | Agricultural machinery and equipment | Construction machinery and equipment | Electrical machinery and equipment | Metal working machinery and equipment [5] | Total [4] | Heating equipment | Iron and steel | Nonferrous metals | Total [4] | Clay products, structural, excluding refractories [6] | Concrete products | Gypsum products |
| | 1967 = 100 | | | | | | | | | | | | | | | |
| 1947 | 73.4 | 71.5 | 53.7 | 53.3 | 44.0 | 62.2 | 46.0 | 54.9 | 84.9 | 51.3 | 59.1 | 66.3 | 62.3 | 71.3 | 70.3 |
| 1948 | 84.0 | 81.2 | 58.2 | 59.7 | 49.8 | 65.1 | 49.5 | 62.5 | 90.1 | 59.6 | 65.4 | 71.6 | 67.1 | 74.7 | 76.8 |
| 1949 | 77.7 | 74.3 | 61.0 | 63.8 | 53.0 | 66.8 | 51.9 | 63.0 | 92.2 | 60.5 | 61.0 | 73.5 | 69.0 | 76.4 | 76.1 |
| 1950 | 89.3 | 86.6 | 63.1 | 65.2 | 54.5 | 68.9 | 55.1 | 66.3 | 93.5 | 64.6 | 64.4 | 75.4 | 72.1 | 78.2 | 77.8 |
| 1951 | 97.2 | 93.7 | 70.5 | 70.8 | 60.5 | 78.9 | 61.6 | 73.8 | 102.0 | 70.4 | 76.8 | 80.1 | 78.0 | 83.3 | 87.4 |
| 1952 | 94.4 | 91.3 | 70.6 | 71.1 | 61.4 | 77.8 | 62.6 | 73.9 | 101.3 | 71.2 | 76.3 | 80.1 | 77.8 | 83.4 | 87.5 |
| 1953 | 94.3 | 90.5 | 72.2 | 72.1 | 63.2 | 80.0 | 63.5 | 76.3 | 102.3 | 75.0 | 77.3 | 83.3 | 79.2 | 85.5 | 90.1 |
| 1954 | 92.6 | 88.9 | 73.4 | 72.0 | 64.4 | 81.6 | 64.5 | 76.9 | 101.8 | 76.0 | 76.8 | 85.1 | 80.5 | 87.1 | 90.9 |
| 1955 | 97.1 | 94.5 | 75.7 | 72.6 | 67.0 | 82.9 | 67.9 | 82.1 | 102.5 | 80.3 | 88.3 | 87.5 | 83.8 | 88.0 | 90.9 |
| 1956 | 98.5 | 96.5 | 81.8 | 75.2 | 72.6 | 89.5 | 74.3 | 89.2 | 105.9 | 88.4 | 96.5 | 91.3 | 88.1 | 91.1 | 94.6 |
| 1957 | 93.5 | 90.9 | 87.6 | 78.7 | 78.2 | 96.4 | 78.8 | 91.0 | 108.4 | 95.0 | 85.0 | 94.8 | 89.4 | 93.6 | 94.6 |
| 1958 | 92.4 | 89.5 | 89.4 | 81.9 | 81.2 | 98.4 | 80.8 | 90.4 | 107.4 | 96.4 | 79.0 | 95.8 | 90.1 | 94.9 | 98.2 |
| 1959 | 98.8 | 96.4 | 91.3 | 84.5 | 84.1 | 99.9 | 82.7 | 92.3 | 107.9 | 98.3 | 84.2 | 97.0 | 92.2 | 96.1 | 99.0 |
| 1960 | 95.3 | 92.1 | 92.0 | 86.1 | 85.9 | 99.5 | 85.1 | 92.4 | 105.8 | 97.1 | 85.9 | 97.2 | 93.7 | 97.2 | 99.1 |
| 1961 | 91.0 | 87.4 | 91.9 | 87.7 | 87.3 | 98.2 | 85.9 | 91.9 | 101.8 | 97.2 | 83.0 | 97.6 | 94.2 | 97.2 | 101.0 |
| 1962 | 91.6 | 89.0 | 92.0 | 89.5 | 87.5 | 96.7 | 87.3 | 91.2 | 100.5 | 95.8 | 82.1 | 97.6 | 95.0 | 97.3 | 102.1 |
| 1963 | 93.5 | 91.2 | 92.2 | 90.8 | 89.0 | 95.7 | 87.6 | 91.3 | 100.2 | 95.7 | 82.0 | 97.1 | 95.5 | 96.5 | 102.5 |
| 1964 | 95.4 | 92.9 | 92.8 | 92.2 | 91.2 | 95.1 | 89.3 | 93.8 | 99.2 | 97.0 | 87.6 | 97.3 | 95.8 | 95.7 | 105.3 |
| 1965 | 95.9 | 94.0 | 93.9 | 94.0 | 93.6 | 95.1 | 91.8 | 96.4 | 98.9 | 97.9 | 95.3 | 97.5 | 96.6 | 96.3 | 101.2 |
| 1966 | 100.2 | 100.1 | 96.8 | 96.8 | 96.5 | 97.2 | 96.0 | 98.8 | 99.8 | 98.7 | 100.0 | 98.4 | 98.2 | 97.7 | 99.6 |
| 1967 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1968 | 113.3 | 117.4 | 103.2 | 103.9 | 105.7 | 101.3 | 104.0 | 102.6 | 102.7 | 101.9 | 103.5 | 103.7 | 102.6 | 102.6 | 103.6 |
| 1969 | 125.3 | 131.6 | 106.5 | 108.5 | 110.4 | 102.9 | 108.0 | 108.5 | 105.4 | 107.0 | 113.5 | 107.7 | 106.2 | 106.5 | 103.6 |
| 1970 | 113.6 | 113.7 | 111.4 | 113.2 | 115.9 | 106.4 | 114.1 | 116.6 | 110.6 | 115.1 | 124.7 | 112.9 | 109.9 | 112.2 | 99.7 |
| 1971 | 127.0 | 135.5 | 115.5 | 117.2 | 121.4 | 109.5 | 117.3 | 119.0 | 115.5 | 121.8 | 116.0 | 122.4 | 114.2 | 120.6 | 106.8 |
| 1972 | 144.3 | 159.4 | 117.9 | 122.3 | 125.7 | 110.4 | 120.2 | 123.5 | 118.2 | 128.4 | 116.9 | 126.1 | 117.3 | 125.6 | 114.7 |
| 1973 | 177.2 | 205.2 | 121.7 | 125.9 | 130.7 | 112.4 | 125.5 | 132.8 | 120.4 | 136.2 | 135.0 | 130.2 | 123.3 | 131.7 | 120.9 |
| 1974 | 183.6 | 207.1 | 139.4 | 143.8 | 152.3 | 125.0 | 146.9 | 171.9 | 135.0 | 178.6 | 187.1 | 153.2 | 135.2 | 151.7 | 137.6 |
| 1975 | 176.9 | 192.5 | 161.4 | 168.6 | 185.2 | 140.7 | 171.6 | 185.6 | 150.7 | 200.9 | 171.6 | 174.0 | 151.2 | 170.5 | 144.0 |
| 1976 | 205.6 | 233.0 | 171.0 | 183.0 | 198.9 | 146.7 | 182.7 | 195.9 | 158.0 | 215.9 | 181.6 | 186.3 | 163.5 | 180.1 | 154.4 |
| 1973 January | 151.0 | 169.0 | 118.9 | 123.6 | 126.6 | 110.9 | 121.8 | 125.6 | 118.8 | 131.9 | 117.9 | 128.2 | 120.3 | 128.5 | 117.4 |
| February | 161.0 | 182.3 | 119.4 | 124.4 | 127.4 | 111.0 | 122.5 | 126.9 | 119.2 | 133.0 | 121.0 | 128.4 | 121.5 | 128.9 | 115.8 |
| March | 173.2 | 195.8 | 120.0 | 124.7 | 128.6 | 111.3 | 123.4 | 129.2 | 119.5 | 133.3 | 128.3 | 129.0 | 122.2 | 129.6 | 118.1 |
| April | 182.0 | 207.2 | 120.8 | 124.7 | 130.4 | 111.7 | 124.5 | 130.5 | 120.5 | 134.0 | 131.4 | 130.0 | 123.0 | 130.8 | 119.6 |
| May | 188.9 | 215.4 | 121.5 | 125.0 | 130.9 | 112.3 | 125.2 | 131.7 | 120.2 | 135.3 | 133.2 | 130.5 | 123.6 | 131.5 | 120.4 |
| June | 183.1 | 214.8 | 121.9 | 125.4 | 131.3 | 112.7 | 125.6 | 132.5 | 120.7 | 135.9 | 135.1 | 131.1 | 123.8 | 132.3 | 124.1 |
| July | 177.8 | 209.6 | 122.0 | 125.5 | 131.3 | 112.7 | 125.8 | 132.8 | 120.9 | 135.9 | 135.9 | 130.0 | 123.8 | 132.3 | 122.9 |
| August | 178.8 | 210.8 | 122.3 | 125.5 | 131.4 | 112.7 | 125.8 | 133.7 | 120.7 | 136.0 | 137.9 | 130.0 | 123.9 | 132.3 | 122.5 |
| September | 181.9 | 216.9 | 122.6 | 125.6 | 131.4 | 112.8 | 126.6 | 134.4 | 120.7 | 136.5 | 138.5 | 129.9 | 123.9 | 132.5 | 122.0 |
| October | 180.3 | 214.5 | 123.1 | 127.5 | 132.5 | 113.0 | 127.5 | 135.9 | 120.8 | 138.6 | 140.7 | 130.9 | 124.6 | 133.6 | 122.4 |
| November | 184.7 | 211.1 | 123.8 | 128.9 | 132.7 | 113.3 | 128.0 | 138.5 | 121.1 | 141.6 | 144.9 | 131.5 | 124.6 | 134.1 | 122.0 |
| December | 186.1 | 214.8 | 124.6 | 129.4 | 134.1 | 114.0 | 128.9 | 141.6 | 121.6 | 142.4 | 155.6 | 132.6 | 124.8 | 134.5 | 123.3 |
| 1974 January | 183.7 | 213.3 | 126.0 | 130.9 | 135.6 | 115.1 | 131.2 | 145.0 | 122.9 | 144.7 | 161.1 | 138.7 | 127.2 | 139.8 | 127.9 |
| February | 184.1 | 212.6 | 127.0 | 131.2 | 137.0 | 115.7 | 132.1 | 148.0 | 123.7 | 148.9 | 165.0 | 142.1 | 128.3 | 142.3 | 130.0 |
| March | 191.3 | 221.4 | 129.0 | 132.6 | 138.6 | 116.9 | 134.3 | 154.7 | 124.4 | 157.7 | 178.3 | 144.2 | 130.8 | 144.7 | 129.6 |
| April | 200.2 | 230.9 | 130.8 | 133.4 | 140.1 | 118.5 | 136.6 | 161.2 | 127.5 | 164.9 | 186.5 | 146.7 | 131.5 | 145.3 | 132.7 |
| May | 198.0 | 227.3 | 134.1 | 137.8 | 145.1 | 120.6 | 140.9 | 168.7 | 130.0 | 169.1 | 200.4 | 150.7 | 132.7 | 147.7 | 133.3 |
| June | 192.2 | 220.2 | 137.2 | 141.1 | 148.9 | 123.4 | 144.6 | 174.0 | 132.7 | 177.9 | 200.5 | 152.3 | 134.2 | 149.9 | 137.6 |
| July | 188.6 | 214.2 | 140.3 | 143.9 | 151.4 | 126.3 | 149.3 | 180.3 | 137.1 | 190.4 | 198.4 | 156.4 | 135.2 | 155.2 | 138.8 |
| August | 183.7 | 206.7 | 144.3 | 147.9 | 161.3 | 128.5 | 152.7 | 185.6 | 140.0 | 195.7 | 200.4 | 157.6 | 137.3 | 156.4 | 142.9 |
| September | 180.4 | 199.6 | 146.8 | 152.0 | 163.4 | 130.4 | 156.1 | 187.1 | 141.4 | 198.1 | 197.0 | 159.8 | 139.2 | 157.1 | 145.7 |
| October | 169.4 | 183.6 | 150.0 | 155.0 | 167.0 | 132.4 | 159.9 | 186.9 | 145.0 | 199.0 | 190.8 | 162.2 | 141.2 | 159.5 | 144.6 |
| November | 166.8 | 178.1 | 152.7 | 159.7 | 169.0 | 135.4 | 161.9 | 186.7 | 147.0 | 199.7 | 187.2 | 163.4 | 141.2 | 160.4 | 143.8 |
| December | 165.4 | 177.2 | 154.0 | 160.3 | 170.0 | 136.5 | 163.0 | 184.6 | 148.5 | 196.7 | 181.8 | 164.3 | 143.2 | 161.8 | 144.3 |
| 1975 January | 164.7 | 176.5 | 156.6 | 163.6 | 177.3 | 138.1 | 164.9 | 185.5 | 148.3 | 199.4 | 178.8 | 168.5 | 145.4 | 167.1 | 143.7 |
| February | 169.3 | 181.3 | 157.7 | 164.4 | 180.4 | 138.7 | 167.1 | 186.3 | 149.0 | 200.5 | 176.1 | 170.3 | 146.8 | 168.1 | 143.7 |
| March | 169.6 | 182.3 | 158.8 | 166.0 | 182.0 | 139.1 | 168.8 | 186.1 | 149.5 | 200.6 | 173.9 | 170.8 | 146.8 | 169.0 | 145.6 |
| April | 174.9 | 189.3 | 159.7 | 166.7 | 183.8 | 139.5 | 169.6 | 185.7 | 149.8 | 201.1 | 172.2 | 173.0 | 148.7 | 169.9 | 144.0 |
| May | 183.0 | 200.7 | 160.4 | 167.5 | 184.0 | 140.1 | 170.2 | 185.1 | 150.2 | 200.6 | 171.1 | 173.1 | 149.2 | 170.0 | 143.5 |
| June | 181.0 | 199.7 | 161.0 | 167.8 | 184.4 | 140.4 | 171.9 | 184.5 | 150.6 | 199.4 | 169.1 | 173.3 | 151.0 | 170.3 | 143.4 |
| July | 179.6 | 196.8 | 161.7 | 168.5 | 184.9 | 140.8 | 172.7 | 183.4 | 150.2 | 197.3 | 167.7 | 174.7 | 151.3 | 171.2 | 140.8 |
| August | 179.7 | 197.8 | 162.2 | 168.9 | 185.4 | 140.9 | 173.0 | 184.3 | 150.3 | 198.4 | 169.3 | 175.8 | 152.3 | 171.3 | 143.2 |
| September | 179.9 | 196.6 | 163.1 | 169.2 | 187.6 | 141.8 | 173.1 | 185.5 | 150.3 | 200.4 | 170.8 | 176.1 | 154.0 | 171.2 | 143.8 |
| October | 179.1 | 196.0 | 164.1 | 171.3 | 188.6 | 142.3 | 175.1 | 187.2 | 151.9 | 204.7 | 170.7 | 177.1 | 155.8 | 172.3 | 145.2 |
| November | 178.3 | 193.1 | 165.3 | 174.2 | 191.2 | 143.1 | 176.3 | 187.0 | 152.9 | 204.1 | 170.1 | 177.7 | 156.3 | 172.6 | 146.9 |
| December | 183.1 | 200.2 | 165.8 | 175.1 | 192.5 | 143.1 | 176.9 | 187.1 | 155.2 | 204.3 | 169.4 | 178.0 | 156.3 | 173.1 | 144.3 |
| 1976 January | 190.7 | 210.2 | 167.1 | 177.0 | 193.4 | 144.2 | 178.2 | 187.8 | 155.4 | 206.1 | 169.0 | 181.2 | 159.0 | 177.6 | 150.2 |
| February | 196.3 | 219.6 | 167.8 | 178.0 | 194.5 | 144.7 | 178.6 | 189.2 | 155.3 | 209.7 | 169.7 | 181.5 | 160.2 | 178.2 | 148.4 |
| March | 202.6 | 230.4 | 168.4 | 179.3 | 195.0 | 145.0 | 179.3 | 190.7 | 155.1 | 211.4 | 171.7 | 182.7 | 160.6 | 178.1 | 150.4 |
| April | 203.3 | 230.4 | 169.2 | 179.9 | 195.3 | 145.3 | 180.5 | 193.0 | 156.8 | 213.3 | 177.7 | 185.4 | 161.3 | 178.4 | 150.9 |
| May | 202.4 | 227.3 | 169.6 | 181.1 | 196.4 | 145.5 | 181.4 | 194.2 | 156.8 | 213.3 | 181.6 | 186.0 | 161.7 | 179.4 | 153.7 |
| June | 199.9 | 224.2 | 170.4 | 182.1 | 197.8 | 146.0 | 182.1 | 196.6 | 157.0 | 218.2 | 183.1 | 186.3 | 162.1 | 179.5 | 153.5 |
| July | 203.7 | 231.2 | 171.2 | 182.9 | 199.9 | 146.4 | 182.6 | 198.9 | 158.4 | 220.1 | 187.2 | 187.3 | 163.1 | 181.0 | 153.4 |
| August | 207.5 | 236.2 | 171.6 | 183.8 | 200.6 | 146.7 | 183.7 | 199.5 | 159.3 | 219.9 | 187.8 | 188.0 | 164.9 | 181.4 | 155.1 |
| September | 212.8 | 244.3 | 172.8 | 185.6 | 201.0 | 148.2 | 184.4 | 200.1 | 160.3 | 218.8 | 189.9 | 188.6 | 166.1 | 181.2 | 157.6 |
| October | 213.6 | 245.6 | 174.0 | 186.3 | 202.7 | 149.2 | 185.8 | 200.0 | 160.1 | 218.8 | 188.4 | 189.4 | 166.2 | 181.4 | 159.1 |
| November | 214.3 | 244.3 | 174.5 | 188.8 | 204.5 | 149.5 | 187.3 | 200.1 | 160.9 | 218.9 | 187.5 | 189.5 | 168.2 | 182.4 | 160.1 |
| December | 220.0 | 252.1 | 175.4 | 190.6 | 205.8 | 150.0 | 188.7 | 200.9 | 161.8 | 222.6 | 185.1 | 189.6 | 168.8 | 183.0 | 160.1 |

## COMMODITY PRICES--WHOLESALE PRICES--Con.

ELECTRIC
POWER

U S DEPARTMENT OF LABOR INDEXES [1]

Industrial commodities [2]

1947-1976

1967 = 100

| YEAR AND MONTH | Chemicals and allied products | | | | Fuels and related products, and power | | | | | Furniture and household durables | | | | Hides, skins, leather, and related products | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Chemicals industrial | Drugs and pharmaceuticals [3] | Fats and oils, inedible | Prepared paint | Total [4] | Coal | Electric power [5] | Gas fuels [5] | Petroleum products, refined | Total [4] | Appliances, household | Furniture, household | Home electronic equipment [6] | Total [4] | Footwear | Hides and skins | Leather |
| 1947 | 82.1 | 119.8 | 260.6 | 70.6 | 76.9 | 69.1 | | | 74.2 | 77.0 | 102.5 | 68.7 | 124.2 | 83.3 | 63.3 | 170.8 | 97.8 |
| 1948 | 87.2 | 114.9 | 236.8 | 71.8 | 90.5 | 83.3 | | | 92.8 | 81.6 | 107.5 | 74.0 | 129.2 | 84.2 | 67.6 | 159.8 | 93.2 |
| 1949 | 79.9 | 106.5 | 115.5 | 72.6 | 86.2 | 83.1 | | ... | 81.4 | 82.9 | 106.9 | 73.0 | 133.7 | 79.9 | 66.7 | 139.1 | 86.3 |
| 1950 | 84.0 | 105.2 | 140.3 | 71.2 | 87.1 | 83.3 | | | 85.1 | 84.7 | 107.6 | 75.6 | 124.9 | 86.3 | 70.2 | 161.4 | 98.8 |
| 1951 | 100.2 | 106.8 | 181.4 | 78.1 | 90.3 | 85.1 | | | 91.8 | 91.8 | 114.0 | 83.7 | 119.9 | 99.1 | 80.1 | 186.2 | 115.3 |
| 1952 | 95.6 | 105.2 | 102.2 | 79.1 | 90.1 | 85.4 | | | 90.6 | 90.1 | 113.4 | 81.2 | 119.7 | 80.1 | 74.0 | 98.6 | 82.7 |
| 1953 | 97.6 | 105.7 | 107.6 | 79.7 | 92.6 | 88.5 | | | 92.6 | 91.9 | 114.5 | 81.8 | ... | 81.3 | 73.7 | 106.9 | 86.3 |
| 1954 | 97.6 | 106.8 | 118.0 | 80.9 | 91.3 | 83.4 | | | 90.2 | 92.9 | 115.7 | 81.5 | ... | 77.6 | 73.7 | 86.5 | 78.8 |
| 1955 | 98.2 | 105.6 | 115.6 | 82.1 | 91.2 | 82.3 | | | 92.0 | 93.3 | 112.9 | 81.9 | 120.0 | 77.3 | 74.0 | 88.6 | 78.2 |
| 1956 | 100.8 | 104.8 | 114.8 | 86.0 | 94.0 | 89.8 | | | 97.2 | 95.8 | 111.4 | 85.6 | 120.1 | 81.9 | 78.7 | 92.6 | 84.4 |
| 1957 | 102.6 | 108.2 | 125.3 | 90.6 | 99.1 | 97.6 | | | 104.1 | 98.3 | 111.4 | 88.0 | 121.8 | 82.0 | 79.9 | 86.5 | 83.3 |
| 1958 | 102.6 | 106.9 | 127.9 | 91.9 | 95.3 | 96.5 | [5] 99.7 | [5] 76.1 | 94.9 | 99.1 | 110.6 | 88.4 | 121.7 | 82.9 | 80.5 | 90.0 | 86.3 |
| 1959 | 102.9 | 106.1 | 115.7 | 91.9 | 95.3 | 96.2 | 100.1 | 82.9 | 94.4 | 99.3 | 110.5 | 89.2 | 119.7 | 94.2 | 85.4 | 142.0 | 103.4 |
| 1960 | 103.2 | 106.6 | 100.2 | 92.1 | 96.1 | 95.6 | 101.2 | 87.2 | 96.5 | 99.0 | 107.5 | 90.0 | 117.8 | 90.8 | 87.6 | 106.7 | 93.8 |
| 1961 | 101.0 | 104.6 | 107.6 | 94.8 | 97.2 | 94.6 | 101.7 | 88.7 | 97.2 | 98.4 | 106.5 | 91.1 | 115.4 | 91.7 | 88.0 | 114.5 | 96.1 |
| 1962 | 98.9 | 102.1 | 93.8 | 95.0 | 96.7 | 93.7 | 102.1 | 89.2 | 96.1 | 97.7 | 104.2 | 91.9 | 110.3 | 92.7 | 88.9 | 112.7 | 98.4 |
| 1963 | 97.3 | 101.2 | 98.8 | 95.0 | 96.3 | 93.8 | 101.3 | 91.8 | 95.1 | 97.0 | 101.8 | 92.6 | 107.3 | 90.0 | 88.7 | 89.2 | 92.4 |
| 1964 | 98.7 | 101.1 | 119.1 | 95.8 | 93.7 | 93.6 | 100.4 | 90.7 | 90.7 | 97.4 | 101.2 | 93.3 | 106.6 | 90.3 | 88.9 | 92.9 | 93.3 |
| 1965 | 97.5 | 100.4 | 138.6 | 96.4 | 95.5 | 93.4 | 100.1 | 92.8 | 93.8 | 96.9 | 98.9 | 94.1 | 103.1 | 94.3 | 90.7 | 118.0 | 98.0 |
| 1966 | 98.3 | 100.5 | 126.4 | 97.7 | 97.8 | 95.6 | 99.6 | 96.7 | 97.4 | 98.0 | 98.8 | 96.6 | 101.2 | 103.4 | 96.8 | 149.5 | 109.8 |
| 1967 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1968 | 101.0 | 99.3 | 90.9 | 104.8 | 98.9 | 103.7 | 100.9 | 92.7 | 98.1 | 102.8 | 101.8 | 103.9 | 98.1 | 103.2 | 104.8 | 106.1 | 102.1 |
| 1969 | 100.3 | 99.9 | 109.1 | 109.1 | 100.9 | 112.6 | 101.8 | 93.3 | 99.6 | 104.9 | 102.9 | 108.4 | 94.6 | 108.9 | 109.5 | 124.1 | 108.7 |
| 1970 | 100.9 | 101.2 | 132.8 | 112.4 | 106.2 | 150.3 | 105.9 | 103.6 | 101.1 | 107.6 | 106.3 | 111.7 | 93.3 | 110.3 | 113.3 | 104.2 | 107.7 |
| 1971 | 102.0 | 102.4 | 133.5 | 115.6 | 114.2 | 181.8 | 113.6 | 108.0 | 106.8 | 109.9 | 107.2 | 114.8 | 93.8 | 114.0 | 116.8 | 115.1 | 112.5 |
| 1972 | 101.2 | 103.0 | 115.8 | 118.0 | 118.6 | 193.8 | 121.5 | 114.1 | 108.9 | 111.4 | 107.6 | 117.3 | 92.7 | 131.3 | 124.5 | 213.7 | 140.3 |
| 1973 | 103.4 | 104.3 | 228.3 | 122.2 | 134.3 | 218.1 | 129.3 | 126.7 | 128.7 | 115.2 | 108.5 | 123.0 | 91.9 | 143.1 | 130.5 | 253.9 | 160.1 |
| 1974 | 151.7 | 112.7 | 338.2 | 145.7 | 208.3 | 332.4 | 163.1 | 162.2 | 223.4 | 127.9 | 117.9 | 136.6 | 93.1 | 145.1 | 140.0 | 195.0 | 154.3 |
| 1975 | 206.9 | 126.6 | 255.2 | 166.9 | 245.1 | 385.8 | 193.4 | 216.7 | 257.6 | 139.7 | 132.3 | 146.3 | 93.5 | 148.5 | 147.8 | 174.5 | 151.5 |
| 1976 | 219.3 | 134.0 | 249.9 | 174.4 | 265.6 | 368.7 | 207.6 | 286.8 | 276.6 | 145.6 | 139.2 | 153.8 | 91.3 | 167.8 | 158.9 | 258.4 | 188.1 |
| 1973 January | 101.4 | 103.5 | 130.3 | 119.4 | 122.2 | 205.5 | 123.8 | 118.4 | 112.3 | 112.6 | 107.8 | 119.1 | 92.4 | 143.9 | 129.0 | 274.0 | 162.8 |
| February | 101.8 | 103.6 | 139.1 | 119.4 | 126.0 | 206.9 | 125.9 | 118.6 | 118.7 | 113.1 | 108.2 | 119.4 | 92.4 | 144.9 | 130.9 | 272.7 | 162.9 |
| March | 101.9 | 103.8 | 173.9 | 119.9 | 127.4 | 207.4 | 126.8 | 118.9 | 120.9 | 113.5 | 108.4 | 120.0 | 92.2 | 143.6 | 131.1 | 248.4 | 164.5 |
| April | 102.6 | 103.8 | 184.0 | 120.3 | 129.2 | 213.8 | 127.6 | 120.1 | 122.6 | 114.1 | 108.3 | 121.8 | 92.2 | 145.0 | 131.5 | 270.2 | 161.1 |
| May | 102.7 | 104.0 | 232.0 | 120.8 | 131.1 | 214.2 | 128.2 | 121.4 | 126.0 | 115.1 | 108.0 | 122.3 | 92.2 | 142.2 | 129.3 | 253.5 | 159.7 |
| June | 103.0 | 104.4 | 263.6 | 121.0 | 133.4 | 215.1 | 128.4 | 128.0 | 127.6 | 115.2 | 107.4 | 123.3 | 91.6 | 140.9 | 129.3 | 241.6 | 156.4 |
| July | 103.4 | 104.4 | 263.2 | 121.0 | 134.7 | 214.0 | 129.0 | 128.7 | 129.9 | 115.2 | 107.7 | 123.2 | 91.8 | 141.4 | 129.5 | 248.3 | 156.8 |
| August | 103.5 | 104.3 | 273.2 | 121.0 | 135.2 | 214.4 | 129.1 | 130.4 | 130.3 | 115.9 | 109.0 | 123.6 | 92.0 | 143.0 | 129.7 | 261.6 | 157.5 |
| September | 104.3 | 104.7 | 279.5 | 121.2 | 137.4 | 222.6 | 130.9 | 132.2 | 131.2 | 116.0 | 109.0 | 124.4 | 91.5 | 143.8 | 130.3 | 257.3 | 162.8 |
| October | 105.3 | 104.7 | 273.0 | 126.0 | 139.3 | 224.1 | 132.1 | 133.4 | 134.0 | 116.8 | 109.1 | 125.2 | 91.5 | 143.8 | 131.0 | 256.3 | 160.7 |
| November | 106.4 | 104.9 | 241.8 | 128.1 | 144.1 | 239.0 | 133.5 | 133.1 | 140.3 | 117.2 | 109.5 | 126.6 | 91.5 | 143.0 | 131.9 | 239.8 | 160.4 |
| December | 105.9 | 105.1 | 286.0 | 128.6 | 151.5 | 240.7 | 135.9 | 137.5 | 151.7 | 117.5 | 109.8 | 127.1 | 91.1 | 141.9 | 132.5 | 227.3 | 156.1 |
| 1974 January | 108.1 | 105.3 | 298.0 | 130.1 | 162.5 | 249.3 | 137.5 | 137.1 | 166.4 | 119.0 | 111.3 | 128.9 | 91.3 | 142.6 | 134.0 | 220.9 | 155.7 |
| February | 110.2 | 105.7 | 335.7 | 130.1 | 177.4 | 252.9 | 142.2 | 146.4 | 187.8 | 120.2 | 111.6 | 129.8 | 91.4 | 143.4 | 134.9 | 222.0 | 155.1 |
| March | 122.0 | 106.2 | 372.4 | 132.5 | 189.0 | 259.3 | 148.9 | 148.6 | 206.3 | 121.3 | 112.5 | 130.3 | 92.2 | 143.4 | 135.9 | 201.7 | 158.7 |
| April | 130.9 | 107.6 | 385.4 | 135.4 | 197.9 | 303.7 | 153.4 | 149.0 | 215.8 | 122.9 | 113.2 | 132.8 | 92.2 | 145.4 | 138.1 | 211.2 | 158.4 |
| May | 138.2 | 109.1 | 359.3 | 136.0 | 204.3 | 307.7 | 159.7 | 150.0 | 224.4 | 124.5 | 114.0 | 134.8 | 92.5 | 146.3 | 138.7 | 218.6 | 159.3 |
| June | 146.9 | 111.3 | 361.3 | 146.5 | 210.5 | 321.5 | 164.7 | 151.4 | 232.2 | 126.1 | 115.4 | 135.5 | 93.1 | 146.0 | 139.5 | 207.2 | 156.6 |
| July | 155.5 | 112.7 | 347.4 | 149.7 | 221.7 | 344.0 | 167.8 | 187.4 | 239.4 | 128.2 | 116.7 | 136.7 | 93.6 | 146.6 | 139.8 | 215.5 | 155.3 |
| August | 167.8 | 115.3 | 380.2 | 152.3 | 226.0 | 357.7 | 170.6 | 189.9 | 243.9 | 129.8 | 118.3 | 137.9 | 93.6 | 148.2 | 140.7 | 204.3 | 154.4 |
| September | 174.4 | 117.0 | 325.3 | 154.8 | 225.0 | 371.8 | 173.8 | 166.6 | 243.0 | 132.8 | 120.9 | 139.9 | 94.1 | 148.1 | 144.1 | 194.8 | 155.3 |
| October | 181.9 | 119.1 | 328.3 | 157.6 | 228.5 | 394.3 | 178.3 | 167.2 | 244.3 | 135.5 | 125.1 | 142.8 | 94.1 | 145.2 | 144.3 | 161.2 | 151.5 |
| November | 190.1 | 121.0 | 301.3 | 161.8 | 227.4 | 398.0 | 179.7 | 175.5 | 238.2 | 136.9 | 126.9 | 144.5 | 94.5 | 144.5 | 144.8 | 158.5 | 147.4 |
| December | 194.8 | 121.8 | 264.3 | 161.8 | 229.0 | 428.4 | 180.3 | 177.2 | 238.5 | 137.7 | 128.7 | 144.6 | 94.7 | 143.2 | 144.8 | 136.7 | 145.3 |
| 1975 January | 196.8 | 123.8 | 235.3 | 163.7 | 232.2 | 428.8 | 183.3 | 181.0 | 242.3 | 138.8 | 130.1 | 145.4 | 95.4 | 142.1 | 145.4 | 124.7 | 141.1 |
| February | 202.1 | 124.1 | 231.6 | 194.0 | 232.3 | 409.9 | 186.5 | 188.5 | 240.7 | 139.1 | 130.6 | 145.5 | 95.6 | 141.7 | 145.9 | 122.3 | 138.8 |
| March | 207.5 | 124.5 | 218.2 | 164.7 | 233.0 | 388.3 | 191.1 | 188.1 | 242.3 | 138.5 | 130.1 | 145.3 | 95.4 | 143.2 | 146.0 | 138.5 | 141.6 |
| April | 207.4 | 125.9 | 261.5 | 164.7 | 236.5 | 387.3 | 194.6 | 208.9 | 243.6 | 138.5 | 130.6 | 146.4 | 91.9 | 147.5 | 146.8 | 173.9 | 151.5 |
| May | 208.8 | 125.9 | 250.5 | 166.1 | 238.8 | 389.3 | 192.9 | 219.1 | 248.1 | 138.6 | 131.0 | 145.3 | 91.9 | 147.7 | 146.9 | 170.6 | 153.3 |
| June | 207.0 | 126.4 | 246.7 | 165.9 | 243.0 | 385.9 | 190.6 | 220.0 | 252.2 | 139.0 | 132.2 | 145.3 | 93.0 | 148.7 | 146.9 | 182.5 | 153.2 |
| July | 206.3 | 127.5 | 260.4 | 167.1 | 248.6 | 382.2 | 192.6 | 226.4 | 258.8 | 139.2 | 132.2 | 145.4 | 93.3 | 149.3 | 147.3 | 186.8 | 152.6 |
| August | 207.4 | 127.5 | 285.7 | 167.1 | 252.4 | 377.9 | 195.2 | 226.8 | 268.6 | 139.6 | 132.4 | 145.5 | 94.6 | 149.3 | 147.5 | 186.6 | 151.5 |
| September | 208.2 | 127.4 | 289.7 | 169.7 | 254.9 | 373.3 | 197.5 | 231.5 | 272.1 | 140.1 | 133.6 | 146.1 | 92.8 | 151.3 | 149.5 | 192.3 | 154.1 |
| October | 209.2 | 128.5 | 264.3 | 169.7 | 256.6 | 371.3 | 199.5 | 231.6 | 274.2 | 141.1 | 134.1 | 147.8 | 92.8 | 152.4 | 150.1 | 201.0 | 154.9 |
| November | 210.4 | 128.8 | 260.6 | 170.2 | 257.0 | 364.6 | 199.3 | 235.3 | 275.0 | 141.5 | 135.4 | 148.5 | 92.8 | 154.4 | 150.2 | 209.1 | 162.4 |
| December | 211.1 | 129.3 | 257.3 | 170.2 | 258.0 | 371.2 | 197.6 | 245.6 | 274.7 | 142.0 | 135.7 | 149.6 | 92.8 | 154.6 | 150.5 | 205.2 | 162.9 |
| 1976 January | 213.6 | 130.8 | 246.4 | 170.6 | 257.2 | 370.1 | 198.6 | 244.0 | 272.8 | 143.3 | 136.4 | 150.9 | 92.3 | 158.2 | 152.2 | 224.6 | 164.9 |
| February | 216.6 | 131.7 | 245.3 | 172.0 | 255.6 | 369.2 | 199.2 | 246.7 | 272.5 | 143.7 | 137.5 | 150.5 | 91.7 | 160.8 | 153.7 | 229.6 | 172.7 |
| March | 217.9 | 132.2 | 256.2 | 172.0 | 255.8 | 368.1 | 201.6 | 254.3 | 269.6 | 144.0 | 138.3 | 150.9 | 91.3 | 162.9 | 154.9 | 239.5 | 178.9 |
| April | 218.3 | 132.9 | 243.6 | 173.2 | 257.0 | 367.3 | 204.4 | 266.1 | 267.2 | 144.5 | 138.8 | 151.1 | 91.3 | 166.1 | 156.1 | 270.6 | 183.8 |
| May | 218.7 | 133.1 | 235.5 | 173.2 | 257.2 | 367.6 | 204.7 | 267.6 | 266.9 | 144.9 | 138.8 | 151.8 | 91.3 | 170.1 | 156.8 | 285.9 | 203.3 |
| June | 218.4 | 134.4 | 243.5 | 173.9 | 260.5 | 366.6 | 206.3 | 275.9 | 270.6 | 145.3 | 139.1 | 153.0 | 91.2 | 166.1 | 158.7 | 261.1 | 191.2 |
| July | 219.2 | 134.7 | 258.9 | 173.9 | 265.3 | 367.7 | 210.1 | 277.3 | 276.8 | 145.7 | 139.7 | 153.5 | 91.2 | 170.3 | 160.7 | 278.6 | 192.2 |
| August | 221.2 | 135.2 | 249.4 | 175.7 | 269.2 | 367.8 | 213.6 | 286.6 | 280.7 | 146.1 | 140.0 | 153.9 | 91.2 | 171.6 | 161.2 | 264.8 | 196.3 |
| September | 221.7 | 135.4 | 262.9 | 176.2 | 271.2 | 368.0 | 214.5 | 289.5 | 283.7 | 146.7 | 140.2 | 155.0 | 91.2 | 173.6 | 162.5 | 292.1 | 197.5 |
| October | 222.2 | 135.4 | 251.2 | 176.9 | 277.1 | 368.4 | 213.2 | 330.9 | 285.0 | 147.2 | 140.4 | 156.5 | 91.3 | 170.9 | 162.6 | 251.4 | 193.1 |
| November | 222.6 | 135.9 | 251.2 | 177.3 | 281.6 | 369.1 | 214.0 | 365.0 | 285.8 | 147.5 | 140.6 | 157.5 | 91.0 | 169.8 | 162.9 | 231.8 | 191.4 |
| December | 221.5 | 136.4 | 254.6 | 177.3 | 279.0 | 374.0 | 211.5 | 337.6 | 287.6 | 147.9 | 141.0 | 158.6 | 90.9 | 171.5 | 163.8 | 251.2 | 191.7 |

## COMMODITY PRICES—Continued

| Unless otherwise stated in footnotes below, data through 1974 and descriptive notes are as shown in the 1975 edition of BUSINESS STATISTICS | 1976 | 1977 | 1977 | | | | | | | | | | | | 1978 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Annual | | Jan | Feb. | Mar. | Apr | May | June | July | Aug. | Sept. | Oct | Nov. | Dec. | Jan. | Feb. |
| **WHOLESALE PRICES♂—Continued** *(U.S. Department of Labor Indexes)*—Continued | | | | | | | | | | | | | | | | |
| All commodities—Continued | | | | | | | | | | | | | | | | |
| Farm prod., processed foods and feeds 1967=100 | 183.1 | ...... | 184.8 | 188.4 | 190.9 | 195.9 | 196.8 | 191.5 | 189.3 | 184.2 | 183.9 | 184.2 | 186.8 | 189.5 | 192.1 | 196.6 |
| Farm products♀ do | 191.0 | ...... | 193.5 | 199.1 | 202.5 | 208.2 | 204.3 | 192.7 | 190.5 | 181.2 | 181.9 | 182.4 | 185.5 | 188.3 | 192.2 | 198.9 |
| Fruits and vegetables, fresh and dried do | 178.4 | ...... | 198.5 | 212.7 | 219.2 | 205.7 | 201.8 | 176.2 | 182.0 | 176.4 | 182.8 | 187.9 | 192.9 | 170.1 | 197.1 | 204.6 |
| Grains do | 205.9 | ...... | 184.9 | 185.8 | 183.4 | 184.4 | 171.2 | 157.7 | 153.3 | 142.5 | 144.2 | 144.7 | 164.6 | 167.3 | 169.1 | 170.8 |
| Live poultry do | 166.9 | ...... | 153.7 | 183.7 | 177.2 | 182.3 | 183.1 | 182.7 | 193.7 | 176.1 | 181.7 | 170.5 | 162.7 | 157.8 | 170.2 | 188.8 |
| Livestock do | 173.3 | ...... | 166.0 | 166.2 | 163.5 | 167.9 | 180.2 | 172.3 | 180.5 | 175.2 | 172.9 | 177.5 | 171.6 | 182.7 | 188.2 | 202.1 |
| Foods and feeds, processed♀ do | 178.0 | ...... | 179.3 | 181.9 | 183.9 | 188.5 | 191.9 | 190.1 | 187.8 | 185.1 | 184.2 | 184.5 | 186.7 | 189.3 | 191.3 | 194.6 |
| Beverages and beverage materials do | 173.5 | ...... | 184.1 | 189.3 | 199.6 | 202.1 | 206.0 | 207.7 | 204.7 | 205.5 | 204.8 | 204.3 | 200.6 | 201.3 | 201.9 | 201.1 |
| Cereal and bakery products do | 172.1 | ...... | 168.4 | 169.9 | 171.5 | 171.6 | 172.0 | 171.3 | 172.0 | 172.1 | 172.8 | 175.4 | 179.7 | 182.0 | 183.6 | 184.7 |
| Dairy products do | 168.5 | ...... | 166.8 | 166.9 | 168.0 | 173.5 | 174.2 | 174.3 | 175.1 | 175.3 | 175.7 | 175.9 | 176.9 | 178.2 | 178.0 | 178.7 |
| Fruits and vegetables, processed do | 170.2 | ...... | 175.4 | 182.9 | 184.0 | 185.2 | 185.8 | 187.8 | 188.5 | 190.1 | 191.2 | 190.3 | 193.0 | 194.4 | 194.4 | 194.6 |
| Meats, poultry, and fish do | 181.6 | ...... | 176.6 | 177.4 | 174.2 | 174.9 | 183.8 | 183.4 | 189.5 | 182.7 | 182.7 | 184.7 | 183.4 | 190.8 | 193.6 | 204.7 |
| Industrial commodities do | 182.4 | ...... | 188.4 | r 190.1 | 191.7 | 193.3 | 194.2 | 194.6 | 195.8 | 196.9 | 197.8 | 199.1 | 199.2 | 200.0 | 201.5 | 202.8 |
| Chemicals and allied products♀ do | 187.2 | ...... | 188.9 | 190.1 | 191.2 | 192.9 | 194.0 | 193.9 | 193.5 | 193.5 | 193.2 | 193.5 | 193.8 | 193.9 | 194.0 | 195.2 |
| Agric. chemicals and chem. prod do | 188.3 | ...... | 182.2 | 183.5 | 187.1 | 189.0 | 187.7 | 189.0 | 188.4 | 188.9 | 189.9 | 190.0 | 188.1 | 186.9 | 187.3 | 188.9 |
| Chemicals, industrial do | 219.3 | ...... | 222.1 | 222.9 | 222.4 | 223.5 | 224.0 | 224.1 | 224.4 | 224.7 | 224.2 | 224.7 | 224.9 | 225.2 | 224.2 | 224.4 |
| Drugs and pharmaceuticals do | 134.0 | ...... | 137.5 | 138.4 | 139.0 | 139.6 | 139.7 | 140.8 | 141.2 | 141.2 | 141.4 | 141.8 | 142.2 | 142.9 | 144.1 | 144.9 |
| Fats and oils, inedible do | 249.9 | ...... | 253.9 | 253.9 | 273.7 | 304.9 | 337.5 | 318.8 | 281.9 | 268.9 | 246.9 | 260.9 | 265.4 | 266.1 | 263.2 | 281.5 |
| Prepared paint do | 171.4 | ...... | 177.3 | 177.3 | 178.9 | 180.6 | 181.7 | 182.3 | 183.0 | 183.9 | 185.1 | 185.1 | 186.7 | 185.0 | 186.1 | 188.5 |
| Fuels and related prod., and power♀ do | 265.6 | ...... | 278.8 | 289.1 | 293.7 | 298.8 | 302.4 | 304.0 | 306.6 | 309.5 | 309.7 | 310.6 | 310.4 | 311.9 | 312.8 | 312.9 |
| Coal do | 368.7 | ...... | 376.3 | 377.5 | 378.8 | 379.8 | 386.9 | 390.6 | 393.0 | 394.5 | 395.2 | 397.8 | 400.1 | 402.2 | 404.1 | 405.1 |
| ➡Electric power do | 207.6 | ...... | 214.0 | 219.8 | 223.4 | 229.4 | 230.7 | 234.4 | 239.2 | 244.7 | 242.7 | 242.6 | 237.8 | 237.2 | 239.7 | 242.8 |
| Gas fuels do | 286.8 | ...... | 322.2 | 363.7 | 370.9 | 379.0 | 390.2 | 396.6 | 391.9 | 400.9 | 405.4 | 407.0 | 414.1 | 422.4 | 420.5 | 417.9 |
| Petroleum products, refined do | 276.6 | ...... | 289.2 | 295.1 | 301.9 | 306.8 | 310.1 | 311.6 | 312.9 | 313.0 | 312.8 | 313.8 | 313.4 | 313.7 | 314.1 | 312.8 |
| Furniture and household durables♀ do | 145.6 | ...... | 148.8 | 149.1 | 149.6 | 150.1 | 150.6 | 151.3 | 151.2 | 152.4 | 152.5 | 153.0 | 153.6 | 154.0 | 155.6 | 156.3 |
| Appliances, household do | 139.2 | ...... | 141.2 | 142.1 | 142.9 | 143.3 | 143.2 | 144.5 | 145.4 | 146.2 | 147.1 | 147.4 | 147.5 | 147.6 | 149.1 | 149.4 |
| Furniture, household do | 153.6 | ...... | 158.7 | 158.9 | 159.7 | 160.7 | 161.1 | 162.2 | 162.8 | 163.1 | 163.1 | 164.1 | 165.1 | 166.4 | 168.2 | 168.8 |
| Home electronic equipment do | 91.3 | ...... | 89.6 | 89.3 | 89.4 | 88.3 | 88.4 | 88.3 | 86.8 | 86.8 | 86.3 | 86.3 | 86.4 | 86.4 | 86.8 | 88.1 |
| Hides, skins, and leather products♀ do | 167.8 | ...... | 175.3 | 176.9 | 177.9 | 179.9 | 181.9 | 179.7 | 180.3 | 180.5 | 179.9 | 179.6 | 180.3 | 181.8 | 186.1 | 187.5 |
| Footwear do | 158.9 | ...... | 164.5 | 165.9 | 166.4 | 167.2 | 168.2 | 168.6 | 170.3 | 170.4 | 170.5 | 171.7 | 172.0 | 172.1 | 173.8 | 176.2 |
| Hides and skins do | 258.4 | ...... | 278.9 | 282.5 | 285.9 | 305.0 | 313.0 | 288.8 | 291.5 | 288.3 | 274.4 | 268.3 | 273.2 | 291.9 | 300.4 | 298.2 |
| Leather do | 188.1 | ...... | 192.9 | 201.3 | 201.4 | 204.1 | 210.7 | 202.1 | 198.6 | 200.3 | 200.5 | 196.4 | 197.0 | 200.4 | 210.8 | 211.9 |
| Lumber and wood products do | 205.6 | ...... | 222.8 | 221.4 | 229.0 | 229.8 | 229.5 | 228.7 | 235.5 | 242.7 | 252.4 | 247.3 | 243.2 | 249.1 | 256.3 | 263.7 |
| Lumber do | 233.0 | ...... | 257.8 | 259.3 | 266.4 | 268.8 | 267.8 | 264.6 | 275.9 | 286.4 | 301.3 | 292.4 | 284.8 | 291.0 | 300.4 | 308.5 |
| Machinery and equipment♀ do | 171.0 | ...... | 176.7 | 177.5 | 178.2 | 178.9 | 180.0 | 180.8 | 181.9 | 182.8 | 183.9 | 185.7 | 186.7 | 187.3 | 189.1 | 190.1 |
| Agricultural machinery and equip do | 183.0 | ...... | 192.3 | 193.1 | 194.5 | 194.8 | 195.1 | 196.0 | 196.6 | 198.4 | 200.4 | 201.4 | 209.1 | 205.2 | 205.9 | 207.2 |
| Construction machinery and equip do | 198.9 | ...... | 208.8 | 209.1 | 208.3 | 210.2 | 213.0 | 213.2 | 214.9 | 215.8 | 215.7 | 218.3 | 221.4 | 221.8 | 222.6 | 224.0 |
| ➡Electrical machinery and equip do | 146.7 | ...... | 151.3 | 151.1 | 152.0 | 151.9 | 152.7 | 153.0 | 154.1 | 154.6 | 155.8 | 157.3 | 157.8 | 157.9 | 160.0 | 160.5 |
| Metalworking machinery and equip do | 182.7 | ...... | 190.9 | 192.[illegible] | 193.7 | 194.7 | 195.7 | 197.9 | 199.2 | 200.6 | 201.7 | 203.6 | 204.9 | 205.8 | 208.1 | 209.2 |
| Metals and metal products♀ do | 195.9 | ...... | 202.1 | 203.2 | 206.5 | 208.[illegible] | 208.5 | 207.8 | 210.7 | 211.7 | 212.6 | 211.8 | 212.0 | 213.3 | 216.2 | 219.1 |
| Heating equipment do | 158.0 | ...... | 162.9 | 163.1 | 163.7 | 163.5 | 164.0 | 164.5 | 165.4 | 166.0 | 166.5 | 168.0 | 168.3 | 169.3 | 171.0 | 170.4 |
| Iron and steel do | 217.9 | ...... | 224.2 | 221.7 | 227.4 | 228.3 | 227.9 | 226.9 | 231.1 | 233.1 | 235.7 | 234.2 | 233.4 | 235.5 | 237.7 | 244.6 |
| Nonferrous metals do | 181.6 | ...... | 185.3 | 188.3 | 195.8 | 200.1 | 200.9 | 197.3 | 198.0 | 198.5 | 195.1 | 193.5 | 194.2 | 195.1 | 198.0 | 199.7 |
| Nonmetallic mineral products♀ do | 186.3 | ...... | 192.4 | 193.6 | 195.1 | 198.6 | 199.3 | 200.4 | 201.5 | 202.4 | 204.2 | 205.3 | 205.6 | 206.5 | 212.7 | 215.0 |
| Clay prod., structural, excl. refrac do | 163.5 | ...... | 170.1 | 167.8 | 170.7 | 177.5 | 174.2 | 180.2 | 183.8 | 184.5 | 185.7 | 187.8 | 185.1 | 185.5 | 189.6 | 191.3 |
| Concrete products do | 180.1 | ...... | 187.0 | 187.8 | 188.4 | 189.9 | 190.5 | 190.9 | 192.8 | 193.5 | 194.0 | 195.0 | 195.4 | 195.7 | 202.7 | 205.2 |
| Gypsum products do | 154.4 | ...... | 160.8 | 160.8 | 164.0 | 172.2 | 175.9 | 187.1 | 186.6 | 189.8 | 193.7 | 201.6 | 203.2 | 204.9 | 209.7 | 215.9 |
| Pulp, paper, and allied products do | 179.4 | ...... | 182.9 | 184.0 | 183.6 | 185.3 | 186.2 | 187.3 | 187.7 | 187.8 | 188.5 | 188.8 | 188.3 | 187.6 | 188.2 | 186.7 |
| Paper do | 182.3 | ...... | 188.9 | 189.1 | 192.0 | 193.3 | 194.1 | 194.3 | 195.6 | 196.2 | 196.3 | 197.1 | 197.5 | 197.1 | 197.8 | 198.3 |
| Rubber and plastics products do | 159.2 | ...... | 164.6 | 164.2 | 164.6 | 165.7 | 166.3 | 167.4 | 168.9 | 169.1 | 169.4 | 170.0 | 170.0 | 169.8 | 169.9 | 170.2 |
| Tires and tubes do | 161.5 | ...... | 170.0 | 163.6 | 165.6 | 169.9 | 167.8 | 167.8 | 171.3 | 171.1 | 171.1 | 171.9 | 171.6 | 171.9 | 172.1 | 170.8 |
| Textile products and apparel § do | 148.2 | ...... | 150.8 | 151.7 | 152.4 | 153.7 | 154.0 | 154.4 | 154.4 | 154.4 | 155.1 | 155.2 | 155.3 | 155.9 | 156.4 | 157.0 |
| Synthetic fibers Dec. 1975=100 | 102.4 | ...... | 102.6 | 103.4 | 103.2 | 106.4 | 107.0 | 109.5 | 109.2 | 109.6 | 109.6 | 109.5 | 109.6 | 109.6 | 110.3 | 110.5 |
| Processed yarns and threads do | 99.5 | ...... | 96.6 | 97.2 | 98.7 | 101.5 | 102.3 | 103.4 | 103.4 | 103.0 | 102.1 | 101.2 | 100.4 | 100.6 | 100.6 | 101.0 |
| Gray fabrics do | 106.1 | ...... | 105.1 | 103.8 | 104.5 | 105.0 | 105.1 | 104.5 | 104.9 | 103.3 | 103.0 | 103.7 | 106.2 | 107.2 | 108.9 | 109.9 |
| Finished fabrics do | 101.1 | ...... | 100.4 | 101.2 | 103.0 | 101.3 | 104.9 | 104.5 | 101.3 | 104.2 | 104.2 | 104.1 | 103.3 | 103.4 | 103.4 | 103.5 |
| Apparel 1967=100 | 139.9 | ...... | 144.8 | 145.6 | 146.0 | 146.5 | 146.6 | 147.2 | 147.2 | 147.4 | 148.4 | 148.6 | 149.1 | 149.4 | 149.8 | 148.8 |
| Textile house furnishings do | 159.3 | ...... | 165.5 | 167.1 | 170.4 | 170.4 | 169.7 | 169.7 | 169.7 | 171.2 | 174.7 | 175.6 | 175.6 | 175.7 | 175.7 | 176.2 |
| Transportation equipment♀ Dec. 1968=100 | 151.1 | ...... | 157.1 | 157.2 | 158.4 | 158.7 | 159.1 | 159.4 | 159.5 | 160.6 | 161.4 | 167.9 | 168.0 | 168.3 | 169.0 | 169.4 |
| Motor vehicles and equip 1967=100 | 153.8 | ...... | 159.2 | 159.4 | 160.7 | 161.0 | 161.4 | 161.8 | 161.8 | 163.1 | 163.8 | 170.8 | 170.6 | 170.9 | 171.3 | 171.7 |
| **Seasonally Adjusted‡** | | | | | | | | | | | | | | | | |
| All commodities, percent change from previous month | ...... | ...... | 0.5 | 1.1 | 1.1 | 1.0 | 0.4 | −0.5 | 0.1 | 0.2 | 0.3 | 0.6 | 0.7 | 0.4 | • 0.9 | 1.0 |
| By stage of processing: | | | | | | | | | | | | | | | | |
| Crude materials for further processing 1967=100 | ...... | ...... | 210.2 | 219.0 | 221.0 | 225.5 | 222.3 | 213.4 | 209.8 | 205.9 | 205.7 | 207.7 | 214.4 | 217.2 | • 221.6 | 228.7 |
| Intermediate materials, supplies, etc do | ...... | ...... | 195.7 | 197.3 | 199.3 | 201.1 | 202.0 | 201.6 | 202.2 | 202.6 | 203.5 | 204.3 | 205.2 | 205.9 | • 207.8 | 209.7 |
| Finished goods: | | | | | | | | | | | | | | | | |
| Consumer finished goods do | ...... | ...... | 173.0 | 175.2 | 176.8 | 178.1 | 179.6 | 179.5 | 179.5 | 179.7 | 180.2 | 180.8 | 181.9 | 182.7 | • 184.0 | 186.3 |
| Food do | ...... | ...... | 181.3 | 185.9 | 188.3 | 189.6 | 192.2 | 190.3 | 189.9 | 189.4 | 188.9 | 189.4 | 191.7 | 192.6 | • 194.7 | 200.4 |
| Finished goods, exc. foods do | ...... | ...... | 167.2 | 168.1 | 169.2 | 170.7 | 171.5 | 172.4 | 172.6 | 173.0 | 174.2 | 174.8 | 175.4 | 176.0 | • 176.9 | 177.5 |
| Durable do | ...... | ...... | 148.0 | 148.7 | 149.4 | 150.6 | 151.3 | 151.9 | 152.4 | 153.6 | 153.9 | 154.9 | 155.4 | 156.0 | • 157.1 | 157.6 |
| Nondurable do | ...... | ...... | 180.0 | 181.2 | 182.7 | 181.2 | 185.2 | 186.1 | 186.2 | 186.1 | 187.6 | 188.0 | 188.7 | 189.5 | • 190.2 | 190.8 |
| Producer finished goods do | ...... | ...... | 178.9 | 179.9 | 180.7 | 181.7 | 182.8 | 183.7 | 184.5 | 185.5 | 186.4 | 188.9 | 189.9 | 191.1 | • 192.0 | 193.3 |
| By durability of product: | | | | | | | | | | | | | | | | |
| Total manufactures do | ...... | ...... | 184.4 | 186.0 | 187.5 | 189.3 | 190.4 | 190.4 | 190.5 | 190.9 | 191.5 | 192.3 | 193.7 | 194.7 | • 196.2 | 198.3 |
| Durable manufactures do | ...... | ...... | 182.3 | 183.1 | 184.5 | 185.4 | 186.2 | 186.5 | 188.3 | 189.5 | 191.1 | 192.2 | 193.2 | 194.2 | • 196.2 | 197.9 |
| Nondurable manufactures do | ...... | ...... | 186.0 | 188.5 | 190.2 | 192.8 | 194.9 | 193.7 | 192.2 | 191.5 | 191.4 | 192.0 | 193.5 | 194.4 | • 195.7 | 198.0 |
| Farm products do | ...... | ...... | 193.0 | 197.1 | 203.5 | 208.8 | 203.4 | 192.3 | 188.0 | 181.8 | 181.1 | 183.5 | 189.2 | 188.7 | • 192.0 | 197.4 |
| Processed foods and feeds do | ...... | ...... | 178.8 | 182.3 | 185.5 | 189.1 | 192.2 | 189.2 | 184.7 | 184.7 | 183.6 | 184.8 | 188.1 | 189.3 | 190.8 | 195.2 |
| **PURCHASING POWER OF THE DOLLAR** | | | | | | | | | | | | | | | | |
| As measured by— | | | | | | | | | | | | | | | | |
| Wholesale prices 1967=$1.00 | $0.546 | ...... | $0.532 | $0.526 | $0.521 | $0.515 | $0.512 | $0.514 | $0.513 | $0.514 | $0.512 | $0.509 | $0.508 | $0.505 | $0.500 | $0.495 |
| Consumer prices do | .587 | .551 | .570 | .565 | .561 | .557 | .551 | .550 | .548 | .546 | .543 | .542 | .539 | .537 | [6] .534 | .531 |

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r Revised. • See note "‡" for this page. ♂ See corresponding note on p. S-8. ♀ Includes data for items not shown separately. § Effective with Jan. 1976 reporting, the textile products group has been extensively reclassified, no comparable data for earlier periods are available for the newly introduced indexes. ‡ Beginning in the February 1978 SURVEY, data have been revised (back to 1973) to reflect new seasonal factors. [6] Beginning Jan. 1978, based on CPI-U, see note "¶" for p. S-8.

## COMMODITY PRICES—Continued

| Unless otherwise stated in footnotes below, data through 1976 and descriptive notes are as shown in the 1977 edition of BUSINESS STATISTICS | | 1978 | 1979 | 1979 | | | | | | | | | | 1980 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Annual | | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
| **PRODUCER PRICES §** *(U S Department of Labor Indexes)* | | | | | | | | | | | | | | | | | |
| **Not Seasonally Adjusted** | | | | | | | | | | | | | | | | | |
| Spot market prices, basic commodities | | | | | | | | | | | | | | | | | |
| 22 Commodities | 1967 = 100 | r234.1 | | 277.4 | 276.3 | 277.1 | 278.1 | 281.2 | 279.5 | 281.1 | 283.8 | 281.0 | 286.2 | 287.1 | 294.1 | 285.3 | 272.5 |
| 9 Foodstuffs | do. | r239.2 | | 261.8 | 251.8 | 254.4 | 256.5 | 259.3 | 254.3 | 259.1 | 252.3 | 250.7 | 255.4 | 249.5 | 257.2 | 245.0 | 235.0 |
| 13 Raw industrials | do | r230.6 | | 288.5 | 294.5 | 293.8 | 293.9 | 297.3 | 298.1 | 297.3 | 307.7 | 304.0 | 309.6 | 316.2 | 322.5 | 316.9 | 301.9 |
| All commodities | do | 209.3 | | 226.7 | 230.0 | 232.0 | 233.5 | 236.9 | 238.3 | 242.0 | 245.6 | 247.2 | r249.7 | 254.7 | 259.8 | 261.5 | 262.3 |
| By stage of processing | | | | | | | | | | | | | | | | | |
| Crude materials for further processing | do | 240.1 | | 276.6 | 279.9 | 282.3 | 283.0 | 287.1 | 281.7 | 288.3 | 289.5 | 290.8 | r296.2 | 296.9 | 308.3 | 303.3 | 296.9 |
| Intermediate materials, supplies, etc | do | 215.5 | | 231.5 | 235.8 | 238.2 | 240.3 | 244.6 | 247.5 | 251.0 | 255.0 | 256.3 | r258.7 | 265.6 | 271.1 | 273.2 | 274.5 |
| Finished goods # | do | 194.6 | | 209.1 | 211.4 | 212.7 | 213.7 | 216.2 | 217.3 | 220.7 | 224.2 | 226.3 | r228.1 | 232.1 | 235.4 | 238.2 | 240.0 |
| Finished consumer goods | do | 192.6 | | 207.9 | 210.2 | 211.6 | 212.7 | 215.6 | 217.5 | 221.7 | 224.7 | 227.1 | r229.1 | 233.2 | 237.3 | 240.6 | 241.6 |
| Capital equipment | do | 199.1 | | 211.7 | 214.0 | 215.1 | 215.8 | 217.2 | 216.5 | 217.8 | 222.8 | 223.9 | r225.3 | 229.1 | 230.3 | 231.8 | 235.8 |
| By durability of product | | | | | | | | | | | | | | | | | |
| Durable goods | do | 204.9 | | 221.0 | 223.9 | 224.7 | 225.8 | 227.6 | 228.0 | 230.1 | 234.6 | 235.3 | r237.0 | 243.4 | 246.4 | 246.6 | 247.2 |
| Nondurable goods | do | 211.9 | | r230.4 | 234.1 | 236.9 | 238.8 | 243.7 | 245.8 | 251.1 | 253.7 | 256.2 | r259.3 | 263.0 | 270.0 | 273.1 | 274.0 |
| Total manufactures | do | 204.2 | | 219.7 | 223.1 | 225.0 | 226.5 | 229.8 | 231.7 | 235.2 | 239.0 | 240.6 | r242.6 | 248.2 | 252.7 | 254.8 | 256.5 |
| Durable manufactures | do | 204.7 | | 219.8 | 222.7 | 223.8 | 224.6 | 226.6 | 227.2 | 229.4 | 234.0 | 234.6 | r236.2 | 242.4 | 245.0 | 245.2 | 246.2 |
| Nondurable manufactures | do | 203.0 | | 219.0 | 222.8 | 225.6 | 227.8 | 232.5 | 235.9 | 241.0 | 244.0 | 246.6 | r249.0 | 253.8 | 260.7 | 264.7 | 267.3 |
| Farm prod, processed foods and feeds | do | 206.6 | | 229.0 | 231.2 | 230.8 | 229.0 | 232.2 | 227.5 | 231.8 | 230.6 | 232.3 | r234.6 | 231.9 | 236.9 | 234.9 | 229.2 |
| Farm products # | do | 212.5 | | 242.8 | 246.0 | 245.4 | 242.8 | 246.8 | 238.5 | 241.0 | 239.6 | 240.2 | 242.5 | 236.4 | 242.3 | 239.3 | 228.9 |
| Fruits and vegetables, fresh and dried | do | 216.5 | | 235.7 | 239.1 | 228.2 | 226.4 | 226.7 | 241.7 | 208.3 | 218.0 | 216.5 | r210.7 | 218.9 | 220.5 | 218.3 | 223.0 |
| Grains | do | 182.5 | | 192.0 | 198.3 | 210.3 | 218.7 | 247.4 | 229.1 | 224.4 | 229.0 | 226.6 | 227.9 | 214.6 | 223.3 | 217.9 | 210.8 |
| Live poultry | do | 199.8 | | 217.6 | 209.4 | 216.3 | 182.9 | 183.8 | 171.9 | 173.5 | 162.0 | 195.5 | 194.7 | 195.2 | 184.6 | 180.1 | 171.9 |
| Livestock | do | 220.1 | | 275.8 | 284.0 | 280.7 | 264.0 | 256.0 | 240.2 | 256.4 | 251.7 | 246.3 | 252.5 | 247.8 | 257.2 | 251.8 | 230.5 |
| Foods and feeds, processed # | do | 202.6 | | 220.5 | 222.3 | 222.0 | 220.6 | 223.3 | 220.5 | 225.8 | 224.8 | 227.1 | r229.3 | 228.5 | 233.1 | 231.5 | 228.5 |
| Beverages and beverage materials | do | 200.0 | | 201.2 | 201.5 | 205.3 | 208.5 | 214.1 | 216.5 | 217.9 | 218.9 | 221.2 | r221.6 | 224.1 | 224.7 | 226.0 | 227.9 |
| Cereal and bakery products | do. | 190.3 | | 200.1 | 203.0 | 204.9 | 206.3 | 212.4 | 216.0 | 218.7 | 219.8 | 222.5 | r223.6 | 225.4 | 229.7 | 231.3 | 231.5 |
| Dairy products | do | 188.4 | | 204.9 | 207.1 | 207.9 | 208.4 | 209.0 | 215.2 | 218.3 | 218.1 | 219.3 | r219.9 | 221.4 | 221.2 | 223.3 | 227.8 |
| Fruits and vegetables, processed | do | 202.6 | | 219.6 | 220.5 | 221.4 | 221.5 | 223.6 | 224.6 | 225.1 | 223.4 | 222.4 | r222.6 | 222.8 | 223.1 | 223.6 | 224.5 |
| Meats, poultry, and fish | do | 217.1 | | 250.6 | 253.0 | 250.4 | 241.4 | 237.7 | 225.5 | 239.9 | 234.2 | 239.3 | 242.8 | 239.5 | 239.5 | 239.2 | 226.0 |
| Industrial commodities | do | 209.4 | | 225.4 | 229.0 | 231.6 | 234.0 | 237.5 | 240.6 | 244.2 | 249.0 | 250.6 | r253.1 | 260.3 | 265.4 | 268.2 | 270.7 |
| Chemicals and allied products # | do | 198.8 | | 209.9 | 215.1 | 218.0 | 219.2 | 225.0 | 228.5 | 230.8 | 234.2 | 236.0 | r238.2 | 245.5 | 247.6 | 251.6 | 258.1 |
| Agric chemicals and chem prod | do | 198.4 | | 206.3 | 209.8 | 210.0 | 209.2 | 211.2 | 215.3 | 219.4 | 224.3 | 229.5 | r232.9 | 238.1 | 242.8 | 256.0 | 256.3 |
| Chemicals, industrial | do | 225.6 | | 239.7 | 248.2 | 255.6 | 259.3 | 270.4 | 277.1 | 280.0 | 285.7 | 288.4 | r292.3 | 302.6 | 306.7 | 310.7 | 316.8 |
| Drugs and pharmaceuticals | do | 148.1 | | 156.6 | 157.5 | 157.7 | 159.0 | 159.2 | 159.6 | 161.0 | 162.8 | 163.0 | 164.4 | 166.5 | 167.7 | 168.9 | 172.8 |
| Fats and oils, inedible | do | 315.8 | | 398.5 | 448.7 | 418.3 | 374.1 | 381.6 | 376.4 | 379.9 | 366.9 | 344.3 | 327.1 | 325.6 | 302.2 | 299.9 | 296.2 |
| Prepared paint | do | 192.3 | | 202.3 | 203.3 | 201.3 | 201.3 | 205.3 | 205.3 | 208.0 | 206.7 | 209.4 | 210.7 | 223.3 | 223.3 | 223.3 | 231.5 |
| Fuels and related prod, and power # | do | 322.5 | | 350.9 | 361.5 | 377.6 | 393.7 | 411.8 | 432.8 | 454.8 | 468.5 | 476.9 | r487.9 | 507.8 | 533.0 | 553.5 | 566.3 |
| Coal | do | 430.0 | | 445.3 | 447.1 | 450.8 | 452.0 | 452.5 | 454.2 | 452.5 | 454.6 | 455.1 | r458.6 | 458.1 | 458.7 | 460.7 | 463.3 |
| Electric power | do | 250.6 | | 257.3 | 260.6 | 265.9 | 269.9 | 274.8 | 278.8 | 280.5 | 283.5 | 281.9 | r237.0 | 290.7 | 299.5 | 305.7 | 310.4 |
| Gas fuels | do | 428.7 | | 471.0 | 477.4 | 507.2 | 522.3 | 548.4 | 572.4 | 603.4 | 619.9 | 637.0 | r662.4 | 679.6 | 719.8 | 720.3 | 730.2 |
| Petroleum products, refined | do | 321.0 | | 360.3 | 378.6 | 400.0 | 423.6 | 449.8 | 482.8 | 513.7 | 533.7 | 545.4 | r555.2 | 582.4 | 620.3 | 657.9 | 677.3 |
| Furniture and household durables # | do | 160.4 | | 168.3 | 168.7 | 169.6 | 170.2 | 170.7 | 171.5 | 172.7 | 175.1 | 176.4 | r177.9 | 182.1 | 183.4 | 184.6 | 183.1 |
| Appliances, household | do | 153.0 | | 158.8 | 158.7 | 159.3 | 160.0 | 161.1 | 162.2 | 162.7 | 163.2 | 164.5 | r165.3 | 166.6 | 168.7 | 169.7 | 170.2 |
| Furniture, household | do | 173.5 | | 181.8 | 182.7 | 184.8 | 185.3 | 185.8 | 186.2 | 188.5 | 190.1 | 193.0 | r194.8 | 195.4 | 196.5 | 196.9 | 198.9 |
| Home electronic equipment | do | 90.2 | | 92.3 | 92.3 | 92.4 | | 90.2 | 90.2 | 90.3 | 90.3 | 90.3 | r90.5 | 88.5 | 88.7 | 88.8 | 88.9 |
| Hides, skins, and leather products # | do | 200.0 | | 253.3 | 258.9 | 269.6 | 268.0 | 261.9 | 257.9 | 251.1 | 253.9 | 248.9 | r249.2 | 255.3 | 251.0 | 246.8 | 243.6 |
| Footwear | do | 183.0 | | 209.9 | 212.0 | 216.3 | 221.1 | 221.8 | 225.4 | 226.9 | 227.5 | 227.9 | r227.9 | 228.5 | 228.1 | 231.8 | 231.9 |
| Hides and skins | do | 360.5 | | 639.6 | 642.2 | 666.9 | 611.0 | 566.5 | 511.9 | 465.3 | 478.8 | 447.6 | 443.9 | 468.8 | 404.8 | 348.7 | 328.6 |
| Leather | do | 238.6 | | 371.9 | 393.6 | 429.4 | 414.6 | 385.2 | 365.9 | 330.0 | 343.6 | 319.8 | 324.8 | 347.6 | 340.3 | 311.0 | 297.6 |
| Lumber and wood products | do | 276.0 | | 300.5 | 304.9 | 302.8 | 299.8 | 300.1 | 304.7 | 309.7 | 308.8 | 298.9 | r290.1 | 290.0 | 294.8 | 295.7 | 275.2 |
| Lumber | do | 322.4 | | 350.5 | 355.4 | 354.8 | 354.8 | 355.0 | 365.3 | 373.9 | 370.3 | 355.6 | r339.5 | 336.3 | 341.5 | 340.6 | 310.1 |
| Machinery and equipment # | do | 196.1 | | 207.9 | 209.8 | 211.4 | 212.4 | 214.8 | 216.0 | 217.7 | 220.0 | 221.3 | r223.4 | 227.1 | 229.7 | 231.9 | 235.8 |
| Agricultural machinery and equip | do | 213.1 | | 224.8 | 226.4 | 228.3 | 229.4 | 231.2 | 233.3 | 237.4 | 240.0 | 243.4 | r244.2 | 247.6 | 249.1 | 250.4 | 252.8 |
| Construction machinery and equip | do | 232.9 | | 248.7 | 251.7 | 253.7 | 254.0 | 257.0 | 258.5 | 256.9 | 263.9 | 265.4 | r268.8 | 275.4 | 277.5 | 278.4 | 282.9 |
| Electrical machinery and equip | do | 164.9 | | 173.8 | 175.0 | 176.5 | 177.6 | 179.9 | 181.2 | 182.5 | 184.3 | 184.9 | r186.6 | 190.5 | 194.2 | 195.9 | 198.7 |
| Metalworking machinery and equip | do | 217.0 | | 233.0 | 235.3 | 237.6 | 239.1 | 241.4 | 243.5 | 246.4 | 249.6 | 252.2 | 254.6 | 258.7 | 261.3 | 264.1 | 269.9 |
| Metals and metal products # | do | 227.1 | | 251.7 | 256.0 | 256.2 | 258.2 | 260.8 | 261.8 | 263.7 | 269.6 | 271.1 | r273.6 | 284.5 | 288.6 | 286.3 | 284.6 |
| Heating equipment | do | 174.4 | | 183.4 | 183.8 | 185.7 | 185.2 | 166.0 | 188.1 | 191.3 | 192.2 | 193.1 | r195.6 | 197.3 | 199.9 | 202.0 | 204.2 |
| Iron and steel | do | 253.6 | | 279.9 | 280.2 | 279.5 | 283.2 | 286.8 | 286.1 | 285.5 | 289.2 | 292.0 | r292.8 | 297.3 | 300.2 | 301.6 | 307.0 |
| Nonferrous metals | do | 207.8 | | 246.6 | 259.6 | 258.2 | 259.7 | 262.3 | 263.1 | 269.3 | 283.1 | 284.1 | r291.9 | 326.1 | 336.5 | 320.9 | 298.9 |
| Nonmetallic mineral products # | do | 222.8 | | 240.8 | 243.4 | 245.6 | 246.9 | 249.5 | 249.9 | 254.6 | 256.2 | 257.4 | r259.6 | 268.0 | 272.6 | 276.1 | 282.8 |
| Clay prod, structural, excl refrac | do | 197.2 | | 212.8 | 211.8 | 215.7 | 216.5 | 220.3 | 222.3 | 223.7 | 221.1 | 221.0 | r226.7 | 229.6 | 231.1 | 231.5 | 234.4 |
| Concrete products | do | 214.0 | | 237.8 | 240.5 | 241.6 | 243.7 | 245.2 | 246.3 | 248.7 | 250.1 | 250.6 | 253.2 | 264.9 | 266.2 | 268.6 | 273.0 |
| Gypsum products | do | 229.1 | | 251.0 | 252.2 | 248.8 | 251.3 | 251.8 | 252.3 | 254.9 | 255.3 | 256.2 | 255.0 | 255.4 | 262.2 | 267.6 | 264.0 |
| Pulp, paper, and allied products | do | 195.6 | | 212.3 | 215.0 | 216.2 | 216.6 | 218.3 | 222.2 | 223.0 | 227.5 | 229.5 | r231.7 | 237.4 | 238.9 | 241.6 | 246.5 |
| Paper | do | 206.1 | | 223.3 | 226.3 | 227.2 | 227.5 | 228.2 | 229.5 | 230.3 | 238.7 | 241.8 | r242.7 | 245.5 | 247.5 | 250.5 | 253.6 |
| Rubber and plastics products | do | 174.8 | | 185.9 | 188.8 | 190.8 | 193.1 | 195.5 | 198.8 | 200.7 | 203.0 | 204.9 | r205.9 | 208.2 | 210.9 | 212.7 | 214.6 |
| Tires and tubes | do | 179.2 | | 195.0 | 196.1 | 197.3 | 198.9 | 206.2 | 211.6 | 215.0 | 218.3 | 223.1 | r223.1 | 224.7 | 231.2 | 231.2 | 231.3 |
| Textile products and apparel | do | 159.8 | | 165.2 | 166.4 | 167.2 | 168.4 | 169.3 | 170.5 | 171.3 | 172.0 | 172.8 | r173.1 | 174.9 | 176.5 | 178.9 | 180.6 |
| Synthetic fibers | Dec 1975 = 100 | 109.6 | | 113.6 | 115.1 | 117.4 | 118.5 | 119.5 | 120.6 | 123.6 | 124.7 | 124.2 | r124.7 | 126.9 | 127.1 | 129.4 | 130.7 |
| Processed yarns and threads | do | 102.4 | | 107.0 | 106.8 | 107.8 | 108.6 | 109.5 | 110.6 | 111.7 | 112.1 | 112.5 | r112.7 | 114.4 | 117.3 | 118.9 | 122.1 |
| Gray fabrics | do | 118.6 | | 123.1 | 124.5 | 124.7 | 125.4 | 128.3 | 128.7 | 128.7 | 129.7 | 130.7 | r132.3 | 132.2 | 131.7 | 133.7 | 136.1 |
| Finished fabrics | do | 103.8 | | 105.4 | 105.9 | 107.0 | 107.6 | 108.2 | 109.0 | 109.1 | 108.9 | 109.7 | r109.9 | 109.8 | 110.8 | 113.1 | 114.5 |
| Apparel | 1967 = 100 | 152.4 | | 158.3 | 159.8 | 159.8 | 160.2 | 160.3 | 161.4 | 161.6 | 162.2 | 163.1 | r162.6 | 165.3 | 167.3 | 168.3 | 169.1 |
| Textile house furnishings | do | 178.6 | | 187.4 | 187.6 | 188.0 | 189.3 | 189.9 | 190.5 | 193.9 | 196.3 | 196.5 | r197.1 | 199.2 | 200.0 | 201.2 | 201.6 |
| Transportation equipment # | Dec 1968 = 100 | 173.5 | | 183.8 | 186.8 | 187.2 | 187.5 | 188.4 | 185.9 | 186.6 | 194.2 | 194.8 | r195.6 | 198.3 | 198.1 | 198.8 | 202.6 |
| Motor vehicles and equip | 1967 = 100 | 176.0 | | 186.1 | 189.4 | 189.8 | 190.1 | 190.8 | 187.8 | 188.6 | 197.1 | 197.4 | r198.2 | 200.3 | 199.9 | 200.8 | 204.9 |
| **Seasonally Adjusted ‡** | | | | | | | | | | | | | | | | | |
| Finished goods, percent change from previous month * | | | | 1.0 | 0.8 | 0.5 | 0.6 | 1.2 | 1.1 | 1.5 | 1.1 | 1.2 | r0.8 | r1.5 | 1.5 | 1.4 | 0.5 |
| By stage of processing | | | | | | | | | | | | | | | | | |
| Crude materials for further processing | 1967 = 100 | | | 274.2 | 273.2 | 275.1 | 278.4 | 284.6 | 285.2 | 291.4 | 294.5 | 290.8 | r301.7 | 299.5 | 307.4 | 300.7 | 290.3 |
| Intermediate materials, supplies, etc | do | | | 231.6 | 235.0 | 237.3 | 239.7 | 243.6 | 247.1 | 250.7 | 255.0 | 256.3 | r260.2 | 267.1 | 272.0 | 273.4 | 273.8 |
| Finished goods # | do | | | 209.4 | 211.1 | 212.1 | 213.4 | 215.9 | 218.3 | 221.5 | 223.9 | 226.3 | r228.5 | 231.9 | 235.3 | 238.6 | 239.8 |
| Finished consumer goods | do | | | 208.4 | 209.7 | 210.8 | 212.0 | 214.8 | 218.3 | 222.2 | 224.8 | 227.1 | r229.9 | 233.2 | 237.3 | 241.2 | 241.2 |
| Food | do | | | 226.7 | 225.8 | 223.5 | 221.3 | 222.8 | 226.2 | 229.3 | 229.1 | 230.5 | r234.1 | 232.0 | 230.9 | 233.4 | 226.8 |
| Finished goods, exc foods | do | | | 197.3 | 199.7 | 202.4 | 205.3 | 208.7 | 212.3 | 216.4 | 220.4 | 222.8 | r225.5 | 231.5 | 238.2 | 242.7 | 246.0 |
| Durable | do | | | 177.0 | 178.1 | 179.5 | 180.6 | 182.0 | 182.0 | 184.7 | 187.7 | 190.0 | r191.6 | 197.2 | 200.7 | 199.9 | 200.3 |
| Nondurable | do | | | 210.6 | 213.7 | 217.5 | 221.7 | 226.6 | 232.7 | 237.8 | 242.6 | 245.5 | r248.4 | 254.7 | 263.5 | 271.9 | 277.3 |
| Capital equipment | do | | | 211.6 | 211.0 | 215.0 | 216.4 | 218.2 | 217.9 | 219.5 | 221.4 | 223.9 | r224.8 | 228.2 | 229.8 | 231.6 | 235.9 |

# APPENDIX C

# ENERGY MANAGEMENT MODEL

## General

The package of simulation and energy management programs under development at the RSC has been designed to meet two categories of objectives--functional objectives defining what the package is expected to do and architectural objectives defining how the package is to be built.

- Functional Objectives
  - Realistically model and simulate power flows, energy consumptions and energy costs of existing and anticipated electric powered transportation systems.
  - Separate a system's overall energy consumption into its important end uses. Identify the cause-effect relationships governing these end uses and determine their sensitivities to changes in equipment, system design and operating practices.
  - Provide the means to develop, refine and test energy conservation strategies before they are implemented in actual systems.
  - Provide flexibility - allowing the package to be improved and upgraded as necessary to accommodate new models, new strategies and new technology.
- Architectural Objectives

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

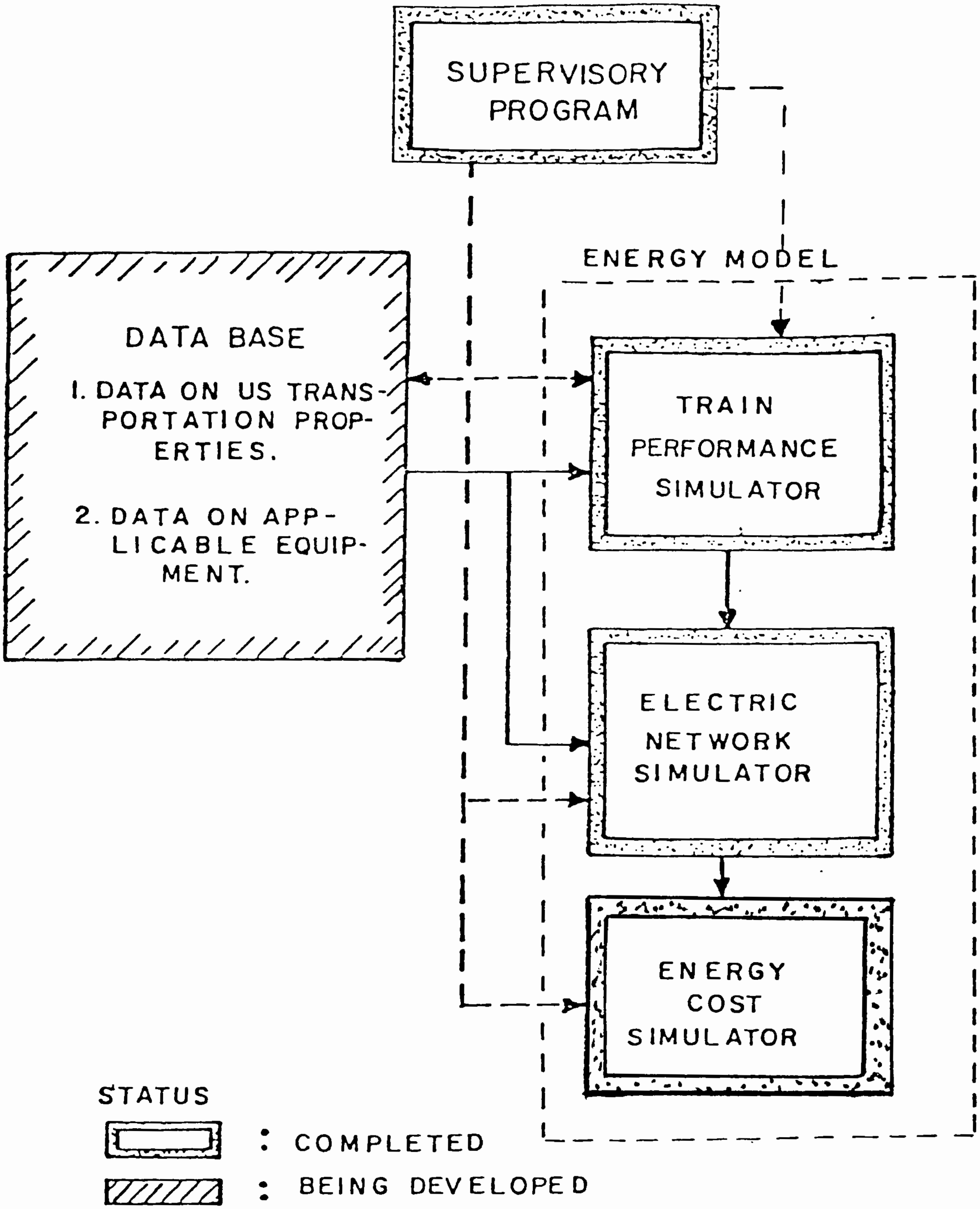
  - developed, tested and verified independently,
  - inserted into the package or replaced without requiring a major retrofit affecting the package's integrity.

  To be, as far as possible, machine independent (no large package can come even close to being completely independent but steps can be taken to minimize the effort required to move the package from one computer system to another) and to be written in a widely used language.

The approach to simulating a transit system, that is, to determine its performance, power flows, energy consumptions and energy costs, involved the following steps:

- For each train in the system assemble data on its performance characteristics, the route and schedule it is to follow and the characteristics of the track on which it is to run.
- Assemble data on the electrical configuration of the network supplying power to the trains and/or costs of energy.
- Treating each train separately, calculate tables of its speed, position and power demand against time.
- From these tables assemble a master table, which, for selected time instants spanning the period under investigation, contains data on the locations and electric power demands of every train in the system.
- At each of the selected time instants, calculate the voltages, currents and real and reactive power flows for all salient points in the electrical network.
- Integrate the power flows to give energies and wattless flow, and process them in accordance with a selected energy-billing-schedule to obtain the energy costs.

The transportation-system-model consists of three components: a Train Performance Simulator, an Electric Network Simulator and a Metered Energy Cost Simulator. The last simulator has not yet been built.



PRINCIPAL COMPONENTS (MODULES) OF A SIMULATION AND ENERGY MANAGEMENT PACKAGE

C-2

## ENERGY MANAGEMENT MODEL

### Train Performance Simulator

This program accepts as input, vehicle parameters such as weight, propulsion system characteristics (tractive effort and efficiencies vs. speed), train resistance, numbers and types of vehicles in train, auxiliary electric loads, and passenger load factors; wayside parameters such as power distribution system type (DC, single phase AC or three phase AC), voltage, and right-of-way profile (grade, curve, and speed restriction as a function of location); and system operational characteristics such as acceleration and braking rates, maximum speed and station dwell times. The program simulates the operation of a single train under the input conditions. Outputs include power profiles (real power for DC distribution and real and reactive power for AC distribution as a function of location). The program will accept trains with dynamic braking capability and the energy can be fed into storage devices aboard the vehicles (batteries or flywheels), dissipative devices aboard the vehicle (resistors) or to storage/dissipative devices, or other trains external to the train (regeneration) using the power distribution system. The program also incorporates coasting.

### Electric Network Simulator

This program accepts as input, single train power and time profiles as a function of location along the right-of-way, timetables for movement of multiple trains, power rail, catenary or trolley impedances, running rail impedances, substation locations and characteristics, operating voltage both nominal, maximum and minimum, characteristics of the distribution network, the substation feeders, and metering point locations. This program simulates the movement of the trains by taking snapshots of the entire system at fixed intervals of time. The calculated output of this program is a complete electrical picture of the system including power flows, voltages, currents and losses at all salient points. In particular, power through metering points (forward and reverse), power distribution system and substation losses is computed. Capability for regeneration to other trains, to storage devices on the track side of substations, and/or through regenerative substations, even through metering points, is also included.

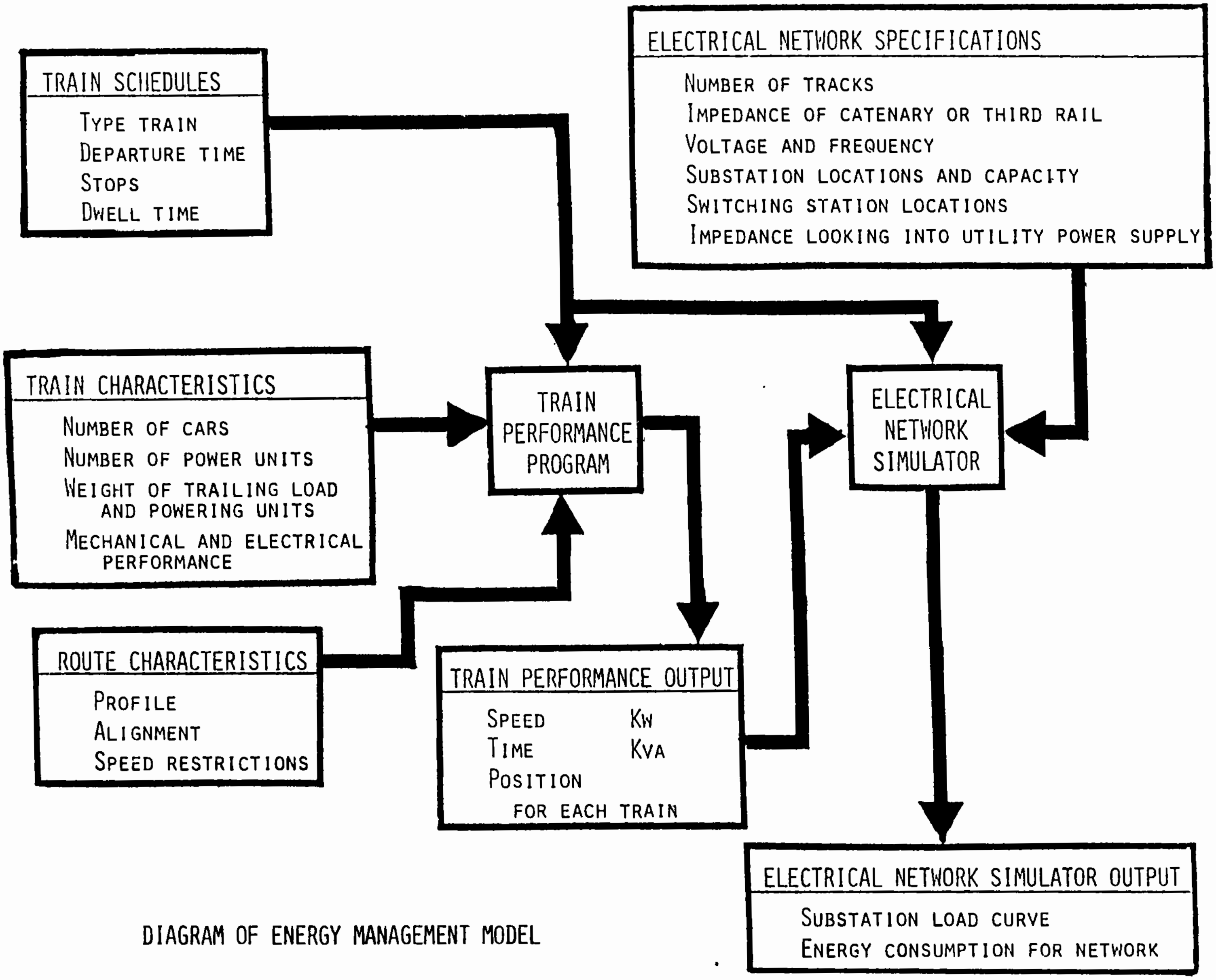


DIAGRAM OF ENERGY MANAGEMENT MODEL

# APPENDIX D

## ROI COSTING PROCESS

This appendix describes the manner in which capital investment, annual operating costs and annual savings were obtained. All figures in this section are based on data provided by officials from the Port Authority Transit Corporation of Pennsylvania and New Jersey (PATCO).

To determine the capital investment cost of any system, the maximum power input to the system must first be calculated. In the case of PATCO, the maximum power input is 43,880 KW (Table 5-7). This is not applicable to the on-board systems. For on-board systems, the maximum power per car times the number of cars is the basis of cost estimation. PATCO cars have a maximum power input of 1060 KW per car. The maximum energy storage per PATCO car is 3.34 KWH. The capital investment costs were determined as follows:

<u>On-board Battery</u> $TC = C\$/KW \times I_{car} \times n$

<u>On-board Flywheel</u> $TC = C\$/KWH \times E_{car} \times n$

<u>Off-board</u> $TC = C\$/KW \times I_{substations}$

where

TC = total capital investment
C$/KW = capital cost per KW
C$/KWH = capital cost per KWH
I = maximum input power
E = maximum energy storage per car
n = number of cars

Operating costs were calculated in the same manner as capital investment costs.

<u>On-board Battery</u> $OC = OC\$/KW \times I_{car} \times n$

<u>On-board Flywheel</u> $OC = OC\$/KWH \times E_{car} \times n$

<u>Off-board</u> $OC = OC\$/KW \times I_{substations}$

where

OC = operating costs per year
OC$/KW = operating cost per KW
OC$/KWH = operating cost per KWH

The annual savings from implementation of an energy-storage system are determined as follows:

$$S = (KWH/CM_{base} - KWH/CM_{test}) \times M \times \$/KWH$$

where

S = $ savings/year
KWH/CM = KWH per car mile
base = usage without any energy-storage system
test = any of the energy-storage systems
M = system car miles per year
$/KWH = electric cost per KWH

The figures for KWH per car mile, both base and test, were taken from Figure 5-8, Table 5 (timetable average).