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ENERGY STUDY OF RAIL PASSENGER TRANSPORTATION

Volume 4: Efficiency Improvements and Industry Future

Final Report

By
Clark Henderson
James P. Wilhelm

August 1979

MASTER

Work Performed Under Contract No. EY-76-C-03-1176

Stanford Research Institute International
Menlo Park, California

U. S. DEPARTMENT OF ENERGY

Division of Transportation Energy Conservation

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Prepared for:

U. S. Department of Energy
Systems Efficiency Branch
Transportation Programs Office

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PREFACE

The Energy Research and Development Administration (ERDA),* recognizing the need for an assessment of energy usage by railroad freight and passenger services and by rail transit systems, has sponsored the Energy Study of Rail Transportation as part of a comprehensive energy conservation program. The objectives of the study were:

- To describe rail transportation systems in terms of physical, operating, and economic characteristics; and to relate energy usage, services rendered, and costs.
- To describe the roles of private and public institutions in ownership, operation, regulation, tariff, and fare determination, and subsidization of rail transportation.
- To describe possible ways to improve efficiency.
- To provide data that the Government may use to determine its future role

Work was organized in four tasks:

- Descriptions of rail transportation industries
- Regulation, tariff, and institutional relations
- Efficiency improvements
- Industry future and federal role

Results of the study are published in two report series of four volumes each, as follows:

ENERGY STUDY OF RAILROAD FREIGHT TRANSPORTATION:

Executive Summary, Volume I
Industry Description, Volume II
Regulation and Tariff, Volume III
Efficiency Improvements and Industry Future, Volume IV

ENERGY STUDY OF RAIL PASSENGER TRANSPORTATION

Executive Summary, Volume I
Description of Operating Systems, Volume II
Institutions, Volume III
Efficiency Improvements and Industry Future, Volume IV

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*The functions of ERDA were transferred to the Department of Energy.

The Energy Study of Rail Transportation was performed by SRI International, Menlo Park, California, under Contract EY-76-C-03-1176. Ms. Estella Romo and Mr. Richard Alpaugh of ERDA were the contract monitors. Dr. Robert S. Ratner was the project supervisor. Mr. Albert E. Moon was project leader and task leader for freight railroad studies. Mr. Clark Henderson was task leader for passenger rail studies.

This report is Volume IV of the Rail Passenger Transportation series. Mr. Clark Henderson was principal author. Mr. James P. Wilhelm contributed material on technical innovations.

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I INTRODUCTION

Purposes

Volume IV identifies and briefly describes measures that offer promise of efficiency improvements or economy in energy usage in rail passenger transportation; comments on the future of rail passenger transportation in the United States; and discusses possible future roles of federal agencies.

Definition of Classes of Energy Demand

Energy demands generated by rail passenger transportation systems are grouped in three classes: direct, indirect, and capital. Demands are generated in many different ways; consequently, innovations in efficiency improvement can take many forms. Classes of demand are defined and illustrated here:

- Direct Demands: the petroleum fuel (or petroleum fuel equivalent of other energy sources) used day-by-day to supply electrical power and fuel for the operation of rail passenger transportation equipment and facilities. The following outline is a breakdown of the major elements of direct demand.
  - Operation of vehicles (by type of operation and type of consumption)
    - Type of operation
      - Passenger vehicles
        - Revenue service
          - Passenger transportation
          - Nonproductive travel
        - Nonrevenue movements and other
        - Deadhead mileage--between storage and revenue service
        - Live or "hot" storage--with auxiliaries operating
      - Maintenance and service vehicles
    - Types of consumption
      - Propulsion--acceleration and motoring (less braking energy if recycled)
        - Empty vehicles
        - Payload--weight of passengers
      - Mechanical and aerodynamic friction
      - Power conversion and regulation on board vehicles
      - Auxiliaries
        - Heating, ventilating and air conditioning
        - Lighting
        - Compressors for brakes

Controls
Communication
Fixed facilities
Power conversion and distribution
Signals and communications
Shops
Yards
Stations
Heating, ventilating and air conditioning
Lighting
Elevators and escalators
Communications
Fare collection
Parking lots
Suppliers of energy
Production and distribution of fuel
Losses of heat in electrical power plants
Losses of electrical energy in distribution and conversion
Energy consumed by suppliers

- Indirect Demands: the energy content of goods, labor and services consumed in current operations of rail passenger systems
- Capital Demands: the energy embodied in newly acquired capital assets including replacements, improvements, extensions, expansions, and new construction in the rail passenger systems and in the industries engaged in supplying energy and other goods and services.

Methods for Energy Economic Studies

New analytical methods are required to plan and manage an energy conservation program in rail passenger transportation. The methods should allow evaluation of the net, long-term changes in energy demand that will result from any significant change in an existing rail passenger system or from the development of a new system. The methods now available are not sufficient for this purpose.

The term "energy economy study" has been adopted here as a name for the needed methods. The term is borrowed from "engineering economy," a long-established discipline for economic evaluations and comparisons of engineering and other alternatives. This analytical method uses reasoning substantially parallel to that needed for the energy economy studies. Another term that might be suitable is "energy impact assessment," which is suggested by the commonly used term "environmental impact assessment."

One definition of economy is "management without loss or waste." In this report, "economy" means *the exercise of care in planning, designing, constructing, operating, renewing or discontinuing rail passenger transportation systems to avoid loss or waste of energy.*

Impact, or energy impact, refers to any change (either an increase or decrease) in energy demand resulting from a measure under consideration.

Conservation of direct energy (that is, energy that is consumed day-by-day to operate rail equipment and facilities) is usually the focus of attention in conservation programs, but direct energy demand is only one of the three classes of energy demand that can be affected by a decision regarding changes in rail systems. All three classes must be studied. The second class, indirect energy, is consumed in factories, homes, and other places to supply labor, services, and material for day-by-day operations. The third class, capital energy, is used to construct, equip, renew, and support a rail passenger system. Total energy demand is the sum of direct, indirect, and capital demands.

From the viewpoint of energy conservation, the worth of any proposed change in a rail passenger transportation system should be measured in terms of the net effect of the change upon total energy demand. Comparisons should reveal the differences between alternatives in total demand and should also break down the total by components of energy demand in each class. *The net changes or the differences between the total demands of pairs of alternatives are used to evaluate the worth of specific energy conservation measures.*

The estimates and comparisons of energy demands produced by energy economy studies can be used to answer questions or make decisions such as the following:

- *Why change an existing rail system to something different?* This question requires comparison of energy demands under existing and prospective changed conditions.
- *Why follow one system design and set of operating practices rather than another?* This question requires the formulation of two or more alternative plans for routes, facilities, equipment, and operation; and the comparison of energy demands for pairs of alternatives.
- *Why develop a new rail system or continue to operate one presently in existence?* This question requires the comparison of demands for the entire region served under two alternatives: with and without rail transportation service. Total energy demands for auto and bus must be included. This question may arise when the construction of a new system is under consideration, when extensions are proposed, or when abandonment of a line or an existing system is under consideration.
- *Why follow one staging plan for system development rather than another?* This question requires the formulation of alternatives having different schedules for development or change and the comparison of demands among alternative schedules.

Many of the energy effects of a change in rail transportation will occur outside the rail system and beyond its suppliers of energy, goods, and services. For example, changes in rail transportation will affect travel via auto and bus, the total amount of travel in a region, and the pattern of land development and use in a region. All of those effects should enter into energy economy studies to the extent they can be quantified.

Naturally, energy economy is not the sole criterion in making decisions about changes in rail systems. Other important considerations are the effects on capital and operating costs; consumption of scarce resources such as land; availability and quality of services to users; and social, economic and environmental conditions. However, assessment of energy effects is at least as important as assessment of effects of other kinds. The present lack of methods for energy economy studies or energy effect assessments is a serious deficiency. We strongly recommend that ERDA develop appropriate methods for energy economy studies as part of the energy conservation program.

Conservation Measures

Measures that offer promise of improvements in energy efficiency have been identified from three sources: in the course of site visits and interviews conducted by the project team; by analysis of unpublished data furnished by operators; and by literature search. Concepts for other measures have been developed by the project staff while conducting some 30 case studies and are presented here.

Energy conservation can be sought by single measures or groups of measures used in combinations. Existing systems, including some that have been built or modernized recently, do not incorporate many of the conservation measures that are now available. Technical advances will provide additional opportunities in the future.

Measures that offer at least the promise of net energy savings are outlined here:

- Economy in operations
- Economy in system design
  - Facilities
  - Equipment
- Economy in energy supply systems
- Economy in modal choice

While energy can be conserved by exploiting existing technology and design capabilities, some measures must await the development and evaluation of new components and subsystems; some measures can be achieved only by changes in legislation, institutions, financing, and public policy.

No standard reference works or texts treat energy conservation measures as related to the design and operation of rail passenger system, nor is there a comprehensive list of wasteful system characteristics. However, in our research on existing systems, we noted many examples of both wasteful and too conservative economical conditions in operations and system design. Further, in interviews and literature search, we identified concepts and proposals for measures that depend on technical advances. In conducting the research, we envisioned measures that would depend on legislation, institutional changes, new financing programs, shifts in modes of travel, and changes in public policy that would encourage energy conservation. These measures are discussed (and illustrated in examples where possible) in the sections that follow.

Some energy demands are interrelated and involve tradeoffs--that is, changes of several kinds may be combined in a single project or program. The following hypothetical case indicates how a technical innovation could be combined with other changes. The case assumes that a transit property purchases a fleet of small, energy-efficient, and economical railcars--a technical innovation. The cars are acquired to supplement cars of standard size. The new cars provide 24-hr service with frequent schedules on lines that would otherwise be closed at night--an operational innovation. The improvement in rail service availability causes some travelers to depend entirely on rail transportation for trips to work and central city activities rather than to use autos or bus--a modal shift. However, the improvement (that is, the 24-hr availability of rail service) encourages some workers to move to residences further from their jobs--a change in trip length.

The sections that follow treat operations, systems design, energy supply systems, and modal choice. Examples are presented as early in the text as appropriate. However, readers are asked to keep in mind that specific characteristics have multiple effects in several subject areas. Consequently, the examples in one section are often relevant to others. Cross-references are made where appropriate.

Industry Future

Rail passenger transportation in the U.S. is dominated mainly by policy decisions of public agencies and its future cannot be forecast on the basis of historical experience, future economic trends in related fields, or technical advances. Conventional methods of forecasting are not applicable. However, "boundary" conditions can be identified and are discussed in Section VI.

Federal Role

The federal government now provides major subsidies for technical planning studies, capital investments, and operating support of rail passenger transportation but has little or no direct influence on local decisions affecting energy economy. Energy saving projects must compete with all other proposals when plans are developed at the local level. Energy economy receives no special weight or priority when grant applications are reviewed at the federal level. Under these conditions, energy conservation programs will make slow progress. Section VII outlines changes in legislation and in procedures that appear likely to accelerate implementation of cost-effective energy measures.

II ENERGY ECONOMY IN OPERATIONS

Measures for energy economy or conservation in operation of rail passenger systems are described in terms of avoidance of wasteful practices. High productivity in the usage of equipment and energy is the objective.

Nonproductive Activity

Rail passenger vehicles are considered nonproductive (either totally or significantly) in the following situations:

- Moving empty trains.

  Moving trains in scheduled passenger service on established routes (in "revenue service") to the extent that the number of cars in a train is greater than is needed to accommodate the load.
- Moving trains when the horsepower of the locomotive is significantly greater than needed to draw the loads.

Passenger equipment (the entire train or individual locomotives and cars) is nonproductive while in the following "nonrevenue" operations:

- Moving between storage facilities and passenger routes at the start and end of periods of revenue service (usually called "deadhead" travel).
- Moving within yards and shops.
- Making up and separating trains.
- Turning trains at the ends of revenue routes.
- Removing "in bad order" or malfunctioning passenger equipment from passenger routes to repair facilities.

Nonproductive activity wastes energy in all three classes of demand: (1) the movement of vehicles generates direct energy demands; (2) the use of labor, goods, and services for operations and maintenance generates indirect energy demands; and (3) the wearout of capital assets and, in some cases, requirements for larger vehicle inventories to cover nonproductive activities, generates capital energy demands. Avoiding nonproductive operation of equipment is of special interest as an energy conservation measure since the equipment movements and the associated energy usage do not *directly* produce passenger service. Of course, some nonproductive operations are needed under all but perfect conditions. However, much of the nonproductive operation of vehicles results from fundamental design characteristics of equipment and facilities selected long ago, and therefore is not subject to the control of persons presently responsible for operations. Improvements must await corrections of the design defects.

Examples are used to illustrate both desirable and wasteful practices.

Example: Productivity. PATCO's Lindenwold heavy-rail transit line connects downtown Philadelphia and Camden with numerous suburban stations in New Jersey. It illustrates several aspects of productivity.

Deadhead travel is low because of good layout of track and storage. The storage yard is located a short distance beyond the last station at the residential end of the line. Consequently, cars have a short run to enter revenue service after leaving the yard each morning and another short run to enter storage in the evening.

Train lengths are varied and excess capacity is largely avoided by favorable design characteristics in cars, track layout, and storage. The Lindenwold line has an exceptional ability to vary train lengths. Throughout the day, train consists are changed from one to six cars to match changes in passenger load. As a result, 15% of the trains operate with a single car, which, in slack periods, often provides more seats than needed. Two-car trains, the most common, make up 38% of the total; six-car trains, which are only required in peak periods, make up 20%.

Even with these advantages, the Lindenwold line has some design features and patronage characteristics that force it to provide capacity that cannot be used. For instance, there is little if any car storage at the downtown end of the line, which means that trains must always turn back promptly and return whether or not there is a passenger load.

In periods of peak traffic, trains usually have considerable excess capacity during major parts of each roundtrip. For example, during the morning peak, Lindenwold trains leave the outer end of the line empty. The load increases at each station stop and the train is usually fully loaded or crowded as it approaches downtown; on the average, such a train is about one-half full. On the return trip, the trains are usually very lightly loaded. Thus, a *load factor* of about 25% is the normal expectation (load factor is the ratio of passenger-miles to seat-miles).

To avoid some of this unproductive activity, Lindenwold can lower capacity on part of the line by using the storage tracks and switches at an intermediate station. This flexibility allows some trains to make short roundtrips, thereby avoiding nonproductive travel on the outer parts of the line.

One result of PATCO's practices is the attainment of a load factor of 29% which is relatively high when it is recognized that the system experiences severely unbalanced flows in the morning and evening peaks, yet avoids extreme crowding in rush hours, and provides 24-hr service every day of the year.

These qualities are not peculiar to Lindenwold. For example, the Cleveland RTA varies train lengths during slack times and turns back trains at intermediate stations. NYCTA also turns trains back at intermediate stations.

Example: Productive Cars and Excessive Power. The Southern Pacific (SP) suburban rail service between San Jose and San Francisco, California, operates on a double-track line about 47 miles in length; both ends of the line have storage facilities. Peak traffic is toward San Francisco in the morning and toward San Jose in the evening. Traffic is light in the non-peak directions, both morning and evening, and light in both directions at other times.

Deadhead travel is low. Trains travel only short distances from storage tracks to the start of the revenue line. Excess passenger capacity is avoided, to a great degree, except in periods when passenger loads are insufficient to fill trains of the minimum length commonly employed, i.e., two cars. This tailoring of passenger capacity is made possible by the availability of storage tracks at both ends of the line. Cars stored overnight in San Jose travel in the morning to San Francisco, where all cars but those needed for midday trains are stored. As the evening peak approaches, cars are reconnected to form longer trains, the length varying from two to eight cars to match passenger loads.

Excess capacity would be avoided if trains could be turned at intermediate stations: all trains make full roundtrips.

Excess passenger capacity is provided during slack periods. This cannot be avoided, but might be reduced. When traffic is light, train consists (locomotives and cars making up a train) are standardized to avoid the need for workers in the yards. Although one car would often provide more seats than required, the standard short train includes two cars and a locomotive. One reason for not using one-car trains is said to be the need to provide separate cars for smokers and nonsmokers. If this were the only reason, the direct energy demand generated by the second car would be about 22 gal of fuel or 3 million Btu for each train making the 47-mile run. (See Volume II.)

Excess locomotive power is unavoidable in SP operation, as in other systems using diesel-electric locomotives. Locomotives

of three sizes (1500 hp, 3000 hp, and 3600 hp) are used to draw trains of seven different lengths (two to eight cars). Consequently, trains are often drawn by locomotives having excess horsepower, thereby wasting energy. Since locomotives of seven sizes are not economically or technically feasible, excess horsepower and the associated waste of energy are necessary at present.
Rail diesel cars (RDC) might be substituted for locomotive and coaches. (See Rail Diesel cars, Section III, below.)

Example: High Deadhead Mileage. Deadhead mileage adds significantly to direct, indirect, and capital energy demands. The Muni streetcar system in San Francisco, which has one trunk line and five branches, has deadhead travel that is unusually high (12.4%), about 1 mile for each 7 miles of revenue service.

The inability of Muni to avoid deadhead travel is explained by the layout of the system, specifically by the location of the principal storage facility and shop in relation to the revenue routes. The Muni system has a downtown terminal, a main or "trunk" line, five branch lines distributed through predominantly residential neighborhoods, and five revenue routes, one on each branch line, but all concentrated on the trunk line. The principal car storage facility is at the end of the K line branch.

In the early morning, most of the fleet of cars must be deployed from the yard to the residential ends of each branch line to prepare for revenue service during the morning peaks. Cars assigned to the K line enter revenue service near the yard portal, thereby experiencing little deadhead travel. However, cars assigned to the other four lines must travel empty to the residential ends of their revenue routes. First, each car travels toward the downtown terminal on the K line, then onto the trunk line. Cars then turn back at a suitable point and travel outbound to the end of the appropriate branch line. A similar procedure after the evening peak returns the cars to storage. Other deadhead movements occur during the day to adjust the number of cars in service.

One measure has been planned to reduce deadhead travel, and several others have been considered. A second branchline, the L line, will be extended about 0.7 mile to terminate in the yard, permitting L cars to enter revenue service near the yard portal and thus causing little deadhead travel. The construction of a new track to link the yard to the residential terminals of J and N lines has also been considered. However, both projects would be costly in money and in capital resources, and any savings in direct and indirect energy demands would be partly offset by increases in capital demands. Also, when the plan reached an advanced stage of development and was publicized, the N line connection was met by vigorous opposition from residents near the proposed rights-of-way and the plan was defeated.

A more ambitious solution to the problem, one not under consideration, would require construction of connecting tracks and a yard on a site near the downtown terminal. All cars could then be deployed each morning over the trunk and appropriate branch lines to begin revenue service. This scheme would reduce deadhead travel, but it should be noted that the outbound passenger traffic in the early morning is usually very light. A few outbound cars can be used for revenue service, but most are empty and nonproductive. Excess capacity would also be experienced in the evening.

To minimize deadhead mileage, storage yards must be provided at both ends of each revenue line. This solution would be costly and difficult for systems, such as Muni, having numerous branches; it is less difficult for systems having a single revenue route.

Nonproductive Activity to Turn Trains at the Ends of Routes

Readying trains for return trips at the ends of revenue routes often requires nonproductive activity, including car movements, labor and other operating expenses, and substantial investments in cars, locomotives, tracks, and switches. All of these requirements can be translated into direct, indirect, and capital energy demands.

Nonproductive activity in turning trains is principally caused by poor system designs, specifically in the characteristics of locomotives, cars, track alignments, and stations. Therefore, measures to avoid nonproductive activity in turning trains are discussed in the section III, Economy in System Design.

Frequent Stops

In transit systems, a large fraction of the direct energy for propulsion is used during acceleration rather than in traveling at normal speed. Consequently, if the number of starts and stops per trip can be reduced, direct energy should be saved and travel should be faster.

Example: Express and Skip Stop Operations. NYCTA has 4-track lines to supply both local and express service on heavily traveled routes. Local trains stop at each station, whereas express trains skip several local stations between each stop. Although express trains reach higher speeds, energy is conserved by the less frequent stops. Since considerable capital investment and energy demand are needed to build extra track, express stations, and switches, any savings in direct and indirect energy are offset, to some degree, by higher capital energy demands.

The CTA normally operates A and B services over most lines. Except for several common stations, the A trains serve one-half of the stations and the B trains serve the other. This operation not only reduces the frequency of stops and reduces energy consumption, but it also provides faster travel time for passengers who do not have to change trains and avoids the need for a second pair of tracks for express trains.

High Acceleration and Speed

Changes in the *speed profiles* of trains--the pattern of accelerations and speeds during station-to-station travel--will change passenger travel times, productivity of train crews and cars, operating costs, and long-term capital costs, as well as direct, indirect, and capital energy demands. Speed profiles for existing rail systems should be changed as part of an energy conservation program.

For rail systems now under development, energy economy studies should formulate, compare, and evaluate alternative speed profiles.

Care in the selection of speed profiles for systems now in design will be even more rewarding in energy economics than changes in existing systems. Automatic controls appear superior to manual controls in managing speed-distance profiles and in coasting to achieve energy savings. Although avoidance of excessive acceleration and speed is a measure having significant potential for energy savings, readers should remember that the potential saving is only a fraction of propulsion energy demands and that propulsion energy demands are a surprisingly small part of the total energy demands of rail passenger transportation systems.

Example: Speed Reductions. In recent months, both BART and the Lindenwold lines have reduced top speeds. The change conserves direct energy and indirect energy as well, by reducing maintenance.

Example: Speed Profile Changes. NYCTA has tested and evaluated the effects of coasting on energy usage. Trains were accelerated to top operating speed and then allowed to coast until the beginning of braking for the next station stop. APTA estimates that coasting increases running time by less than 5%.

Example: Models. Carnegie Mellon has developed models and computer programs to evaluate the energy and travel time effects of alternative speed profiles. To aid in the design of the new heavy-rail system being built in Baltimore, the Mass Transit Administration is developing a computer program to predict the tradeoff between the energy saved by reducing the peak operating speed as opposed to the added cost of purchasing more cars to provide adequate service during peak patronage hours (due to the slower train speeds).

Idle Vehicles and Facilities

Modern rail passenger cars are often stored "hot"--that is, connected to the third-rail power supply and with auxiliary equipment operating (heating, ventilating, air conditioning, lighting, brakes communications and controls). This practice is often adopted because some equipment is so complex that a considerable amount of time and labor is required to ready a "cold" car for revenue service. Savings of direct energy from a change in storage practices would be partly offset by increases in indirect energy demands. A second factor favoring hot storage is that some subsystems are less likely to fail if kept on than if turned off and on. Redesign and retrofitting of the cars would be needed to eliminate most of the time, labor, and malfunctions now associated with turning power off and on again. An energy economy study could be made to compare total energy demands under present and possible alternative conditions.

Example: Hot Storage. BART's practice is to store cars hot. It has been estimated that an average demand of 20 kW/car is generated by operation of the auxiliary equipment. Operation of the auxiliaries on a 400-car active fleet (while in service and while in storage) was estimated in 1975-76 to require about 70 million kWh, or about 30% of the electrical energy purchased. The potential saving from discontinuation of hot storage would be about 50 million kWh. The BART system operates only about 60% of the hours each week. The average number of cars in use during revenue service probably does not exceed 200, or 50% of the active inventory. These rough estimates suggest that individual BART cars are in hot storage about 70% of the time. If so, avoiding hot storage would save about 50 million kWh/year, or about 22% of the electrical energy purchased by BART.

An unknown amount of energy is wasted because electrical equipment is not turned off in idle facilities--mainly stations, parking lots, yards, shops, offices, and tunnels. Certainly, the total energy consumption in facilities is significant. For example, at BART these facilities used almost 64 million kWh in 1975-76, or 28% of the electrical energy purchased. While a substantial amount of this energy usage is necessary, BART does have a program to reduce energy use at idle facilities. No estimate of potential savings is available for BART or for any other system studied.

Example: Cold Storage. In an effort to reduce energy consumption, NYCTA is developing standard operating procedures to turn off lights, air conditioning, and heaters of cars stored in yards. The New York Long Island Rail Road has justified using three men to change the heater thermostat settings on cars to 55°F for yard layup and back to 68°F for revenue service. Energy savings are expected to be significant. An energy economy study could be made to compare the direct energy saving from this program with the indirect energy demands generated by the three employees.

III ENERGY ECONOMY IN SYSTEM DESIGN

System design characteristics strongly influence energy demands in all three classes: direct, indirect, and capital. In planning and managing an energy conservation program it is important to understand the numerous effects of system design on energy economy. This section discusses some important design considerations and provides examples of economical and wasteful designs.

Background

Of the rail passenger facilities now in existence, some designs make wasteful, nonproductive use of energy unavoidable, while others include features that avoid the same wastes. If all existing rail passenger systems could be redeveloped to include the best practices now observed in other existing systems, direct and indirect energy demands would be lowered considerably. However, the savings would be partly offset by increased capital energy demands. Economical measures can be incorporated or avoided only by designing new systems.

Some of the design features introduced in recent years have undoubtedly added increments of direct, indirect, and capital energy demands. Among such designs are air conditioning of cars and stations; improved station lighting; use of escalators and elevators; illuminated parking lots; and design, realignment, and maintenance of track for high-speed travel. However, these increases can be defended. Rail transit systems are in competition with buses and autos, which have also added comfort, safety, and environmental control features, all with major effects on energy. Such energy consumption for rail transit is probably no less appropriate than for other modes.

Many of the rail passenger systems in operation today were designed and built between 1900 and 1925, long before conservation of nonrenewable energy was an important issue. Then as now, the key objectives in designing equipment were safety, reliability, maintainability and cost-effectiveness; energy cost was simply not a large concern. Consequently, some wasteful conditions in existing systems are so deeply imbedded in the basic system design that correction requires extensive redesign, reconstruction, and retrofitting.

Some of this design-deficient equipment is remarkably durable. Many items 20 to 50 years old are still in service. While more energy-efficient equipment is on the market today, the cost-effectiveness of replacing the older equipment must be determined case by case. Also, lack of capital to purchase and install the new equipment often prevents or delays desirable change.

Energy conservation is more important to the rail passenger transportation industry than formerly, but safety, service, and cost are still seen as more pressing concerns. Energy conservation is viewed more as a means to reduce costs than as a means to conserve irreplaceable resources. Also, the common view is that public transportation is less energy intensive than private transportation, and that the primary efforts to conserve energy should focus on increased patronage.

Although leaders in the transit industry recognize the need to design systems for a future in which energy will be scarce and expensive, these officials are nonetheless cautious in purchasing advanced technical equipment. To qualify for adoption, such equipment must be viewed as safe, reliable, and cost-effective.

Transit properties have traditionally cooperated with manufacturers in testing new equipment. Also, UMTA provides facilities and funds for tests at the Transportation Test Center.

Industry cooperation is further illustrated by sponsorship of the Assured Energy Receptivity Study, which aims to recover and reuse the energy normally wasted in braking electric transit cars. The initial study was funded and sponsored by 11 transit properties in the U.S. and Canada. APTA is currently seeking funds for additional work on specific techniques, including the following:

- Low-resistance third rails
- Connections between parallel tracks midway between substations
- Improved cables
- Wayside energy conserving apparatus, such as flywheels, inverter substations, batteries and/or capacitors
- Hardware development programs.

Energy Economy Study Priorities

Two major conclusions were reached in the Energy Study of Rail Passenger Transportation: (1) there is a need for energy economy studies of existing rail passenger system designs and alternatives; and (2) priority should be given to the larger rail systems, and to systems that would provide knowledge of general value. Energy economy studies would identify and describe wasteful design features, and evaluate alternative conservation programs in terms of their effects on total energy demands.

Equal care and attention should be given to the design characteristics of rail systems now in the planning and design stages and to the effects of their energy usage. With new systems, there is yet time to identify and avoid wasteful practices.

Candidates

The design characteristics and energy usage of certain individual systems or groups are recommended for priority attention because of their size or because their circumstances are such that results are likely to be applicable elsewhere. Among these are selected Amtrak routes and Auto-Train, in the national rail passenger transportation systems; selected suburban railroads in the New York, Philadelphia and Chicago regions, and the all-RDC Boston and Maine in the Boston region; and all of the heavy-rail and light rail transit systems.

Services and Energy Demands

Table 1 contains data on passenger services rendered and direct energy demands made by each of four system types. These data suggest that priority attention should be given in this order:

- Heavy-rail
- National network
- Suburban rail
- Light-rail.

Diesel-Electric Locomotives

Diesel-electric locomotive technology was treated in the companion series (Energy Study of Railroad Freight Transportation) because the great majority of locomotives are used for freight. However, the fact that diesel-electric locomotives used in the national network and suburban systems account for 30% of the energy used for rail passenger transportation indicates that diesel-electric locomotives have a substantial claim for attention in a program for energy conservation in rail passenger transportation.

Three technological features in diesel-electric locomotives are of particular interest for energy conservation in rail passenger service:

- Design engines to use turbosuperchargers driven by exhaust gas. These superchargers are said to promise 5 to 10% savings of fuel.
- Design locomotive engines to simplify starting. At present, locomotives standing for long periods often idle their engines

Table 1

SUMMARY OF PASSENGER-MILES AND DIRECT ENERGY DEMANDS BY MODE

Mode	Passenger-miles		Direct Demand- Petroleum Fuel Required					
			Electric Systems		Diesel-electric Systems		Total of Both Electric and Diesel Systems	
	x 10^6	%	Gal x 10^6	%	Gal X 10^6	%	Gal x 10^6	%
National Network	4,309.9	23	21.23	4	91.98	17	113.21	21
Suburban Rail	3,866.9	21	62.13	12	68.07	13	130.20	25
Heavy-Rail	10,295.8	55	278.45	52	--	--	278.45	52
Light-Rail	315.9	2	8.55	2	--	--	8.55	2
Total	18,788.5	101	370.36	70	160.05	30	530.46	100

to avoid the complexities and risks of damage associated with restarting. This is especially common in cold weather.

- Design auxiliary power units or wayside power sources to operate the "hotel" services for passenger cars (heating, ventilating, air conditioning and lighting) for standing trains, and to warm engines. These facilities would eliminate the need to operate the locomotive engine.

Example: Wayside Power. In Chicago, the Regional Transportation Authority reports that one commuter rail line uses a "hotel" power unit and power cables in the terminal to supply power for standing passenger cars. Wayside power is used to operate diesel engine warmers, thus avoiding the need to idle engines for long periods in cold weather. These features allow engines to be shut down for standing intervals longer than 15 min.

Electrified Systems

Among electric systems, heavy-rail transit, which accounts for 52% of all direct energy demands and 55% of all passenger miles, certainly warrants priority attention. Lower priorities, in order of descending direct energy demands, are electrified suburban railroads (12%), light-rail transit (2%) and electrified Amtrak lines in the national rail passenger network (4%).

Outline of Conservative Design Characteristics

The principal system elements or subsystems* to be addressed here are:

- Vehicles
- Rail lines and storage facilities
- Stations and parking lots
- Shops, offices, and other support facilities.

The discussion of operations in the previous section referred to certain nonproductive and wasteful uses of energy that resulted from system design characteristics, but did not describe the designs. The present discussion briefly describes some of those designs as well as technical innovations to conserve energy. The discussion of electrical supply systems in Section IV encompasses supply elements within rail systems as well as generation and distribution to the rail system. Readers interested in locomotive technology are referred to the companion report series, Energy Study of Railroad Freight Transportation.

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*Electrical supply subsystems are discussed in Section IV, Energy Economy in Electrical Power Supply Systems.

Vehicles

Rail passenger vehicles generate direct energy demands as follows:

- Transportation
  Power conditioning
  Propulsion of the vehicle plus its passenger load
  Operation of braking systems
- Passenger environment - heating, ventilating, and air conditioning, and lighting
- Auxiliary machinery
- Movements to form trains

Transportation

Transportation energy demands include power conditioning or regulation onboard the vehicle, acceleration, motoring (operation at normal speed), and the operation of compressors and related equipment to keep the brakes in a state of readiness and to actuate the brakes. Energy consumption in power conditioning varies widely, depending on the technology used; however, the amount can be significant. Energy consumed in acceleration and motoring is the major element of transportation demand, the exact amount depending on the following: empty weight of the vehicle; passenger load; grades; curvature of track; mechanical and aerodynamic friction; "speed profile"; and efficiency of electrical equipment, gears, and other propulsion components. Energy required for the braking subsystem is small. A complete review of this field is far beyond the scope of this study; however, certain important issues have emerged in this research and will be treated.

Matching Horsepower to Load

Diesel-electric locomotives realize their best fuel economy when the horsepower is properly matched to the load drawn. Passenger trains vary in length from 1 car to a maximum of 18 cars, a limit established by safety regulations. Therefore, locomotives of several different horsepower ratings would be required to match horsepower to loads. The needed variety of locomotive sizes is not available from suppliers and would not be economically feasible. Consequently, diesel electric passenger trains often waste energy because of the mismatches.

Example: Excess Horsepower. Amtrak has difficulty in matching locomotive horsepower to loads. Amtrak's new diesel-electric locomotives were initially designed for freight service, then modified to include passenger train features, such as a power supply and a heating system for cars. This expedient measure was necessary because United States Suppliers no longer design locomotives for passenger service.

Some Amtrak trains have excess power, but others are long enough to fully load one or more locomotive units. The waste of energy on some trains is partly offset by Amtrak's high load factor, 54%. Overall, Amtrak has a relatively good direct energy intensity of 4200 Btu/passenger mile.

Rail Diesel Cars

Rail diesel cars (individual passenger cars, each with its own diesel propulsion systems) may be an attractive alternative to drawing short trains by locomotives.

Example: Substitution of Rail Diesel Cars for Locomotives and Coaches. It appears that using RDCs to form short trains would conserve energy, compared with diesel-electric locomotives and coaches. A rough comparison can be made by using data from the Southern Pacific (SP) and the Boston and Maine (B&M) case studies in Volume 2, Description of Operating Systems.

In normal operations, the SP's shortest train is a 1500-hp locomotive and two coaches. Trains of this type are estimated to consume 89 gal of diesel fuel in a 47-mile revenue trip or 1.9 gal/mile. If SP trains were shortened to one car, energy consumption would be about 67 gal or 1.4 gal/mile. The B&M suburban rail system, which uses only RDCs, averaged 0.7 gal/car mile over the entire system in 1975.

Fuel consumption rates for the two systems reflect factors other than propulsion technology--for example, differences in climate and requirements for heat. However, most of the difference is believed to be due to the propulsion equipment. The data are compared in this tabulation:

	Gallons/Mile	
	One Car	Two Cars
SP - locomotive and coaches	1.4	1.9
B&M - rail diesel cars	0.7	1.4
Difference: SP - B&M	0.7	0.5

Data are not available for longer trains. However, the advantage would appear to shift to locomotive-drawn trains at three or four cars. Partial conversion of the SP to RDCs would probably conserve energy, but complete conversion would probably not.

Energy intensity on the entire B&M was about 3800 Btu/passenger mile, while the system average for the SP was about 2800 Btu/passenger mile. Part of the difference is explained by the additional energy used for heating by the B&M. On the other hand, 27% of the SP's trains have one or two cars and their replacement by RDCs should be considered.

Most RDC cars now in service are old. Budd has recently begun production of a new RDC model, the SPV-2000, and claims it has 6% better fuel economy than the older models. RDC cars are also available from foreign suppliers. Naturally, energy economy studies of possible replacements should consider the energy characteristics of new RDC models rather than the old.

Dual-Powered Vehicles

Both locomotives and multiple-unit rail cars have been designed to use two power sources: electric power drawn from wayside conductors, and power supplied by internal combustion engines onboard the locomotive or cars.

Example: Diesel-Electric/Electric. Dual-powered diesel-electric/electric locomotives are presently used on the Hudson and Harlem suburban rail lines from Grand Central Terminal in Manhattan to suburban communities in Westchester and Putnam counties. Electric propulsion is necessary in the terminal and in the underground lines to the north under Park Avenue. However, electrification ends at North White Plains and Croton-Harmon. Trains traveling beyond those stations depend on diesel-electric propulsion.

Example: Gas Turbine/Electric. The New York Metropolitan Transportation Authority (MTA), the Urban Mass Transportation Administration, and two manufacturers (General Electric and Garrett) have designed two dual-powered MU car models using gas turbine-electric and all-electric propulsion called GTE cars. Like diesel-electric/electric cars, these cars would allow trains to use both electrified and nonelectrified lines, would contribute significantly to the comfort and convenience of travelers and would reduce travel time. The eight GTE cars that have been produced (four of each type) have been demonstrated in service, but information on energy demands is not available.

Turbine-Electric Trains

Amtrak has 13 trains propelled by turbine-electric locomotives. These trains offer a lightweight design, sophisticated suspensions, and high-speed operation. Although data on direct energy demands are not available, it is doubtful that this design saves energy, compared with conventional trains. There are two reasons for this: first, the thermal efficiency of turbine engines is generally lower than diesel engines; second, the consist (number of cars) of Amtrak's turbine trains is not easily adjusted to match variations in passenger loads.

Single-End vs Double-End Controls

Single-end control means that a vehicle has a control cab in one end only and that it must face the "forward" direction in normal operation. Double-end control means that a vehicle or train has control cabs at both ends and can operate normally in both directions of travel.

Most PCC streetcars remaining in service in the United States have single-end controls and, consequently, must make 180° turns to change directions of travel at the ends of revenue routes. Although PCC cars have short turning radii, the need to make 180° turns requires more time, track, and land than is normally needed for double-end controls.

The light-rail vehicles now being manufactured to replace PCC cars have double-end controls and are able to turn back at the ends of revenue routes by means of switches and parallel tracks. Double-end control is generally available for heavy-rail and other rail passenger vehicles, but is sometimes obtained by considerable expenditure of time and effort.

> Example: A and B Cars. BART trains consist of two A cars, each containing one control cab and 1 to 8 B cars without control cabs. The A cars have single-end controls, and double-end control of trains must be achieved by placing an A car at each end of the train, facing opposite directions.

Locomotive-drawn trains are given double-end control capabilities by placing a control cab in the passenger coach at the rear of the train. The cab contains controls for the locomotive, brakes, etc., making possible what is called push-pull control.

Locomotives have double-end controls, but ordinary coaches have no controls. Therefore, in conventional operations, trains are turned by a lengthy sequence of steps: uncoupling the locomotive, switching to a parallel track, traveling past the coaches, switching to the first track, and recoupling the locomotive.

This process, which requires a considerable expenditure of time, labor, and equipment, is avoided by push-pull controls.

Example: Push-Pull Trains. The Burlington Northern (BN) suburban rail service in the Chicago region operates all trains in the push-pull mode, thereby avoiding waste of energy in turning trains at the ends of revenue routes. In 1975, BN had 98 plain coaches in service and 26 coaches with control cabs. In the push-pull mode, the locomotive pushes in the inbound (downtown) direction and pulls in the outbound direction. Trains used in the morning rush can be shortened to an appropriate length for midday service simply by uncoupling the unwanted cars and leaving them at the platform of the downtown station until needed for the evening rush. This assumes, of course, that the train has at least two cars equipped with control cabs. It also assumes sufficient storage track in the station for the idle cars. If not, the changes in train length are accomplished in a yard. Turning trains at the outer ends of routes is equally simple.

Energy intensity for the BN is 1900 Btu/passenger mile, which is quite low. The Southern Pacific, for example, has an energy intensity of 2800 Btu/passenger mile. There is no way to determine how much of the apparent favorable energy intensity results from push-pull operation.

Power Conditioning

Electric passenger cars and locomotives must be equipped to condition power, that is, change the electrical characteristics of power received from wayside conductors before delivery to traction motors and auxiliary equipment. Power conditioning always involves some energy loss. There are major differences among systems with respect to power conditioning requirements, technologies used, and energy losses incurred.

Intercity trains and some suburban trains receive ac power from overhead conductors at 25 or 60 Hz and at 11,000 to 25,000 V. This power is conditioned by transformer, rectifiers, smoothing reactors, and resistors to produce dc power at the various voltages needed by traction motors. Modern locomotives and cars use solid-state power conditioning to provide smooth, gradual changes of voltage needed to control acceleration and speed.

Electric locomotives have up to six axles, each with a traction motor and are up to 6,000 hp. In addition, Amtrak's multiple-unit electric coaches between Washington and New York share track serviced by electric locomotives.

Heavy-rail, light-rail, and some suburban rail passenger trains receive dc power from overhead or third-rail conductors. Nominal voltages vary between systems; 600 V is common, but 1000 V is used by BART. Within systems, voltages also vary greatly from time to time and place to place. Minimum levels are as low as 350 to 750 V; maximum levels are as high as 650 to 1200 V.[2] These variations add to the complexity of power conditioning (and to the recycling of energy for braking, as well).

Traction motors cannot operate on a constant voltage during acceleration or while motoring at various speeds. Conditioning is required to change voltage in steps or, ideally, by continuous variation. Auxiliaries on some cars also require power in a form other than that delivered to the car. That problem, which is relatively simple and small, is not treated here.

Control of Propulsion

A large fraction of the energy delivered to cars (e.g., approximately 80%) is used in acceleration and motoring; the remainder is used for auxiliaries. Consequently, the efficiency of power conditioning for propulsion is a matter of considerable technical interest and is quite important from the viewpoint of energy conservation.

The subsystems used to regulate voltage delivered to traction motors are called controllers. Two types of controllers are used: cam controllers and solid-state controllers.

Cam-Controlled Resistor Banks

Cam control, the older technology, is used on most existing rail passenger systems. The controller uses a bank of resistors and a set of switches, which are opened and closed by cams, to achieve the necessary voltage regulation. The controller delivers low voltage to traction motors at the start of acceleration, increases voltage during acceleration, and delivers the appropriate voltage while motoring. The use of resistors to regulate voltage during acceleration is wasteful, and is said to use 8 to 10% of all energy consumed during acceleration.

Techniques are available to reduce waste of propulsion energy while using cam controllers. For example, if speeds are limited to about 20 mph, traction motors can be operated in series, at one-half the nominal voltage. It is said that this technique will save about 40% of the power normally used for propulsion. At present, the slow speed of 20 mph precludes use of the technique; however, a variation of the technique allows somewhat higher speeds, while still realizing a significant saving in energy.

Example: Series Operation with Reduced Field. NYCTA has proposed modifications to the cam controller that would allow a train to operate at speeds to 35 mph with motors in series.[1] That speed requires little sacrifice of travel time for local service, where station spacings are about one-half mile apart. The change would produce about a 20% energy savings. The technology requires a controller change to add a step between the series notch and the parallel notch of the controller. The cost of car modification is said to be $4,000 per car.[5]

The key element of the second technology is an item of solid-state equipment called a thyristor or chopper. Solid-state control, a relatively new technical advance, is used on a small fraction of the transit fleet.

The chopper rapidly switches power on and off to reduce average voltage, and varies the on-off ratio to regulate voltage. Some energy is lost in this process, but much less than in resistance-heating with cam controllers. Solid-state control is said to save about 10% of the energy required for acceleration with cam controllers.

Example: Solid-State Controller. Choppers are presently used by BART, by the new light-rail vehicles in Boston, by UMTA's prototype state-of-the-art and ACT car, in South America, and in Japan. Tests have been conducted in Toronto and in Stockholm. Chicago Transit Authority is purchasing several cars with solid-state controllers for in-service evaluation. However, solid-state controllers are said to have experienced some reliability problems. Consequently, the technology is not yet fully accepted by the industry.

Other Control Technologies

Two other propulsion systems are currently being developed, and are expected to be very similar to a chopper controlled dc motor system in energy efficiency. General Electric has an ac propulsion system called Pulse Width Modulation (PWM). In this system, the dc power is converted to a form of alternating current which is used to operate "squirrel-cage" induction traction motors. Motor speed is controlled by varying the ac frequency fed to it.

This system has basically the same advantages as the chopper controlled dc motor and also promises reduced motor maintenance problems associated with dc motors, such as flashover, because commutators and carbon brushes are eliminated. The PWM requires more complex controls and a new motor, as compared to a chopper system, and will have a slightly higher acquisition cost. General Electric has done considerable design development and test work on prototypes for transit cars. Currently in prototype status, the PWM will require a minimum of about 4 years for development, testing, and demonstration before an order is expected by APTA[3] estimates.

Delco Electronics is developing a cycloconverter controlled self-synchronous motor. This motor is expected to require less maintenance than dc motors due to its ac configuration. Compared to a chopper system, however, the self-synchronous motor has more components and requires a circulating oil cooling system, more complex control and a new motor design, all of which result in an expected greater acquisition cost.

The self-synchronous motor is in the developmental stage with hardware installation and test planned as part of UMTA's Advanced Subsystem Development Program. APTA expects substantial technology development for at least six years before an order is placed.

Both the PWM and self-synchronous motors are similar to one another with respect to energy usage and all are superior to the cam controllers. Each of these motors have the capacity for regeneration braking with energy savings performance very similar to dc chopper control.

Control of Braking

Most cam-controlled cars are equipped for dynamic braking. During braking, the traction motors are converted to operate as generators. With cam control, resistors are used to vary the load on the generators and to regulate the braking rate. Electrical power produced by the recapture of kinetic energy is converted to heat in the resistor banks and dissipated to the atmosphere. In this low technology system, recovery of the braking energy for reuse as electrical power is not possible.

Braking by traction motors is also possible when solid-state regulation is used, as it is with cam controls. However, solid-state regulation has an important additional capability: the power generated during braking can be reconditioned to a standard, potentially usable form. This technique, called regenerative braking, is a far more complex and technically sophisticated process than that used in dynamic braking, where the characteristic or quality of the electrical power generated is of little concern. Regenerative braking is also one of the most significant potential sources of energy saving in electrical systems. Up to 30% of the propulsion energy of a train may be recovered through regenerative braking (or up to 65% of the kinetic energy of the trains at the start of braking). The additional cost of solid-state control vs. cam control is said to be about $28,000 per car.[6]

At present, few systems use regenerative braking. Nevertheless, the power output from regenerative braking can be made available for reuse when one of two conditions is met: the energy must either be delivered to the third rail and transmitted instantly to another user, or it must be converted to a nonelectrical form and stored for later use. If neither condition is met, the electrical energy produced by regenerative braking is simply delivered to resistors, converted to heat, and dissipated in the atmosphere, as with dynamic braking.

Although the conditions required for recycling or reuse of energy have proven difficult to meet, several possibilities still warrant consideration.

Energy can be redelivered to the third rail for transmission and use by other trains or some other "receiver" of dc power within the rail system dc network. However, for the third rail to be "receptive" at the moment of regeneration, another large demand for power must exist nearby, since low-voltage direct current cannot be transmitted long distances without large losses by resistance heating.

The natural receptivity of a system is the fraction of kinetic energy that can be transformed into electricity during braking and that can be effectively used by nearby loads. Receptivity is greatest when nearby trains are accelerating or motoring; it declines with increasing distance between the trains and with mismatching of braking and accelerating. It is most effective during rush hours, when many trains are running. Over 50% of a day's total train operating energy consumption commonly occurs during such periods.[4,5]

Energy from regenerative braking can also be delivered to the nearest substation, reconverted to ac at commercial standards and resold to the public utility company. Equipment is required for the reconversion, but efficiency as high as 95% may be achieved. In the past, utility companies have shown reluctance to participate in this process, citing difficulty in achieving necessary commercial standards, difficulty in accepting power in short bursts without disturbing their own regulation stability, and recording and billing procedures. However, because of rising costs of fuel, some utilities are now expressing interest in the concept.

<u>Example: Internal ac Distribution Network</u>. All substations of the new heavy-rail rapid transit system in Sao Paulo, Brazil can invert regenerated dc to ac power. The ac power network of the transit property redistributes the ac energy. An ac power network that connects the substations of a transit system is not commonly available. However, where available, the regenerated power can be distributed from any supplying substation to any demanding substation. The probability of achieving receptivity is greatly improved by having an ac network within the transit system; also, the problems of redelivery to the public utility are avoided.

In Montreal, Canada, one inverter substation feeds regenerated ac power into that property's ac power network for distribution to a power-demanding substation. MBTA is the only US rapid transit system having an integrated ac network. However, as MBTA begins to purchase power from the local utility, rather than supplying its own, this ac network may be abandoned. Ironically, such a change would occur shortly after the introduction of new light-rail vehicles that have regenerating capabilities.

A 25-Hz ac network links rotary converter substations that comprised about one-half of MBTA's total conversion apparatus in 1976. MBTA is replacing the rotary converters with 60-Hz silicon rectifiers. The cost of retaining the existing ac network is significant and may be greater than the benefits expected from recycling energy.

Storage

Energy receptivity could be achieved by incorporating energy storage devices at frequent intervals along the wayside (e.g., in stations or at electrical substations).

Wayside storage capacity could be tailored to ensure receptivity and thereby maximize recylcing of energy. As a side benefit, subway passenger station air conditioning and ventilation would be reduced by lessening the heat dissipation that occurs in conventional braking. A wayside energy storage system would require low maintenance because of more protected environment. Use of wayside storage, coupled with an in-system distribution network, might allow cost savings. APTA estimates that to absorb the full braking energy of a train braking from 50 mph, a 75-V differential is required between the maximum car regenerative voltage and the wayside storage device voltage. A 50-V differential would permit no more than 50% receptivity.[4]

Although no wayside energy storage systems have been built, several concepts are being considered. Among these, the wayside flywheel has received greatest attention. In this concept, each facility would contain a flywheel, a dc motor-generator, power conditioning equipment, and controls to permit transfers of energy to the flywheel for storage or from the flywheel for use by accelerating trains. Storage units might be located in stations or at electrical substations.

APTA estimates flywheel motor efficiency of 89% and a gearbox efficiency of 98%. A flywheel system would return a maximum of 76% of the energy received.[4] Since power is required to keep the flywheel at a minimum speed in the absense of braking trains, efficiency is highest when the system is heavily used. APTA estimated that a wayside flywheel of one type would cost $1.4 million. While the flywheel was estimated to reduce energy consumption by a significant amount--perhaps 20% of the energy used for propulsion, it was judged not cost-effective in the system studies because of the high capital cost. An energy economy study was not made, and it is not known whether or not a long-term energy saving would result.

Research and development efforts are devoted to reducing the cost, as well as the size, of flywheel energy storage designs. Present flywheels can store only a few kilowatt-hours of energy, and the cost per kilowatt-hour of storage capacity is excessive. Development of a superior flywheel hinges on the use of low-cost materials, such as high-tensile strength fiber-composite materials that have a high strength-to-density ratio.

Advanced materials have not yet been tried in flywheels of large size, but research is proceeding because it gives promise of reducing the costs of energy storage. A cost of $40/kWh is the goal, which would make economical the storage of several megawatt-hours per unit. If low-cost storage is achieved, flywheels will be used to reduce peak demands on public utilities, as well as to store regenerative braking energy.[6]

Batteries are also technically feasible as wayside storage devices and they can store energy for longer periods than the flywheel. Currently, however, batteries are not economically feasible, even with low-cost lead acid battery technology.

The cost per kilowatt-hour storage capacity would have to be reduced to about one-fifth the cost of lead acid batteries before battery storage would be feasible. Candidate materials for meeting this goal are molten sodium chloride, lithium-sulfur, and sodium-sulfur batteries--all under development for electric utility and electric car applications.

Onboard energy storage subsystems can also be installed. Two onboard storage units are being considered: the onboard flywheel system and the onboard hydraulic energy storage subsystem.

The most promising of the two technologies is an *onboard flywheel system*, including flywheel, motor generator, and power conditioning equipment. The power generated during braking is used to accelerate the flywheel. The stored kinetic energy is reconverted and used when the vehicle next accelerates. Estimates of braking energy recycled are as high as 35 to 38%.

Onboard flywheels, if suitable sized, have the advantage of always being able to accept and reuse generated braking energy. Unlike wayside storage, the flywheel system is as fully effective in nonrush hours as in rush hours. In addition, the flywheel requires no special alterations of the power distribution system, as do most regenerative systems. However, to maintain its speed of rotation, the flywheel requires a power input when the train is idle.

The main barrier to onboard flywheels is cost. NYCTA estimates a cost of about $180,000 to retrofit one car. One manufacturer estimates an incremental cost of about $30,000 per new car for flywheel storage and solid-state controls.[6] The savings in power cost is said to be about $6,000 per car per year. The incremental weight is about 6900 lb/car. Reduced reliability and greater maintenance costs are expected because of the added mechanical components, the complexity of its electronic control unit, and the problems of maintaining a vacuum on the system.

After considering all factors, APTA reports that existing flywheel technology is unacceptable and predicts a delay of at least 6 years before production orders are let.[3]

> Example: Onboard Flywheels. Prototype systems have been built by Garrett AiResearch. In 1976, two modified NYCTA cars were equipped with two flywheels and one chopper controller per car. Each flywheel could furnish 1.6 kWh of energy to accelerate the car. The cars were tested at the DoT Transportation Test Center and on the NYCTA system. MTA reports that 19% energy savings was measured (at the cars) during testing on the NYCTA system.
>
> The Advanced Concept Train-1 (ACT-1) cars, also built by Garrett AiResearch, have two flywheel energy storage units per car. ACT-1 car acceleration is controlled by switching from flywheel power to third-rail power at speeds above 20 mph.

Onboard hydraulic energy storage subsystems and hydraulically propelled cars may prove feasible. In these systems, the car is driven by hydraulic motors located on the axles. Energy is stored by pumping fluid into a high-pressure tank and compressing a gas. Energy is released by allowing hydraulic fluid to leave the tank, thereby lowering compression. This system uses only one electric motor; operated from track power and sized only large enough to maintain pressure in the accumulator and offset losses from train friction and operation of auxiliary equipment. Regenerative braking is accomplished either by using the hydraulic drive motor or a separate shaft-driven unit as a pump. Fluid from the braking pump charges the accumulator.[6] Hydraulic storage systems have attracted some interest, but they are not used.

Compressed air storage systems have also received attention, but no development work has been done. Major development programs would be required to use hydraulic or compression air storage.

Vehicle Accessories

The environment inside vehicles is a matter of concern in all transportation modes. To improve the quality of the interior environment, the measures now being taken by designers of rail vehicles will increase direct, indirect, and capital energy demands. These measures include air conditioning of cars, improved heating and ventilation, better illumination, and reduced noise. Energy studies are needed to evaluate the energy costs and benefits of these measures.

Some cars cannot be stored with auxiliaries turned off or thermostats turned down. Operation of vehicle accessories generates demands for considerable amounts of direct energy (see the Hot Storage examples above).

In other cases, it has been estimated that air conditioning, heating, lights, automatic doors, brakes and train control equipment use about 15% of the total energy consumed by cars in service. Air conditioning and heating are the most significant demands. Waste heat from traction motors and resistors could be exploited for heating.

Example: Passenger Comfort. Heating and air conditioning for cars in revenue service add significantly to energy demands. In tests conducted by Chicago Travel Authority in 1964, instrumented cars were operated and the results were used to estimate energy consumption under various conditions. Without any heat in the passenger space, energy consumption was 4.5 kWh/car-mile. With maximum heat, as would be used in winter months, energy consumption for car operation was 5.2 kWh/car-mile, an increase of about 16%. Air conditioning on new cars was said to add about the same demand in energy.

Car Weight

Power consumption is directly related to the weight of empty cars and the payload weight of passengers. Lightweight materials, shared equipment between married-pair cars, and longer cars are all steps that could be used to reduce weight. According to a computer simulation study, the ratio of energy input does not go up in proportion to the increase in car weight.[5] Rather, transportation of each pound of weight becomes more efficient for the heavier cars. Consequently, several large-capacity, heavy cars are more efficient per passenger than many small, lightweight cars.

Example: Car Weight. The lightweight BART cars weigh 59,000 lb empty for A cars and 56,000 lb for B cars. NYCTA cars of recent design have about the same length and size, but weigh 83,000 to 86,000 lb. The lower weight of the BART cars, a difference of about 27,000 lb, allows a considerable saving of energy. However, this saving is largely offset by BART's high acceleration and high top speed.

The weight of the passengers is small compared with the empty weight of the car. Increasing the payload increases the demand in energy by only a small amount. BART was designed to carry all passengers in seats. A full load (72 passengers) weighs about 10,800 lb, an increase in the gross weight of the vehicle of about 19%. The increased weight has little effect on mechanical friction and operation of auxiliaries and no effect on aerodynamic friction. Most of the energy demands are associated with moving the car and the carriage of the passengers themselves is accomplished with a small increase in energy demand. Thus, increasing the passenger loads of under utilized cars is one of the most effective measures available for energy economy.

Impact of Vehicle Design on Train Formations

The design of vehicles strongly influences the process of train formation and the handling of trains at the ends of revenue routes. The design features of interest are:

- Ease of coupling and uncoupling cars
- Location of control cabs
- Flexibility in the arrangement of cars within trains
- Double-end vs single-end operations

Ease of coupling and uncoupling cars is an important design goal. The designs of existing vehicles (and facilities) often make it necessary to operate trains with more cars and greater passenger capacities than is needed. Since passenger loads vary greatly with the time of day and night, from day to day during the week, and with the direction of travel, adjusting train lengths to match the loads generally reduces direct energy demand for operation of cars and reduces indirect energy demands as well.

Systems differ greatly in their abilities to adjust train lengths. One system appears to make few, if any, adjustments in train lengths. Some find it difficult to vary train length except between two levels--say, eight cars and four cars--and tend to make infrequent changes. Some cannot operate trains shorter than some given minimum, such as two or three cars, because of the design characteristics of the cars, power pickups, track layout, switch locations, and third-rail layout. Some have complete freedom to operate trains ranging in length from one to the maximum number accommodated by stations and can adjust train lengths at each end of each run.

Example: Complex Process for Forming Trains. BART's use of A and B cars, described above, makes it relatively burdensome and costly to makeup and separate trains. Trains are formed by bringing together the desired number of B cars and two A cars, properly oriented to face away from one another. Trains are lengthened or shortened by cutting the train, separating the two parts, inserting or extracting B cars, and recoupling.

From the energy viewpoint, this design forces BART to choose between two wasteful practices: if trains are not shortened, both direct and indirect energy are wasted by trains in revenue service; if trains are shortened, direct, indirect, and capital energy are wasted in yards. A comparison of the alternatives has not been made.

All systems have very light passenger loads on some trains; BART must always operate with at least two A cars (144 seats), regardless of the passenger load and other systems have similar constraints. From the energy viewpoint, it would be desirable to design small double-end cars with controls at both ends (what might be called an A-A car). If all other elements were designed to be compatible, any system could operate single-car trains with, say, 40 seats. The possibility of adding such a car to the BART fleet is worth exploring.

Example: Ease in Train Formation. The Lindenwold system design provides exceptional ability to makeup and separate trains, thereby matching train lengths to passenger loads. This ability is exploited to save direct and indirect energy (see Energy Economy in Operations). The Lindenwold system has four system design features not found in most other systems:

- The storage yard is at the end of the revenue route. The layout of the yard allows trains to bypass the yard and to enter and exit the storage area without changing directions. Numerous parallel tracks allow flexibility in the storage of cars, thereby facilitating the makeup and separation of trains according to a plan prepared before each day's operations.
- The current-collectors on cars, third-rail electrical power lines on the wayside, switches, and controls were all designed to allow one-car train operation.
- The 75-car fleet includes 25 cars with operator's cabs at both ends and 50 cars in married pairs with operators at both ends of the pair. Cars can be assembled in any order. Train consists can vary from one car to the maximum number allowed by platform lengths--six cars at present.
- The mechanical and electrical couplers between cars are reliable and easily operated. The coupler design makes frequent changes in train length possible without taking excessive time and effort and without introducing reliability problems.

Example: Limited Ability to Shorten Trains. Three rail systems in the New York region appear not to have the ability to adjust train lengths to match loads. This is brought out by a survey conducted by Tri-State Regional Planning Commission. (See Volume II.)

- One New York City Transit Authority (NYCTA) line operates four-car trains at 3:00 am, although the average loads observed by a survey team at 60th Street was only 4.2 persons/car. Energy intensity was about 15,000 Btu/passenger miles. If single cars had been substituted, energy intensity would have been about 3800 Btu/passenger mile (see Volume II).
- The Port Authority Trans-Hudson (PATH) system runs full-length trains during peak hours and half-length trains in slack periods.
- The Long Island Rail Road (LIRR) appears to do little to adjust train lengths. According to the same survey, trains entering Manhattan between midnight and 5:00 am had average lengths of 7.5 cars and carried an average of 1.5 passengers/car. One explanation offered for this practice was the lack of reliable electrical connections in the couplers between cars. Presumably, the connections are satisfactory when undisturbed, but often fail to make proper contact when reconnected. If this were the only reason for nonproductive operations, one could say that a very high energy demand was being accepted to avoid solving a technical problem for which solutions have been made elsewhere.

Facilities

General

The design of stations, parking lots, yards, shops, and offices strongly influences energy demands in all classes, but energy usage by these facilities is often neglected entirely in discussing and comparing energy intensities of alternative modes. This omission is partly explained by the lack of a formal methodology for energy economy studies and partly by the practical difficulties in obtaining data on the energy demands of facilities.

Turning Trains

The design of facilities for turning trains at the ends of revenue routes, together with the design of vehicles, strongly influences requirements for nonproductive travel by revenue vehicles; labor, goods and services for operations and maintenance; land or rights-of-way; and capital investments in track, switches and revenue vehicles. These requirements, in turn, generate direct, indirect, and capital energy demands.

Two basic methods are used to turn trains. One method switches the train from one track to another and reverses the traction motors.

The other method moves the train through a 180° turn, either by using a loop track of a Y-pattern of tracks and switches.

Double-end vehicles can reverse directions or make 180° turns; several systems do both. Examples are PATH, NYCTA, and the Lindenwold line. Single-end PCC street cars make 180° turns, but several large systems (San Francisco Muni and MBTA, for example) will soon replace PCC cars with double-end light-rail vehicles.

Diesel-electric locomotives are double-ended and can therefore use either of the two methods for turning. Reversing direction is usually the preferred method, since 180° turns require large amounts of right-of-way, track, and switches. When conventional controls are used to make the turn, the locomotives are uncoupled, shifted to the head of the train, and recoupled. This method requires switches, a parallel track, and yard labor to uncouple and recouple. When push-pull controls are used (see Vehicles above), turning is greatly simplified, since the locomotive need not be moved to the head of the trains and switches and yard labor are not needed.

The ends of revenue routes (where trains are turned) can be at intermediate points rather than at the ends of rail lines. This arrangement accommodates the heavier patronage near the central business district and avoids nonproductive mileage by turning some trains at intermediate stations used in this way, and work schedules must be adjusted for the train crews. Savings in direct and indirect energy would be expected from this practice. Capital energy would decline if the vehicle fleet size were reduced, but would increase for construction of tracks and switches.

Example: Turning Trains at Intermediate Stations. The Lindenwold line can turn trains at both ends of the line and at one intermediate station. This allows operation of revenue routes of two lengths: over the full length of the line and from the intermediate station to downtown. Trains on the short revenue route help meet peak demands but do not have to travel the full length of the line. Similar practices are followed by CTA, NYCTA, and PATH, but not by BART, SP, MUNI, and MBTA.

Adjusting Train Length

The location and layout of facilities used to adjust train lengths can strongly influence nonproductive travel. It is desirable to adjust train lengths at or near the ends of revenue routes, i.e., at the ends of lines and at intermediate stations where trains are turned. However, land is often difficult and costly to obtain in the appropriate places, and, as a consequence, many yards and storage tracks are poorly located, making nonproductive travel unavoidable.

Example: Conceptual System. A system has been conceived, but not yet implemented in rail transportation, that would lower nonproductive mileage to a theoretical minimum. The concept calls for the adding or separating of cars at every station along the route. This scheme would keep train capacities in close correspondence with loads. Storage would be required at each station. Also, advances in rail technology would be required to couple and uncouple cars and to move empty cars by automatic control. At present, this scheme would delay trains excessively, require yard labor at each station, and cause hazardous conditions.

One automated guideway transit system, the Westinghouse Transit Expressway, was originally designed to allow train lengths to be changed at stations and to permit storage or delivery of empty cars automatically. The basic hardware and controls for this system are now in revenue service at the Seattle-Tacoma International Airport. That installation demonstrates the techniques in its daily operations and proves the concept is technically and operationally feasible.

Electrification

Most intercity and suburban rail passenger lines are nonelectric, a few are fully electric, and some are partly electric, partly nonelectric. No cases were found where electrification of nonelectric systems was an issue. However, extension of electrification on partly electrified lines is an important issue on the Long Island Rail Road, on the Hudson-Harlem and New Haven Divisions of Conrail north of New York City, and probably on other lines not noted in the research. Electrification requires large capital investments in wayside substations, third-rail or overhead conductors and other equipment, and large capital energy demands; electric trains are lighter than locomotive-drawn trains and savings in direct energy are claimed for electric systems. An energy economy study would be required to substantiate or counter the claim.

Station Heating, Ventilating, and Air Conditioning (HVAC)

Making rail passenger stations comfortable in all climates and seasons is a challenge that has nowhere been met. If high standards of comfort are to be achieved, large demands for direct, indirect, and capital energy must be accepted. Old stations were designed with few concessions to passenger comfort; consequently, energy demands for this purpose are low. Stations recently constructed or designed for future systems include HVAC systems that are costly in terms of energy and money. UMTA has sponsored a major study by Kaiser Engineers, PBQD, and DeLeuw Cather to identify cost-effective concepts. Treatment of the entire subject is not possible in this report, but a few examples follow.

Example: Timed Heaters. About 15% of Chicago Transit Authority stations provide timed infrared heaters for passengers waiting on the platforms. Typically, three overhead infrared heaters beam heat into a small platform area equipped with wind screens. To get 5 min of heat, the awaiting passenger pushes a button. Heaters are disconnected in warm weather. This demand-response timed heater control has a secondary benefit: it avoids the attraction a warm station would have for loitering persons during cold months.

Example: Train Screen. A train screen is a wall used to isolate the passenger platform from the right-of-way and to provide access to trains through elevator-type doors. The Leningrad subway and at least a dozen automated guideway transit systems in the United States use train screens. One of these, at the Seattle-Tacoma International Airport, is designed for 100-passenger cars and 4-car trains.

Station Lighting

While old rail passenger stations frequently had poor lighting, some new stations appear to have moved to the opposite extreme. Careful consideration should be given to the level of lighting actually required under all conditions of weather, season, station traffic, time of day, and hours of operation. Lighting circuits should allow alteration of lighting levels according to actual needs; control should be automatic or by remote means from central locations.

Tunnel Lighting

Tunnel lighting is a relatively small proportion of the total energy used in the transportation system, but energy can be saved. Tunnel lighting is needed for safety in train operation, for workmen in the tunnel, and on rare occasions, for evacuation of trains. MBTA uses florescent lights rather than incandescent lights to conserve energy. CTA, finding that low-pressure sodium lights are twice as efficient as florescent lights, plans to install these yellow-tinted lights on the outer portions of station platforms.

Heating Rails, Switches, and Electrical Facilities

Rail service on surface and elevated lines can be interrupted by snow and ice deposits on rails, switches, power conductors, and insulators. It is probably not feasible to design systems to avoid these problems during severe winter storms, but on such occasions much of the activity in the affected city is temporarily suspended. Under less severe weather conditions, the rail system is usually kept operating, which usually means that ice deposits on rails and switches are avoided by fuel-burning heaters and icing of wayside power supply elements is controlled by electrical heating. (Ironically, conventional electric trains dissipate large amounts of heat in resistor banks, but no way has been found to apply the heat to wayside components subject to icing.)

Example: Third-Rail Heaters. MBTA has estimated that third-rail heaters rated at 70 W/foot (including a 20-W margin of safety) are needed to avoid icing on exposed track. When operating, this system imposes a 10,000 kW direct energy demand. Operation is required only briefly each year. If operation totaled 100 hr--an assumption--direct demand would total 1,000,000 kWh. That figure is not alarming for a system now using 204 million kWh per year; however, the public utility must have sufficient reserve capacity to satisfy these occasional, short-term demands for electrical energy. The capital costs borne by the utility for generating capacity (and the associated capital energy demand) are far more significant than the direct energy demand for heating *per se*.

Example: Selective Heating and Other Methods. CTA uses three methods to combat icing. Third-rail heaters are used on inclines. A material called "sleet grease" is used as a third-rail coating in selected areas; it tends to prevent bonding of ice to the third-rail surface. Mechanical devices called "sleet scrapers" are mounted on cars, ahead of the current collectors. Scrapers are engaged by the operator, when needed, to remove the ice mechanically.

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IV ENERGY ECONOMY IN ELECTRICAL POWER SUPPLY SYSTEM

This section deals with the supply of fuel and electrical power to rail passenger vehicles and facilities.

Petroleum Fuel as a Measure of Energy Usage

The energy for diesel-powered rail passenger transportation comes from crude oil. Energy for electrical systems comes from oil, gas, and coal products and from hydroelectric, nuclear, and geothermal sources. Because of our ability to transfer electrical energy from region to region, we have assumed that substantially all of the energy saved in rail passenger transportation--regardless of source--can be used elsewhere by customers who now burn oil to generate electrical power. We have assumed that substantially all of the energy savings from a rail energy conservation program can be used to reduce the demand for crude oil. Some electrical supply systems can meet off-peak rail energy demands from nuclear, hydroelectric, or geothermal plants when there are no demands from oil-dependent customers in other areas but this is believed to involve only a small quantity of energy used by rail systems.

In this research, the energy supply "pipeline" has been traced back only as far as the diesel fuel and fuel oil stages. Energy used to extract, transport, and refine the oil has not been studied. Demands for direct energy have been expressed in terms of gallons of fuel, by type, and total thermal energy of the fuel in Btu. Differences in heating values among fuels have been recognized in estimating Btu, but gross measures of fuel consumption add gallons of fuel oil and gallons of diesel fuel without recognizing differences in heating values.

Classes of Energy Losses

A large amount of energy is lost or consumed between the time the fuel is removed from storage tanks at the electrical generating plant and the time it is delivered as electrical energy to the rail vehicle or facility. Also, the efficiency of generating plants and distributing processes differs greatly among suppliers, as does the efficiency of internal conversions and distribution functions among rail systems.

The following general observations are worthy of special notice:

- The energy losses or efficiencies of electrical power systems differ substantially from plant to plant within supplier systems and among suppliers. Efficiencies in generating plants have increased greatly over the past decades, but some of the older generating plants used to supply rail passenger systems are grossly inefficient in comparison to the national averages.
- The quantities of energy used by the power companies, and the losses of energy in delivery to the rail passenger systems, differ among suppliers, but only to a relatively small degree. National average losses between generating plants and customers averaged about 9.3% in 1974.
- Energy is lost in converting from ac to dc at the rail system's substations. The efficiency of conversion equipment has been twice improved in the past few decades with the introduction of advanced equipment. Again some old, energy-wasteful conversion equipment remains in service, awaiting availability of funds for modern replacements.
- Energy is lost between substations and trains by resistance heating in conductors. Significant resistance heat losses occur when transmission distances are excessive, when transmission lines or third-rail tracks have excessive resistance, and when insulators are poorly maintained.

Energy Losses in Generation and Distribution

In 1974, public utilities in the United States consumed 1 gallon of fuel, having an average heating value of 145,719 Btu, to produce 13.90 kWh of electrical energy, of which 12.92 kWh were delivered to consumers. On the average, each kilowatt-hour purchased by a rail system represents 0.077 gal of fuel oil, having a heating value of 11,278 Btu (1 kWh of electrical energy is equivalent to 3415 Btu of thermal energy at 100% efficiency in conversion). Thus, the entire process, from fuel to electrical energy purchased, has an efficiency of 30%. Electrically powered rail systems are found in only eight regions; in two of those regions, the efficiencies of power supply systems are significantly lower than the national average.

Example: Inefficient Steam Plants. During 1975, MBTA obtained about one-third of its electrical power from a public utility and generated about two-thirds of its power in two old and inefficient steam generating plants that used 23,970 Btu/kWh, a figure 113% above the national average. The need to retire the plants has long been evident, and present plans call for refinement by 1981. Reduced energy consumption is an important consideration as is a dependable power supply to avoid train service interruptions.

Example: Low Thermal Efficiency. Consolidated Edison (Con Ed) has supplied electrical power to NYCTA in recent years. Energy use by Con Ed is higher than the national average, both in generation and in distribution. Fuel having a heating value of 13,680 Btu/kWh is consumed to supply NYCTA--21% above the national average. NYCTA is, by far, the largest heavy-rail transit system in the United States. In the year ending June 30, 1975, NYCTA purchased 2.05 billion kWh of electrical energy. About 192 million gal of oil were consumed to produce that energy. The oil consumed would have been reduced to about 159 million gal if Con Ed had been as efficient as the national electrical industry average. The difference, 33 million gal, would reduce NYCTA's energy intensity from 3700 Btu/passenger-mile to 3200 Btu/passenger-mile (or it would supply BART's direct energy needs for 18 months).

The State of New York recently purchased a fossil fuel power plant now under construction. When completed, the plant will supply power to NYCTA. New plants usually are more efficient than the national average for the industry. If the new plant were 10% above the national average, NYCTA's demand for energy, expressed in terms of fuel oil, would drop about 30% below present levels--to the order of 134 million gallons--perhaps the largest single energy conservation gain obtainable for rail passengers transportation.

Losses in Conversion and Delivery

A significant fraction of the electrical energy purchased for operation of cars is lost in the process of conversion and delivery to cars. Equipment now used for ac-dc power conversion are of three technical types:

- *Rotary converters* (motor-generator sets) are the oldest and have the least efficiency (about 90%). Rotary equipment now in service is being phased out as funds become available.
- *Mercury rectifiers,* available for many years, are about 95% efficient and have been used as replacements for rotary equipment.
- *Silicon-controlled rectifiers,* the most modern technology, have 98% efficiency, and are now being installed in most systems as funds become available.

Example: High Losses in Conversion and Distribution. In San Francisco, Muni loses significant amounts of energy in ac-dc conversion and distribution of electrical power to trains. A study of the system showed a dead loss of 11,163,723 kWh/yr in the system. This loss ranged from 9 to 15% of the annual total over a 6 year period. The losses appeared to occur mainly in ac-dc rotary converters and through insulators on the trolley lines.

The Chicago Transit Authority reported a 7% loss of energy in conversion in 1975 but said losses in distribution were negligible. The CTA is reequipping 16 substations with silicon rectifiers. Fourteen substations now have rotary converters and two have mercury rectifiers.

Power from the substation to the vehicle is commonly distributed by copper alloy catenaries for electric intercity rail, suburban rail, and light rail transit. No improvement over copper is anticipated. All heavy-rail transit systems and some suburban rail systems, with track protected from the public, use steel third rails for power distribution. The third rail has a larger cross section than the copper catenary but higher resistance per unit of cross section. Both conductors lose about the same amount of energy, said to be about 5% in typical cases.

A composite aluminum and steel third rail is currently used in several heavy-rail systems. It consists of a steel rail with two aluminum extrusions or castings securely fastened to the rail web to form a composite conductor. Aluminum is the primary current-carrying component; the steel provides the wearing surface for the collector shoes. Composite rails have over twice the electrical conductivity of all-steel third rails.

The power distribution system includes both the third rail and the two running rails. The combined resistance must be low enough to avoid excessive power loss. Use of the composite third rail addresses only half of the problem and promises to produce something less than the full 5% savings. Low-resistance grounds or return conductors are needed to achieve the full savings.

Reduction of distribution losses is only one attraction of the composite third-rail. Another is that substations can be spaced further apart and some can be eliminated, at a cost savings of around $1 million per substation and corresponding savings in capital energy demands.

The technical and economic benefits of the composite third rail appear to be widely accepted; over 160 miles of rail have been installed in five systems. However, the next property scheduled to start operation, MARTA, has decided to use an all-steel third rail because it has a lower capital cost than composite rail.

V ENERGY ECONOMY IN MODAL CHOICE DECISIONS

Estimates of modal split (the division of travel among rail and other available modes) require detailed knowledge of the characteristics of travel demand as well as the characteristics of rail and competing modes. This research deals with rail passenger transportation only and, therefore, has not estimated modal splits. Instead, the research and the discussion that follows treats general factors that influence modal choice and that might increase (or decrease) travel by rail.

Availability of Service

By and large, rail passenger transportation is only available in parts of eight metropolitan regions and on a sparse national rail passenger transportation network; it is not available for the vast majority of travelers and trips. For example, in 1975 rail passenger transportation accounted for only 2% of the passenger-miles in intercity and urban travel.

Choice Riders

In the U.S. about 55% of the population old enough to need independent mobility (assumed to be age 10 and older), have drivers licenses and first claim to a private automobile. These people can be said to enjoy full "auto-mobility." Most of these individuals tend to adopt life styles based on auto-mobility: the places they choose to live, work, and shop are those that can be reached by auto. However, some members of this group use rail transportation by choice. Some live in suburbs and work downtwon; and use rail transportation to avoid travel on congested roads, payment of bridge tolls, and costly parking. Many commuting trips made by these persons are exceptionally long. For example, average trips on suburban railroads are about 25 miles long, which is nearly three times the length of the average auto trip to work. From the viewpoint of energy conservation, very long commuting trips via rail could well be regarded as wasteful, even when the energy intensity per passenger-mile is low for suburban railroads.

Other choice riders use subways, light-rail, and intercity service.

Limited Mobility Riders

At least 41% of the population that is age 10 or older do not enjoy auto-mobility or are auto-mobile to a limited degree. These are the persons who do not drive or who do not have first claim to a private auto. They are large users of rail and other modes of public transportation where good service is available. They tend to congregate in areas where transit service is available--for example, in Manhattan where 78% of the households do not have cars and subway travel is heavy. Otherwise, they are chauffeured by relatives and friends, use taxis and other paratransit modes, ride bicycles, and walk. Unfortunately, many limited mobility persons forego some opportunities enjoyed by the auto-mobile population.

Marketing

The amount of rail passenger transportation supplied and used is very small in comparison with the population of potential riders. This is in sharp contrast to the conditions in the early 20th century when rail transportation systems were the dominant suppliers of intercity service and suburban and urban service in large cities.

The decline in rail transportation market share has resulted from competition form other modes rather than a breakdown in marketing.

Suppliers of rail passenger systems cannot afford to employ a sales force to increase rail modal split by selling services in face-to-face contact with riders. Marketing programs and advertising enjoy some success when they accurately publicize substantial improvements in service and provide information to the public on areas served, station locations, routes, schedules, hours of service, and fares. The value of marketing programs that are based on broader appeals, such as relief of congestion or claims that use of rail transportation saves energy, is difficult to assess.

Service and Cost Effectiveness

If rail patronage is to be increased, the principal measures needed are to improve and increase service. Suppliers of rail passenger transportation and agencies of local, regional, state, and federal government need to focus attention on three factors: the cost-effectiveness of existing systems; the means to improve or extend service; and the effects of possible changes or alternative programs on patronage, costs, and energy usage.

Changes can be of limitless variety. Table 2 lists types of changes and classifies actions under two headings: those that would usually have positive or negative effects on quality and supply of service:

Table 2

MEANS TO ACHIEVE POSITIVE AND NEGATIVE EFFECTS

Type of Change	Positive	Negative
Number of rail systems	New construction	Abandonment
Miles of line	Extensions	Shortening
Number of stations	Additions	Closures
Hours of service	Longer hours--up to 24 hr every day	Fewer hours and days of service
Frequency of service	Short headways	Long headways
Travel time (including enroute stops)	Higher speeds, fewer stops	Lower speeds, more stops
Access to rail service	Parking, integration of bus service, special collector and distributor systems	No access programs

Comfort, convenience, and safety features are provided in varying degrees and are generally regarded as desirable and effective in increasing patronage. Changes promising positive results are outlined here:

- Shelter and seats for waiting passengers
- Heating, air conditioning, and ventilation
- Lighting
- Traveler information (posted routes, schedules, and fares; fixed and changeable direction signs; public address system; and telephone inquiry system)
- Security measures (station attendants, mobile police and dogs, traveler-actuated alarms, TV monitors, and station layouts to facilitate observation of all areas).

Round-the-Clock Service

Some suburban railroads and rail transit systems provide 24-hr service every day of the year, while others discontinue operations during parts of the nights and weekends. Shutting down in slack periods saves money and energy, but it can be argued that the practice should not be followed because the lack of service makes it impossible for some travelers to depend on rail transportation, and discourages patronage by others who travel at irregular times.

Careful consideration should be given to providing round-the-clock service on rail routes without needless expense and energy usage. Several schemes appear worthy of consideration:

- Substitute bus service for rail service in slack periods, as is done by the San Francisco Muni.
- Operate one-car trains in slack periods, as is done by Lindenwold.
- Develop small transit cars and special operating procedures, exploit cars having small capacity, low acceleration and low speed operation, long headways, and with fully automated and stationary vehicle controls. (This might be possible on BART.)
- Close selected stations, operate trains in an "express" mode, and provide "local" service via bus on parallel streets.

Impact of Change on Energy Demands and Intensities

The positive changes outlined above generally increase capital and operating costs and many will increase direct, indirect, and capital energy demands as well. Therefore, all significant changes must be justified by energy economy studies in which energy demands, patronage, and costs for all alternatives--positive, negative, and no change--would be evaluated and compared with one another.

Some spokesmen for rail passenger transportation voice a conventional wisdom that rail passenger transportation is clearly attractive from the viewpoint of energy conservation, as well as other respects, and therefore require no further evaluation. The evidence uncovered in this research shows very clearly that such a generalization is not supportable. There are very large variations in *direct* energy intensities among trains within systems--a 50:1 variation in one case--and there are very large variations among systems with respect to the direct energy intensities averaged over the entire system for a year's operation. Thus, any comparison of direct energy intensities among modes of travel cannot be based on industry averages, but must recognize the great variations within and among systems.

Furthermore, little has yet been accomplished to understand the effect of changes in rail passenger transportation on indirect and capital energy demands.

Evaluation of Prospective Changes

Changes in rail systems cannot be evaluated until costs, patronage changes, and total energy effects can be assessed. Furthermore, adequate evaluation is not possible until comparisons can be made with changes in energy impacts in bus and auto transportation, in community usage of energy, and in supporting industries.

Great improvements are needed in data bases and in methods of analysis before adequate evaluations can be made.

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VI INDUSTRY FUTURE

The outlook for the continuation of existing rail passenger systems and for new construction is mixed. The future depends upon shifts in public policy and availability of funds, which can change abruptly, as well as upon economic forces or energy considerations. However, certain upper and lower boundary conditions appear reasonably predictable.

At one extreme, the rail systems serving "old", rail-oriented cities appear certain to survive. At the other extreme, to argue that rail systems will experience regrowth to a size double that now in existance is difficult to support. Between the extremes are many uncertainties regarding the fates of specific programs now underway or planned.

Continuation of Old Systems

The land use patterns of Boston, New York, Philadelphia, and Chicago (and, to a lesser degree, Cleveland) and the physical development of their suburban railroads and rail transit systems are thoroughly interdependent. Discontinuation of the rail services would reduce greatly the value of the land and buildings throughout those cities and would force major relocations and adjustments of job sites and other economic activities. The same argument can be applied, but with less weight, to discontinuation of the most heavily traveled Amtrak routes, especially between Washington and Boston.

Historical experience supports the belief that these rail systems are generally regarded as necessary. Everytime one of the major "old" systems has experienced financial troubles sufficient to threaten discontinuation of service, an institutional arrangement and financing scheme has been worked out to prevent discontinuation. Unfortunately, many of the schemes have had short useful lives and have had to be revised to meet new crises. Only a few, such as PATH and PATCO, have the appearance of permanence.

New Construction in Progress or Planned

A $1.7 billion improvement program is in progress on Amtrak's northeastern corridor line. Numerous modernization projects are in progress on suburban railroads, heavy-rail systems, and light-rail systems. However, the principal focus of attention is on the extension of existing transit systems and the building of new systems. In that area, the outlook is not encouraging.

A New York Times* news story dealing with federal policy in new investments in rail transit summarized the status of present and planned transit systems as follows:

	Mileage	
	Present	Planned
Atlanta	-	53
Baltimore	-	8
Boston	62	29
Buffalo	-	6.5
Chicago	89	12
Cleveland	19	-
Miami	-	17
New York[a]	231	45
Philadelphia	37	2
San Francisco[b]	71	-
Washington	19	83

[a]NYCTA only

[b]BART only

The same news story quoted federal officials in key positions to the effect that completion of the planned rail additions and of new rail systems is in no way guaranteed. Mr. Richard S. Page, Administrator, Urban Mass Transportation, was quoted as follows:

> *Any recommendation to UMTA for assistance in construction or extension of a rail system will have to demonstrate clear and convincing need for such a system in transit terms--not just marginal need based on future and uncertain possibilities.*

He was quoted further:

> *We have probably seen the last of the big regional subway projects.*

Atlanta may now complete only 13 miles of the 53 miles of line planned. Also, the 8-mile starter line now in progress at Baltimore and the 17-mile starter line being designed for Miami, may in fact, be the only lines constructed in those cities. Parts of the 45 miles of line planned for New York have been under construction for many years; but progress has been slowed by lack of funds and there is doubt that all elements will be finished. Even portions of the 83 miles of heavy rail remaining to be constructed in Washington may never be completed.

*September 13, 1977.

Limitations on Major Regrowth

Leaving aside changes in policy that occur with changes in administration, three durable and unalterable factors argue against the notion that the rail transit industry will grow very far beyond its present size. First, building and operating rail passenger systems is costly in money and energy (see BART in Volume II). Second, heavy patronage is necessary to lower the cost per unit of service (or system cost effectiveness) to an attractive level. Third, the conditions of high population density and high job density needed to achieve heavy patronage are found in few, if any cities, other than the "old" cities mentioned above.

The total energy intensity for new rail transit systems in low-density cities is unlikely to be competitive with either the energy-efficient private autos of the 1980s or with urban buses. (See BART in Volume II). These factors suggest that large-scale development of rail transit systems will not occur (without corresponding major changes in density of land-use patterns) regardless of the cost of energy.

Conditions that would warrant large-scale increases in Amtrak's route structure or in the amount of service offered are also unlikely. In fact, it can be argued that Amtrak carries a heavy burden of proof that its present route structure is justifiable, in the long run, from the viewpoints of energy conservation and economics. This view appears to be held in Congress. Funds appropriated for FY 1978 are not sufficient to maintain services offered in 1977 and Amtrak has had to make painful decisions regarding service reductions.

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VII FEDERAL ROLE

Local Initiative

The institutional structures used to deliver rail passenger transportation services are extremely complex and varied. (See Volume III.) Although the federal government has assumed a large part of the financial responsibility for continuation and improvement of rail passenger transportation, it has not taken direct command. Instead, the power to initiate changes has been left with operating agencies but is limited. (Amtrak's position is somewhat different. The appropriation to cover its deficit must be passed each year, and Congress can therefore mandate changes of certain kinds.)

Energy Economy Studies

On the other hand, federal agencies can establish procedures and rules that must be followed before operating agencies can obtain capital grants and operating assistance. Thus, it appears possible at present to require operating agencies to prepare energy economy studies (or energy impact assessments) as part of their capital grant applications and transportation management plans. In fact, this plan appears the simplest, most direct, and most powerful way to promote energy conservation in rail passenger transportation and to prevent expenditure of federal funds on energy-wasteful projects.

Before instituting a requirement for energy economy studies, there is a need to develop and document methods for the conduct of such studies. Also, there is a need to establish criteria to be used in judging the adequacy of the energy economy measure taken. Sponsorship of methodological work and determination of criteria are appropriate federal roles.

Full Capital Subsidy

Present legislation and policy allow UMTA to make grants covering up to 80% of the unrecoverable investment in capital assets that are purchased by public agencies for use on suburban railroad and transit systems. The requirement for a 20% local investment is intended to ensure serious evaluation of investments at the local level.

We propose that consideration be given to a change of policy to allow DOT and DOE to provide 100% federal grants for those energy economy measures that are supported by competent energy economy studies and that measure up to certain criteria. Legislation would be needed to authorize DOE to participate in the program and to appropriate funds to DOE to cover 20% of the capital costs of approved projects. This proposal assumes that energy conservation is a matter of national concern, and that financial support of worthy measures is a proper function of the federal government. It also recognizes that local rail transit agencies have many goals and limited funds. They tend to have a narrow, short-term view of energy conservation, and find it difficult to allocate limited local resources to energy projects, even to achieve large reductions in operating costs.

Emphasis

The findings of this research make it clear that existing rail passenger systems waste large amounts of energy because of design features and operating practices that could be corrected. Much of the needed technology and hardware is commercially available, and other technical elements would be developed by private firms if there were reasonable assurance of profitable markets. We propose that the federal role in hardware development be limited to high-risk technologies, system level development projects involving several sub-systems, and major demonstrations.

The Department of Energy should place primary emphasis and support on proposals to correct energy deficiencies in existing systems but should support efforts to avoid waste of energy in the design of new systems.

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