TRANSPORTATION RESEARCH RECORD
552

Rail Transit Development

4 reports prepared for the 54th Annual Meeting
of the Transportation Research Board

TRANSPORTATION
RESEARCH BOARD
NATIONAL RESEARCH
COUNCIL
Washington, D. C., 1975

Transportation Research Record 552
Price $2.60
Edited for TRB by Joan B. Silberman

subject areas
82 urban community values
84 urban transportation systems

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LIBRARY OF CONGRESS CATALOGING IN PUBLICATION DATA

National Research Council. Transportation Research Board.
Rail transit development.

(Transportation research record; 552)

1. Local transit–Congresses. I. Title. II. Series.
TE7.H5 no. 552 [TF710] 380.5'08s [388.4'2]
ISBN 0-309-02458-7 75-42199

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RAIL TRANSIT—CHARACTERISTICS, INNOVATIONS, AND TRENDS

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Rail transit, including streetcar, light rail, rapid transit, and regional rail, is a family of transportation modes with a broad range of service, operational, and cost characteristics. Consequently, these modes may be used efficiently for various conditions. As a result of numerous technological and operational innovations of rail systems during the last two decades, rail transit can be highly automated, reliable, and comfortable and can operate with minimal environmental intrusion. Although several U.S. systems (e.g., Lindenwold Line and Bay Area Rapid Transit) have some advanced features, general knowledge and understanding of rail systems in this country lag behind those of some western European countries and Japan. Based on a comparison of the population characteristics of selected European and U.S. cities, this paper shows that, among cities with similar population size and density, European cities generally have a much greater application of rail transit. Despite extensive research into new technologies, no new mode has emerged with performance and cost characteristics superior or comparable to rail technology. Thus, to achieve more efficient and economical transit systems, information about rail modes must be increased and these modes must be included among the alternatives considered in transit planning.

•MODERN transit planning places increasing emphasis on the development of alternatives and their comparative evaluation. For this purpose, a thorough knowledge of different transportation technologies and familiarity with the latest technological developments and general trends in uses of individual modes are needed.

Numerous recent developments and innovations in rail transit have received little coverage in professional literature, and the technical material generally available about modern rail transit technology is limited. The purposes of this paper are to present a definition, description, and classification of modern rail transit systems and to provide an overview of the characteristics of different rail transit modes.

Rail transit consists of a family of modes with different technological, operational, and service characteristics. On the basis of these features, rail modes are classified into four categories: streetcar, light rail, rapid transit, and regional rail. Each mode offers ranges in service quality, types of operation, and costs. The composite range of features among the various rail alternatives permits an efficient use of rail transit over a wide range of travel requirements and conditions.

FAMILY OF RAIL SYSTEMS

Streetcar

Streetcar systems consist of one, two, and occasionally three rail vehicles operating mostly on streets in mixed traffic, sometimes with limited separation from street traffic on private rights-of-way. Although their comfort and dynamic characteristics are good, when they operate in mixed traffic their service quality is often unsatisfactory. Street conditions generally keep operating speeds below 12 mph (20 km/h). The comfort, schedule reliability, speed, and passenger attraction of streetcars are consequently similar to those offered by surface buses and are inferior to those of other rail modes.

The positive qualities of streetcars include a higher capacity and a more distinct image than that of buses, and a lower cost for right-of-way than for other rail modes. Selective application of traffic priority measures including reserved lanes and provision of some private rights-of-way (both of which are inexpensive improvements) can greatly enhance the attractiveness of the streetcar mode. Yet, the greater facility with which buses serve low-density areas and the trend to upgrade heavily traveled streetcar lines into higher quality rail systems have resulted in the conversion of most streetcar lines to either bus or light rail; consequently, this mode has experienced a general decline in ridership and a diminishing role in urban transportation.

Light Rail

Light rail systems (Figures 1 and 2, Table 1) typically have articulated six- or eight-axle vehicles or multiple unit trains of up to three four-axle cars. Modern light rail vehicles, such as the six-axle vehicles produced by Boeing and several European manufacturers, incorporate high comfort levels, high- and low-level boarding capabilities, and modern electronic control and communications equipment. Although their purchase price is high ($300,000 to $400,000/car), their high capacity and operating speed and long life (25 to 30 years) make their cost per passenger-mile (kilometer) similar to the corresponding cost of other transit modes. Costs, however, vary greatly with local conditions, operating practices, system characteristics, and, of course, with time.

Light rail operates substantially on private rights-of-way that are often grade separated. Tunnel sections are frequently used in the most critical areas of the city, and this greatly enhances the quality of service light rail vehicles offer. The alignment standards and station features of light rail systems can be the same as those of rapid transit systems; however, the same light rail vehicles can also operate on existing streetcar lines with curb height stops. This flexibility allows the staged upgrading of a network to new rights-of-way with continuous service and immediate use of new route sections. Such staging permits investments to be tailored to local conditions, the desired service quality, and the availability of capital funds. This is an important advantage of light rail over rapid transit, which requires immediate construction of complete lines at high cost. In fact, many cities are staging their rapid transit construction by using light rail as an interim mode (e.g., Pre-metro in Brussels and Stadtbahn in Hannover and Frankfurt).

Exclusive rights-of-way generally constitute 40 to 90 percent of a light rail network and allow operating speed to average 12 to 16 mph (20 to 25 km/h); individual lines, however, often exceed 20 or even 30 mph (30 or 45 km/h) when they have fully private rights-of-way (e.g., Norristown Line in Philadelphia and lines in Cologne and Gothenburg). On grade-separated sections, frequencies can approach 90 vehicles/hour with little technical or organizational difficulty and high reliability. Frequencies of up to 140 vehicles/hour have been achieved (Philadelphia) with strict operational control and somewhat reduced reliability. Capacities with high service quality can reach a substantial 18,000 persons/hour/track.

Light rail networks are typically characterized by fairly good coverage of central areas (either in tunnels, on viaducts, or on at-grade private rights-of-way) and have extensions branching out at-grade on a number of radial routes. Interstation spacings generally average 1,200 to 2,600 ft (350 to 800 m) and, therefore, attract medium-to-long trips. Occasionally, park-and-ride and kiss-and-ride access modes are used in suburban areas.

There are at least 30 cities in Europe with modern high-quality light rail systems. Most of the cities using light rail have a population between 300,000 and 1,500,000 and

Figure 1. Boeing light rail vehicle.

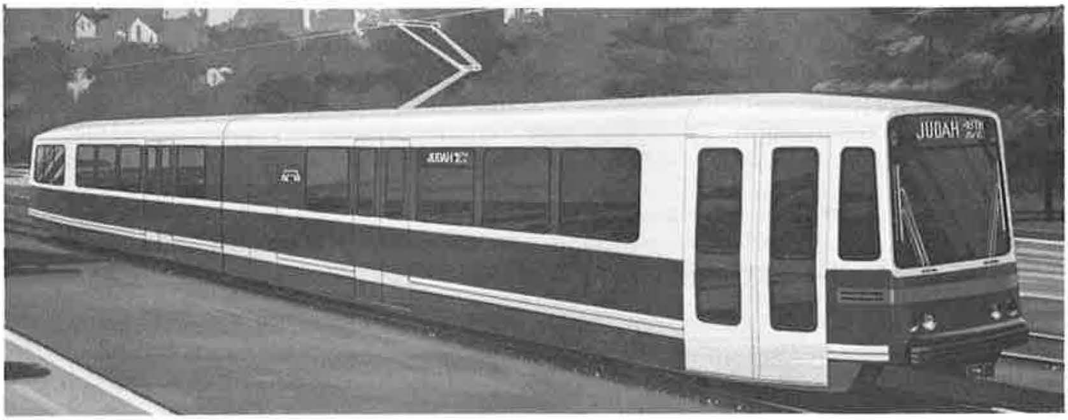


Figure 2. DUWAG light rail vehicle interior.

Table 1. Technical and system characteristics of urban rail modes.

Item	Streetcar	Light Rail	Rapid Transit	Regional Rail
Fixed facilities				
Exclusive right-of-way, percent	<40	40 to 90	100	90 to 100
Way control	Visual	Visual/signal	Signal	Signal
Fare collection	On vehicle	On vehicle or at station	At station	At station or on vehicle
Power supply	Overhead	Overhead or rail	Third rail or overhead	Overhead or third rail
Station platform height and access control	Low	Any type; low or high, fully controlled	Fully controlled; high level	Any type; low or high level
Vehicle characteristics				
Minimum operational unit	1	1 (4-axle)	1 to 3	1 to 3
Maximum train composition	3	2 to 4 (6-axle)	6 to 10	6 to 10
Vehicle length, m	14 to 20	20 to 33	15 to 23	20 to 26
Vehicle capacity, seats/vehicle	16 to 40	16 to 80	36 to 84	80 to 125
Vehicle capacity, total/vehicle	80 to 180	80 to 335	100 to 250	100 to 290
Operational characteristics				
Maximum speed, km/h	60 to 70	60 to 125	90 to 130	90 to 160
Operating speed, km/h	10 to 25	20 to 45	25 to 60	30 to 70
Maximum frequency				
Peak hour, joint section/h	140	40 to 120	20 to 40	6 to 30
Off-peak, single line/h	5 to 12	5 to 12	5 to 12	1 to 4
Capacity	10 000	3 000 to 18 000	6 000 to 30 000	10 000 to 40 000
Reliability	Poor	Good	Excellent	Excellent
System aspects				
Network and area coverage	Dispersed, good area coverage	Good CBD coverage; branching is common	Predominantly radial; some CBD coverage	Radial, limited CBD coverage
Station spacing, m	250 to 500	350 to 800	500 to 2000	1200 to 4500
Average trip length	Short-to-medium	Medium-to-long	Medium-to-long	Long[a]
Relationship to other modes	Can feed higher capacity modes	Park-and-ride, kiss-and-ride, bus feeders possible	Park-and-ride, kiss-and-ride, bus feeders	Outlying: park-and-ride, kiss-and-ride, bus feeders, CBD, walk, bus, light rail

Note: Figures shown are typical ranges for existing systems. 1 mile = 1.6 km. 1 ft = 0.3 m.

[a]U.S. average = 36 km.

a density between 3,000 and 15,000 residents/mile^2 (1,200 and 6,000 residents/km^2), although values outside these ranges can be found. In North America, Shaker Heights, Newark, Philadelphia, and Pittsburgh have some lines that have light rail characteristics but obsolete equipment. Interest in light rail, is, however, rapidly increasing. Boston, San Francisco, and Toronto are modernizing their lines in preparation for new equipment, Edmonton is building a new system, and a number of other cities (Dayton, Austin, and Portland) have been actively planning light rail systems.

Economically, light rail is an extremely attractive mode because of the wide variety of service quality and cost options it offers. Typical cost ranges for different types of facilities are given in Table 2.

There is some similarity between radial lines of light rail and the busway concept represented by the Shirley and El Monte Busways. Most significantly, both light rail and the busway have partially exclusive rights-of-way, but because of different technologies, their operational and service characteristics differ considerably. The bus can provide more extensive residential area coverage, but has a lower quality line-haul service and unreliable at-grade CBD distribution. Light rail offers limited suburban collection but offers an excellent line-haul service with stops and the possibility of reliable, high-capacity service downtown within tunnels. Rail technology further provides a more stable and comfortable ride and less environmental intrusion and has as an advantage the possible conversion of its line-haul and CBD operation to full automation, which would create a viable dual-mode (manual and automated) system. Typical busway costs, e.g., $4 to $5 million/mile ($2.5 to $3.1 million/km) for the El Monte Busway, appear roughly comparable to those for light rail.

Rapid Transit

Rapid transit (Figure 3, Table 1) consists of long four-axle rail vehicles operating in trains on completely private rights-of-way that allow high speed, high reliability, high capacity, rapid boarding, and fail-safe operation.

Rail transit vehicles are usually operated in units from 2-car married pairs to 10-car trains. Rapid transit has the highest service quality of all transit modes, and recorded capacities of lines with stations have been as high as 45,000 passengers/hour. Some of the recently opened systems (in Sao Paolo and in Paris) have been designed for a capacity of 80,000 passengers/hour. Capacity volume, however, results in low comfort. The maximum seated capacity is approximately 30,000 passengers/hour, but most systems are designed for volumes from 8,000 to 25,000 passengers/hour.

Most rail rapid transit lines in U.S. cities are basically radial, and there is limited coverage of city centers except in Manhattan. Modern European rapid transit systems, however, have been designed with networks covering large central areas and, thus, also offer service for the medium and short trip and the longer urban commuter trip. Area coverage in the suburbs is often helped by park-and-ride or kiss-and-ride transfer facilities or by bus feeders. In part, these supplementary services are required because of low population densities and rapid transit's longer station spacings in these areas. Generally, average trip lengths on rapid transit systems are longer than those on surface transit and range from 3 to 7 miles (5 to 12 km).

The need for rapid transit depends greatly on the specific travel patterns, topographical constraints, and character of the city. The typical regional population of these cities that have rapid transit ranges from 1 million upward (exceptions are 450,000 at Oslo and 880,000 at Rotterdam). Similarly, population densities served vary significantly; some rapid transit systems serve an extreme density of 80,000 persons/mile^2 (31 000 persons/km^2), but since park-and-ride and kiss-and-ride have been used as popular feeder modes, higher densities and CBD size no longer are the prerequisites they once were. Thus, the service area of the Lindenwold Line has only 3,400 persons/mile^2 (1313 persons/km^2).

The well-known drawback of rapid transit is its high capital cost brought about mostly by the need to provide fully private rights-of-way (Table 2). Furthermore, costs of automated vehicles are also high. However, because of its high service quality, rapid transit has a greater capability to attract passengers when compared with other modes. This is the major goal for any transit service.

With respect to operations, rapid transit systems are rather diversified. Modern systems operate trains of any length that the station platform can accommodate without full automation and with one-person crews (e.g., eight-car trains in Hamburg since 1957, six-car trains in Philadelphia since 1969). Stations may be operated without personnel by using remote closed-circuit TV surveillance (Lindenwold Line). Most U.S. rapid transit systems, however, still use trains that have two-person crews (up to four persons in Boston) plus station personnel. When there is a modern type of operation and efficient management, however, rapid transit can be highly labor productive; the Lindenwold Line carries 171 daily passengers/employee (including administrative personnel and police).

The latest systems have extensive train automation that also allows some operational improvements and savings in energy and vehicle maintenance. These are significant in high-capacity systems, but for other systems the benefits from automation often do not outweigh the increased cost and reduced reliability at least as long as the train crew is retained. Elimination of the last crew member on rapid transit systems is probably achievable with relatively minor innovations of control and operations. There is presently, however, no serious work in that direction, although unproven automated technologies are being investigated. Consequently, the highly automated rapid transit systems in operation today [e.g., Bay Area Rapid Transit (BART)] require a considerably higher investment cost than do nonautomated systems, but they do not have the reduced operating cost and higher frequency that full automation could bring (21).

Regional Rail

Regional (commuter) rail systems (Figure 4, Table 1) consist of large, high-speed rail vehicles operated individually or in trains, usually by railroad companies. The service is characterized by long average trip lengths, large interstation spacing, and very comfortable riding. Passenger volumes are heavily peaked, highly directional, and predominantly suburb-to-CBD. Most regional rail networks in our cities consist of a number of radial lines from the CBD and have stations located at suburban town centers. Kiss-and-ride, park-and-ride, bus feeders, and walking are used as access modes. Central city stations are often combined with intercity rail stations, but they are limited in number and provide little downtown coverage.

In recent years another kind of regional rail system has emerged. When there are alignments, station spacings, and speeds similar to those for commuter rail, these systems have frequencies of service and CBD distribution similar to those for rapid transit. Examples include Germany's S-Bahn, Paris' R.E.R., Philadelphia's Lindenwold Line, and San Francisco's BART. These modern regional rail systems give metropolitan regions with many distinct satellite communities an excellent regional transportation network.

Because regional rail service is usually provided by railroad companies, the cars are usually larger and heavier than rapid transit cars and have very high seating capacity (in double decker cars, up to 160 passengers/car). The tendency in new cars is to use 2- or 3-vehicle married units in trains of up to 10 vehicles. The service quality of regional rail is generally high for European systems, but it is quite variable among American systems that have been severely hurt by inadequate financing, lack of modernization, disinterested management, and obsolete labor practices.

The capital investment required for regional rail depends heavily on whether modernization of an existing railroad line or an entirely new regional rapid transit system is considered. The former usually involves very low costs (track renovation, electrification, and station construction); the latter, because of high alignment standards, requires an investment cost higher than that for rapid transit. Recent vehicle costs have been about $400,000. Operating costs vary greatly with labor practices, i.e., size of crew, which is typically much larger than the operation actually requires, particularly on U.S. systems.

Table 2. System costs for rail transit modes.

Cost Item	Mode Streetcar	Light Rail	Rapid Transit	Regional Rail
Right-of-way, $millions/km				
At-grade	0.2 to 0.9	0.2 to 0.9	1.9 to 6.0	0.3 to 1.3
Elevated	—	3.1 to 7.5	5.0 to 9.4	—
Tunnel	—	10.0 to 20.0	10.0 to 20.0	1.2 to 31.3
Station, $millions/station				
At-grade	Very low	Very low	0.5 to 2.0	0.5 to 2.0
Elevated	—	0.5 to 2.0	1.0 to 3.0	
Tunnel	—	4.0 to 5.0	4.0 to 6.0	5.0 to 15.0
Vehicle per 1000 vehicles	110 to 200	250 to 400	160 to 400	250 to 400
Operating per car kilometer	0.75 to 1.06	0.94 to 1.44	1.00 to 3.00	1.50 to 4.50

Note: Few new regional rail systems have been built recently in the United States. Conversion of existing track for such service involves low investment, but new center city track would incur very high investment. These data are based on 1972 dollars. 1 mile = 1.6 km.

Figure 3. PATGO rapid transit train.

Figure 4. Regional rail transit in Munich.

About the Family of Rail Systems

Tables 1 and 2 give some important characteristics for each of the four rail mode categories. These features define the modes and distinguish between them. In summarizing, two points are reemphasized. First, rail transit is a family of modes, ranging from operating and service characteristics of the streetcar to those typical for rapid transit and regional rail systems. Depending on local conditions, individual rail modes can be efficiently used for many conditions in medium and large cities.

Second, the combination of service and cost characteristics offered by different rail modes overlaps, as shown in Figure 5. There is no boundary, for instance, between the streetcar and light rail categories. Similarly, light rail can be designed to function much like rapid transit and to be gradually converted to it. Third, when its scale is magnified, rapid transit can become a regional rail system. For these reasons, generalizations regarding rail systems with respect to both cost and service characteristics (e.g., rail systems are expensive) are in most cases incorrect, and they should not be used.

RECENT TRENDS AND INNOVATIONS OF RAIL TRANSIT

In the United States, there is little information on or understanding of the trends and current state of rail transit. The available information is often inadequate or misleading, and many trends in technological modernization, operational changes, and system concepts are ignored or go unnoticed. Recent trends in rail transit systems in this country and other countries are reviewed below.

Patronage Trends on Rail and Other Modes

The trends of transit patronage in the United States since 1945, when transit ridership on all modes was extremely high, show a steep decline in streetcar and trolleybus ridership during the period after World War II. This reflects not only a general shift of the surface transit mode riders to the automobile but, even more, the conversion of streetcar into bus services in most cities.

The reasons for the abandonment of streetcar systems were often legitimate. In many situations the replacement of streetcars by buses improved service and traffic conditions. However, lack of funds for maintaining and improving streetcar systems often encouraged operators to abandon streetcars in favor of buses, even when this meant sacrificing the streetcar's superior operational and service features. Particularly counterproductive were the cases in which streetcars operating on reserved medians that could have been upgraded into light rail systems were replaced by buses operating on streets in mixed traffic. Moreover, pressures to use rubber-tired vehicles were exerted on transit operators by competitive transportation industries. Thus, the streetcar systems were in some cases discontinued for reasons of short-term economic convenience and political pressure. The direct loser was the traveling public; reduced mobility by transit negatively affected urban development.

The steep decline of bus ridership following World War II occurred despite the fact that during this period an intensive conversion of streetcars and trolleybuses to bus operation was under way. Thus, even the expansion of bus services did not compensate for the decline in ridership. The basic causes for this decline were increasing automobile ownership and highway construction and a simultaneous neglect of maintenance and actual deterioration of transit service. Except for incidental purchases of new vehicles, most U.S. systems did not undertake any significant improvement of bus operations, such as provision of bus lanes, signal actuation by transit vehicles, and better information.

Rapid transit systems were equally neglected: poor maintenance, obsolete equipment, lack of information and marketing, and increasing fares. However, their inherent features made them much more competitive with automobile travel than was

Figure 5. Service quality versus investment cost for rail transit modes.

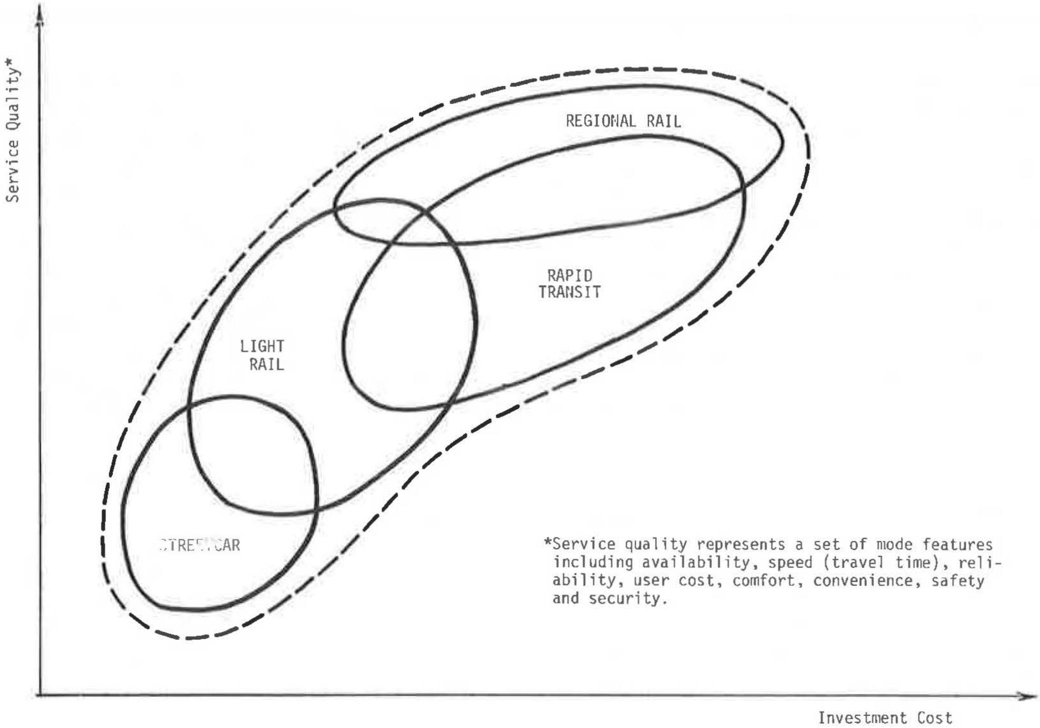
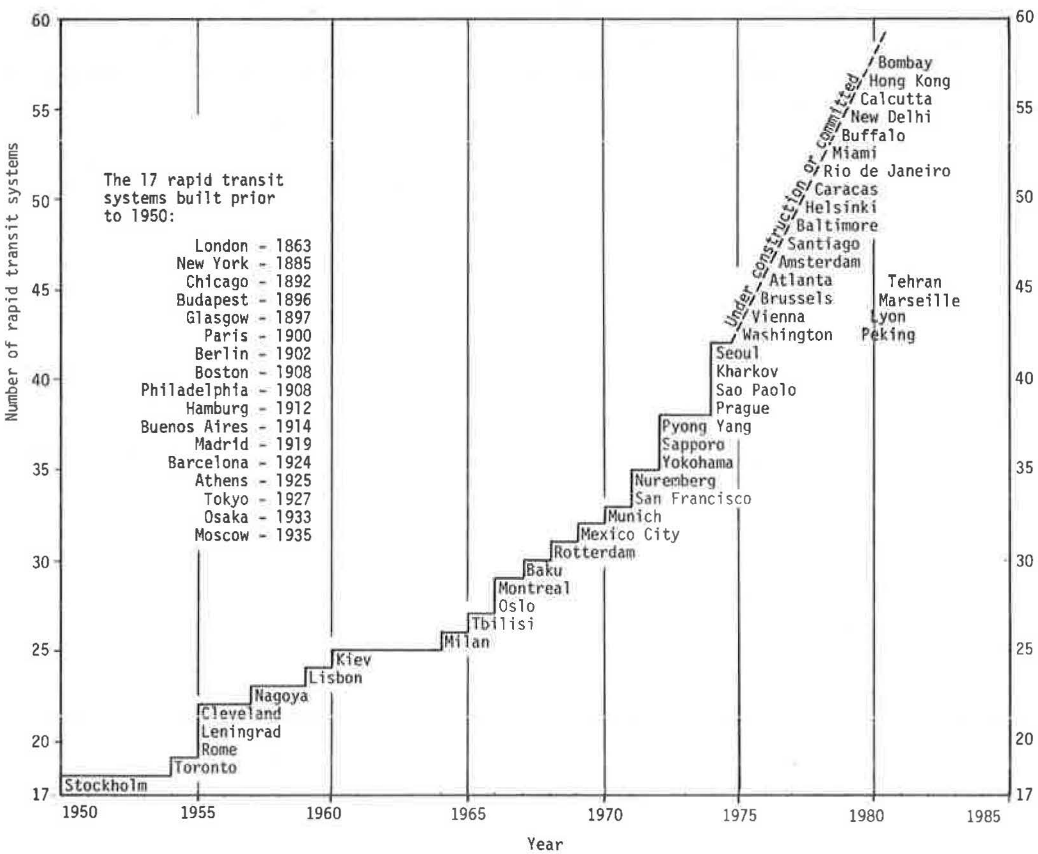


Figure 6. Number of rapid transit systems in the world since 1950.



surface transit. Their total separation of right-of-way secured independence from street traffic conditions and guaranteed high reliability, high frequency of service, and network simplicity. These were important features that contributed to a much higher retention of passengers by rapid than by surface transit.

U.S. regional commuter rail systems have also exhibited high patronage stability. The limited available data show that ridership did not change between 1960 and 1970 (9). In fact, systems increased their share of the transit market during that decade by 5.4 percent. Similar trends have been observed in other countries.

Policies Toward Transportation Modes

Operational experience, performance records of different types of services, and the passenger trends strongly indicate that the most important characteristic that makes transit service competitive with the automobile is the provision of an exclusive right-of-way. Separation of transit from other traffic and interference ensures a certain level of reliability of the total transportation system under all conditions, including major storms and other emergencies. Preferential treatment of transit through special signals and reserved lanes, although highly significant, represents a rudimentary type of service upgrading. Higher types include exclusive medians with grade crossings, underpasses and overpasses at busy intersections, exclusive busways, and, finally, fully controlled transit rights-of-way.

Greatly increased interest in transit improvement in U.S. cities has begun to stimulate interest in semiexclusive and exclusive transit rights-of-way. A number of cities have or will soon have rail rapid transit under construction (Washington, Atlanta, Baltimore, and others) or in planning (Los Angeles, Miami); several have exclusive busways in operation (the Shirley Busway in the Washington, D.C., metropolitan area and the El Monte Busway in Los Angeles) or in planning (Hartford, Milwaukee). Many cities have opened bus lanes in central areas, and there has been a rapid increase in the planning of new light rail transit systems (Edmonton is constructing; Dayton, Portland, Rochester, Vancouver, and Toronto are planning; and Denver and San Diego are considering such systems).

The question of whether to use buses or rail systems on exclusive rights-of-way has been studied carefully in several countries that have much automobile ownership and an interest in major improvements of public transportation (15). Exclusive busways have been built so far only in the United States and in one British city (Runcorn). In several U.S. cities (New York, Boston, and San Francisco), contraflow freeway bus operations have brought considerable improvement to bus service quality. In all other countries, provision of fully grade-separated rights-of-way has always been made only for rail vehicles. The advantages of buses (better suburban distribution and immediate availability) were considered to be heavily outweighed by the following advantages of rail systems:

1. Greater capacity range because of an ability to form trains;
2. Better CBD operation because of ability to operate in tunnels;
3. Greater passenger attraction;
4. Lower operating cost per passenger served;
5. Lower negative environmental impact (lower noise level, no air pollution);
6. Higher safety and conduciveness to full automation; and
7. Higher reliability, particularly under high demand and adverse weather conditions.

Once a decision to choose a rail mode is made, the next choice is that of the specific rail mode. A number of medium-sized cities in Europe that required a high-quality transit system but could not afford the big investment of rapid transit have selected light rail systems that are fully separated from other traffic only in limited areas of the central city where congestion is most acute, transit operations are most seriously impeded, and the beneficial effects of separating transit from surface traffic are the greatest. In outlying areas, it is usually easier to find semiexclusive rights-of-way for transit, and traffic congestion in those areas is lower anyway. Thus, for a limited investment, these cities have alleviated their most serious traffic problems.

A good example of selective separation of transit is in Brussels, which has five streetcar lines that converge into one joint section as they approach the central city. Approximately 2 miles (3 km) required 20 min of travel time during the off-peak and up to 45 min during the peak when transit is operated on streets. A tunnel was built for this section only (the lines continuing at-grade in the outlying areas), and the travel time is now 8 min during the off-peak and during the peak because of full control of operations and no disturbances from other traffic. Solutions similar to this one have been adopted in Cologne, Frankfurt, Stuttgart, and other cities.

Based on the policy of maximum separation of transit from street and highway traffic for over a decade, there has been extensive construction of new systems and extensions of existing rapid transit systems and electrification of existing railroad lines. Construction of such facilities for all rail modes has been accelerating in recent years and is presently more intensive than ever before. In West Germany alone, 15 cities are presently building new rail systems or expanding existing ones. Figure 6 shows the accelerated frequency of openings of new rapid transit systems in the world since 1950.

Financing of Rail Systems

Construction of rail systems is not much cheaper in other countries than it is in the United States. The average cost per mile (kilometer) of way shows a great similarity for most countries. Yet rail transit improvements have been undertaken in many foreign countries much more vigorously than in the United States. In recent years, because of the environmental and energy crises, the urban transportation policies in all countries have become considerably more in favor of public transportation and opposed to additional construction of urban highways and downtown parking facilities. These changes in policy have resulted in further intensification of efforts to expand and improve rail transit systems particularly because of their superior environmental characteristics: low noise, no air pollution, minimum space taking, and low energy consumption per passenger-mile (kilometer).

Although details of financing methods vary from country to country, in most cases the basic philosophy adopted has been that a reliable and efficient transportation system is a prerequisite for the economic and social health of each city and that systems must consist of a modern network of streets and highways and a complete system of adequate public transportation throughout the urbanized area. A total network coverage of the area and all-day, everyday service are particularly emphasized. The concept that transit should be only a supplement to private transportation and operate solely during peak hours in radial directions has been rejected in most developed countries because such a system leaves large segments of the population without adequate mobility and has a detrimental impact on the social, physical, and land use characteristics of the city. In addition, such a system is highly inefficient and uneconomical. An important element in the justification of rapid transit construction is often the reduction of operating costs over those of surface modes (4).

In West Germany, which has a similar governmental organization to the United States, the federal government sponsored a thorough study of urban transportation problems. Based on the principles developed by that study in 1964, legislation was passed that introduced a special tax of \$0.03/gal (\$0.008/liter) on gasoline (3 percent of the total gasoline price) that goes into a special federal fund for the improvement of urban transportation facilities. This fund is matched by the states and divided between improvements of streets and highways (55 percent) and transit facilities (45 percent). This method of financing has resulted in vigorous construction of grade-separated rail facilities, other major additional improvements, and a continuing highway development program in most West German cities.

Had a tax of \$0.02 to \$0.03/gal (\$0.005 to \$0.008/liter) in the United States been introduced, it would have been sufficient for major transit improvements in our cities before conditions reached their present crisis stage. Such proposals, however, were opposed as inequitable and an excessive charge on the motorist although gasoline prices in the United States are only 30 to 50 percent of the prices in most European countries. Recently, however, greater increases in gasoline prices have been introduced without severe complaint or reduced demand but also without any benefit to public components of transportation facilities: improved urban streets and highways and modern transit facilities.

Technological and Operational Innovations

Numerous technological and operational improvements of rail systems have been tested and introduced in various countries during the last 20 years. As a consequence of these developments, many features of rail systems have been virtually perfected. The following are some examples of these improvements.

Land Use and Transit Integration

A careful coordination of rail transit planning and urban design has resulted in the extensive provision of reserved transit rights-of-way and the creation of stations integrated with stores, offices, malls, and plazas. Often these improvements are introduced as components of comprehensive traffic restraint schemes for central cities (e.g., Toronto, Hamburg, Stockholm, Munich, and Vienna).

System Design

The development of modern, large-capacity, lightweight vehicles combined with provisions for reserved rights-of-way and favored treatment at intersections created the concept of light rail systems. Improvements to this mode continue. Hannover, which is constructing tunnels for the CBD sections of its light rail system, is designing a computer-controlled monitoring system for up to 100 vehicles on branch lines to increase its schedule adherence at-grade and to coordinate their travel so that regular 2-min headways are ensured at the converging points to joint tunnel sections. Also under study is direct computer control of key intersections along the branch lines to guarantee regularity of light rail vehicle travel. For its light rail system, Gothenburg has used a tunnel construction method that roughly halved tunnel costs.

Many European systems have tracks of the highest quality. Welded rails are placed on cushioning plates, switches have elastic points that eliminate the sound and shocks caused by joints, and overhead catenaries are automatically regulated for a constant tension, which guarantees good contact and minimum wear throughout the year.

Passenger Comfort

As a result of these technological improvements, comfort and noise levels have been greatly improved on all rail modes. A modern rail vehicle on a well-maintained track now provides more comfort and creates less noise than a single passenger car driving on a concrete roadway at the same speed. The smoothness of ride of the new vehicles of the recently modernized 11-line Munich S-Bahn (regional rail), achieved by preprogrammed acceleration with controlled jerk, sophisticated suspension, and excellent track, is not matched by any rail system in the United States.

Energy Consumption

Vehicle propulsion has been improved to provide the maximum acceleration rates that passenger comfort allows up to speeds of 25 to 32 mph (40 to 50 km/h), e.g., Lindenwold Line and the Munich S-Bahn. At the same time, as a result of numerous analyses and computer simulations, energy consumption has been minimized on several systems through programmed control of speed profiles that use coasting extensively (e.g., Hamburg, Moscow, and Stockholm), introduction of thyristor chopper control, regenerative braking (San Francisco), and even through optimal vertical profiles between subway stations (Munich). The maximum speed versus maximum acceleration trade-off has often been analyzed for different operating conditions to achieve the optimal balance between operating speed and energy consumption.

Operating Productivity

Extensive automation has been achieved, and its primary purpose was to reduce operating costs. When advanced fare collection methods and special vehicle design are used, even eight-axle light rail vehicles that have a capacity of 200 to 300 persons are operated by one person (Cologne). Rapid transit trains, as previously mentioned, are also operated by one person [Philadelphia (Lindenwold Line) and Hamburg].

Based on extensive testing and measurements, the Paris RATP can increase line capacity and improve service regularity by special methods of reducing station standing times and by better enforcement of strict adherence to the schedule. This method has proved to be much cheaper and more effective for achieving the same goals than through larger and better performance vehicles.

Fare collection has been automated on many European transit systems for convenience, boarding speed, and labor cost savings. Features being used range from ticket dispensing equipment to automatic ticket checking equipment to fully automated canceling equipment that are used with self-service (honor) fare collection. Bus systems and light rail and rapid transit systems use the features often on board the vehicle. Generally, more than one mode is integrated into the fare payment for increased user mobility and system flexibility. Furthermore, European systems make extensive use of prepaid tickets and seasonal passes to increase both passenger convenience and operational efficiency (6).

RAIL TRANSIT IN THE UNITED STATES

The United States was the leader in rail technology and operation for a number of years several decades ago. However, while many foreign systems have been vigorously improved and modernized, U.S. systems have suffered from underinvestment and a decrease in technical and managerial expertise. The leading role of the United States was consequently lost after World War II.

Present Condition

Although the Lindenwold Line in Philadelphia and the New York, Chicago, and San Francisco rapid transit systems have some unique features and innovations that do not exist elsewhere, U.S. rail systems are generally extremely obsolete in their technology and type of operation. Several observations confirm this condition.

1. There are few transit systems in the world that have less attractive, less safe transit stations that those, for example, along the Broad Street Line in Philadelphia or along many routes in New York City.
2. A survey of noise levels of rail rapid transit systems in 11 U.S. and European cities undertaken by Operations Research, Inc., in 1964 showed that all 4 U.S. systems

included in the survey were on the top of the list ranking levels of noise (12).

3. The condition of track on many commuter railroads in U.S. cities is probably worse than the condition of any corresponding facilities in Europe or Japan.

4. Labor practices in railroad companies are more obsolete than in any corresponding operations in Europe. Many regional rail systems are operated by crews of up to nine persons although two or three would suffice for modernized operation.

5. The newest streetcar vehicles operating in the U.S. cities are 22 years old; some regional rail vehicles are over 60 years old.

6. Many systems have limited speed because of unsafe track conditions, and some cities require every streetcar to make a safety stop before every diverging switch, a practice abandoned in Europe decades ago.

7. Numerous technical innovations, such as the above-mentioned switches with elastic points, constant-tension overhead catenary, and fare collection machines, are not known to exist even by most persons in the rail industry and operating agencies.

The neglect of rail technology and operations in the United States is also reflected in the extremely expensive and yet unreliable rolling stock and train controls for our most recent systems. Several of them have suffered from rather elementary mechanical and electric failures that result in excessively frequent service slowdowns and interruptions. Low reliability is not a typical problem of rapid transit systems. For example, the newly opened rapid transit system in Munich was built by using extensive experience from other cities so that, although the system was entirely new, it had only two major delays in its service during the first 18 months of operation; both were caused by factors out of control of the operating agency.

Expertise and General Knowledge About Rail Transit

This lagging expertise and lack of information about many modern technological developments in rail systems and policies are a serious problem in the United States. Frequent justification for ignorance of foreign developments is given by claims that U.S. cities are different or that Americans are unique in their love for the automobile. Although it is true that conditions are not identical in any two cities of the world, the claim that solutions from other countries do not apply to U.S. cities is incorrect.

Most frequent is the simplistic argument that rail transit is justified only in large cities that are densely populated; European cities use rail systems because their population density is greater than that of U.S. cities. Neither of these two arguments is correct. First, population size and density are not sufficient factors to determine feasibility of rail systems: A medium-sized city with low average density may have either topography or high-density corridors that require rail transit. Second, European cities that use rail modes extensively do not have more people or more dense populations than many U.S. cities that have no rail systems (Figures 7 and 8).

The belief that Americans are unique in their love for the automobile is also highly questionable because in most West European countries automobile registrations increased several times during the 1960s (in Italy more than six times from 1960 to 1970). However, although this automobile ownership increase in European countries did divert some passengers away from transit, transit patronage trends differ considerably from those in the United States. Although there are many physical, economic, and social differences between the United States and some European countries, it is quite clear that the basic policy toward urban transportation, improving both public and private modes in a coordinated manner, has already shown distinct positive results and is leading toward a stable situation in urban transportation.

The lack of knowledge about rail modes among transportation planners and engineers results in a misinterpretation of their proper application in urban transportation. U.S. cities that could efficiently use light rail systems have been planning systems similar to BART or the Lindenwold Line and, therefore, incur much higher costs than are rationally justified. However, buses and busways are planned for many corridors that would clearly be more efficiently served by rail transit, which would attract

Figure 7. Population densities of selected cities and application of rail transit modes.

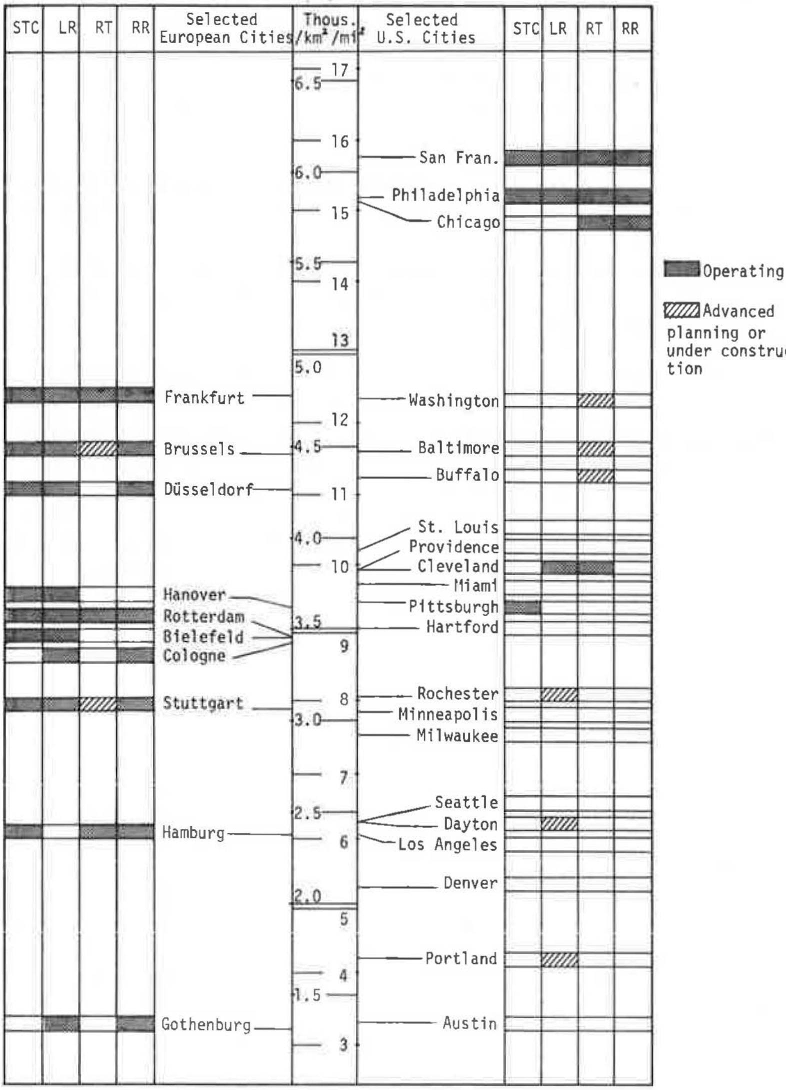
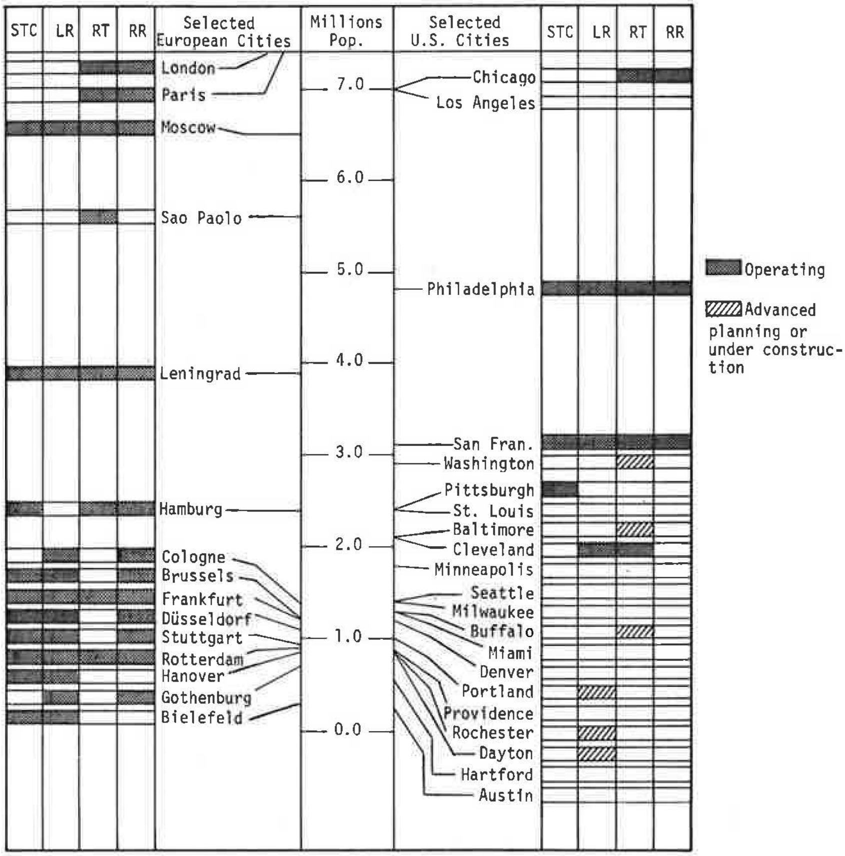


Figure 8. Population of selected cities and application of rail transit modes.



considerably greater patronage and have lower operating costs. Errors of both types result in the introduction of a nonoptimal mode of transportation and a less than optimal allocation of funds.

A major problem is that many consulting firms and planning agencies not having expertise in rail systems simply ignore them or find a superficial justification of the system they had decided to plan. A common practice is not to consider light rail at all and to compare rapid transit of the highest standards with a single type of bus on the basis of minimum cost (articulated buses are also commonly ignored). For understandable reasons, this type of selection is strongly prejudiced toward a lower cost and lower service quality system that, consequently, attracts low patronage.

Another important fact is that modern urban transportation systems cannot be achieved by using minimum investment cost as the sole criterion for decisions on mode selection. The common procedure used by successful modern systems is to base the transit plans and selection of mode on policies for achieving specified levels of public transportation service. The selection is then made of the most economical system (mode) that will provide the specified service quality. Drastically different modes such as rapid transit and surface transit should, therefore, never be compared solely on a cost basis because of the great difference in the quality of service they provide and patronage they attract (23).

Contrary to this procedure, several mode selections (and theoretical studies) in our cities have wrongly focused on the search for the minimum cost solution and ignore the differences in the number of users and service quality, which are often quite drastic.

Underutilization of Rail Systems

Rail technology offers a variety of modes that can operate effectively under different urban conditions. Despite extensive efforts to develop other types of guided technologies, none has so far been proved to be superior or even equal to rail in its overall performance (cost, dynamic characteristics, energy consumption, noise, and so on). However, much funding is being allocated in the United States and in Western Europe to the development of new technologies, most of which are clearly inferior to rail. Why is the large potential of rail transit underutilized?

Several factors cause this underutilization. First, the lack of knowledge about modern rail technology leads to nonoptimal decisions about modes. As a result, an extreme categorization of modes is set up and results in the polarization of alternatives. This tendency to polarize systems into the highest standard of rapid transit and the minimum-investment surface buses is widespread. The fashion to have a real rapid transit system and the belief that the flexibility of bus (a largely misunderstood feature) is the best mode for surface transit have resulted in a large gap between these two modes. Most medium cities fall into this gap, since they have travel demands less than optimal for rapid transit yet too large to be handled efficiently by surface buses. This problem is extremely serious not only in the United States, but also in France and Great Britain. Recently, however, the interest in light rail systems, which are best suited for this intermediate system role, has increased rapidly, and efforts to build new light rail systems in our cities are paralleled by similar actions in Australia, France, the Netherlands, and Great Britain. This mode was recently endorsed by the Organization for Economic and Community Development as the system that offers a better service quality and that is more economical than buses and more quickly implemented than rapid transit.

Second, there is confusion intentionally caused by opponents of improved public transportation through the above-mentioned incorrect statements and modal comparisons.

Third, there are pressures exerted by developers of new modes who capitalize on the low expertise of public officials in transit technology.

Finally, transit agencies also carry part of the blame; they often take a conservative attitude and oppose changes in policies and procedures proved helpful elsewhere rather than lead in their introduction. Reluctance to consider full automation of train running, honor fare collection methods, and lack of initiative in modernizing labor practices are good examples of such an attitude.

CONCLUSIONS

1. Modern rail transit incorporates a family of modes that have undergone a great deal of improvement in technology and operational concepts in recent years. These modes offer a wide range of quality of service and cost options that allow a broad spectrum of applications in different types and sizes of cities.

2. Several European countries have used this potential of rail transit to a much greater extent than the United States and have developed rail systems encompassing all modes. Although transit planning in our country has recently broadened its scope and incorporated some innovations, our lagging behind modern developments in rail systems is still serious. It has resulted in narrower choice of modes, lower reliability, and higher costs of rail systems here than are typical for the countries more advanced in this area.

3. European cities that have successful rail systems do not have more people and are not more densely populated than many U.S. cities that are often claimed to be unsuitable for rail transit.

4. Rail systems, particularly light rail and rapid transit, should be included in studies of alternative transportation solutions for all medium and large cities, especially when partially or totally private transit rights-of-way are considered desirable.

5. Despite extensive work on the development of new modes in recent years, no new technology has emerged that has been proved superior or even comparable to modern rail technology in performance and cost characteristics, including speed, reliability, comfort, noise, and energy consumption.

6. Unlike new systems, no demonstration of rail systems is necessary; their technical and economic feasibility are well known and continue to be substantially reconfirmed worldwide. However, intensification of the research and development of individual components of rail technology (propulsion, energy consumption, weight reduction, reliability, automation, and lower cost construction techniques) appears to be justified by its potential gains in improved performance and reduced cost in the near future.

7. A number of U.S. cities presently have advanced plans for various rapid transit and light rail systems. In most cases these projects are integral parts of plans for major revitalization of cities. This healthy initiative to reverse the trend of our urban decay has been recognized by the Congress and the federal government. The intent of recent legislation for increased federal assistance to transit has been to stimulate that trend. However, the presently allocated funds are inadequate, and inconsistency in their distribution had led to some serious setbacks in implementing these systems. The allocation of funds should be determined on the basis of real needs of our cities rather than by a requirement that the needs be squeezed into an arbitrary level of funding.

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ECONOMIC RELATIONSHIPS AMONG URBAN TRANSIT MODES

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Economic relationships among demand-actuated, scheduled-route, and rapid transit services are examined to determine where the operating economy justifies intensive capital investment in permanent facilities. Analysis of national experience in the more heavily populated urban areas discloses that per capita ridership is much greater in areas served by rapid transit than in areas served only by street transit service, which in turn generates far higher levels of per capita ridership than demand-actuated service. The relationships cover common situations. Unique situations (e.g., New York's unusual costs and densities and San Francisco's experimental technology) are not included. Public acceptance is measured by comparing paid ridership with population and by reference to census data on the percentage of work trips made by transit. A general similarity between the two sources is evident, but rapid transit ridership outside New York is understated because of policies involving free transfers from buses and streetcars to rail transit. This does not impair city totals, however, in which transfers are not counted as additional trips. Costs are measured by financial records based on the number of vehicles operated. The usual denominator of vehicle miles (kilometers) varies based on speed or slowness, and hourly values vastly understate the cost of service provided only during peak hours when employees must be guaranteed pay for 40 hours/week. The results are empirical but appear to be realistic.

•IN most metropolitan areas of the world, those concerned with urban planning and transportation have come to the conclusion that more people must be carried on public transport to relieve highway congestion, to lessen air pollution, to conserve energy, to augment mobility of nonmotorists, and to lessen the total cost of urban transportation. Environmental laws and regulations in the United States indicate this concern. The energy crisis of the first 3 months of 1974 gave considerable additional impetus to this issue.

IMPROVED PUBLIC TRANSPORT

A simplified but accurate method for making relative economic comparisons between the three general types of transit service to provide a meaningful tool for policy and decision making is presented. Greatly improved public transport is essential to induce voluntary use of the service and to ensure economical and convenient radial rush hour movement at reasonable speed. Circumferential movement is more difficult to attract to public transportation, and, therefore, is less likely to justify rapid transit. Toronto's Bloor Street subway is a clever compromise solution for the radial versus circumferential problem. In many cities of North America, planners, engineers, and non-technically oriented citizens have recommended the construction of new and extended rapid transit lines to cope with the projections of metropolitan growth and saturated highway traffic volumes [Table 1 (1, 2)]. [Transit ridership does not entirely depend on characteristics of the community but more on the characteristics of the service. When rapid transit was extended through Camden County, New Jersey, in 1969, total transit use in the immediate corridor increased 115 percent. When Bay Area Rapid Transit service was inaugurated in Alameda and Contra Costa Counties in 1972, the added ridership did not cause any net diminution in bus service in these areas but

Table 1. Metropolitan areas operating or planning rapid transit.

Area	Population	Work Trips by Transit (percent)	Daily Transit Rides	Population Using Transit (percent)
Atlanta	1,390,000	10.3	193,600	13.9
Baltimore[a]	2,071,000	16.6	390,400	18.8
Boston[b]	2,754,000	19.8	580,000	21.1
Buffalo	1,349,000	12.1	120,000	9.0
Calgary	403,320	–	110,400	27.5
Chicago[b]	6,979,000	24.1	1,300,000	18.6
Cleveland[b]	2,064,000	13.8	290,000	14.5
Dallas	1,556,000	7.0	91,700	5.9
Detroit	4,200,000	8.4	330,000	7.8
Denver	1,260,000	4.7	70,000	5.5
Edmonton	495,700	–		
Los Angeles	7,037,000	4.7	665,000	9.4
Miami	1,268,000	9.0	168,000	13.2
Minneapolis-St. Paul	1,814,000	9.3	196,500	10.9
Montreal	2,743,208	–	920,000	33.6
Newark	1,856,000	–	278,000	15.0
New York[b]	11,529,000	38.3	5,000,000	43.4
Philadelphia[b]	4,821,000	24.2	1,000,000	20.7
Pittsburgh[b]	2,401,000	17.5	330,000	13.7
St. Louis	2,363,000	9.0	140,000	6.0
San Francisco	3,110,000	15.7	700,000	22.6
Toronto	2,628,000	–	1,100,000	41.4
Vancouver	1,082,350	–	260,000	24.0
Washington, D.C.[a]	2,861,000	17.3	600,000	21.0
Median without rapid transit		9.2		10.9
Median with rapid transit		22.0		21.0

[a]Electric railway under construction. [b]Includes service by electric railway.

Table 2. Operating cost experience for bus, commuter rail, and rapid transit service for 1973.

Item	Cleveland	Chicago	Philadelphia	Toronto	Pittsburgh	Typical[a]
Bus service						
Maintenance of equipment	4,000,000		12,375,000	6,600,000		6,500
Fuel	700,000		1,500,000	1,050,000		900
Conducting transportation	15,860,000		35,225,000	34,852,000		25,196
Injuries and damages	800,000		4,000,000	1,660,000		2,192
General and administrative	4,272,000		11,220,000	9,276,000		7,308
Taxes	1,068,000		3,000,000	2,222,000		1,754
Annual total	26,700,000		67,320,000	55,660,000		45,135
Number of vehicles	840[b]		1,650[b]	1,097[b]		1[b]
Per vehicle per year	32,000		40,800	50,600		45,135
Seats per bus, standard						53[b]
Per seat per year						852
Commuter rail service						
Maintenance of way and streets		1,800,000	2,900,000		15,000	6,000
Maintenance of equipment		6,000,000	11,600,000		128,000	24,000
Fuel or power		400,000	3,500,000		10,000	7,500
Conducting transportation		10,800,000	16,600,000		220,000	35,600
Injuries and damages		900,000	1,300,000		14,000	2,600
General and administrative		1,200,000	3,600,000		78,000	5,200
Taxes		1,700,000	3,300,000		4,000	6,600
Annual total		22,800,000	42,800,000		470,000	87,500
Number of vehicles		296[b]	446[b]		4[b]	1[b]
Per vehicle per year		77,000	96,000		117,500	87,500
Seats per car						120[b]
Per seat per year						729
Rapid transit service						
Maintenance of way and streets	500,000		2,200,000	3,200,000		6,000
Maintenance of equipment	900,000		3,000,000	3,600,000		7,330
Power	600,000		2,400,000	2,400,000		4,850
Conducting transportation	1,700,000		8,500,000	3,900,000		15,720
Injuries and damages	100,000		700,000	400,000		1,350
General and administrative	1,100,000		4,200,000	800,000		7,500
Taxes	400,000		1,100,000	700,000		2,250
Annual total	5,300,000		22,100,000	15,000,000		45,000
Number of vehicles	118[b]		490[b]	410[b]		1[b]
Per vehicle per year	45,000		45,000	36,600		45,000
Seats per car						83[b]
Per seat per year						542

[a]Per transit vehicle. [b]All values are in dollars except number of vehicles and seats per vehicle.

resulted in a significant overall increase. When rapid transit service was temporarily suspended in Newark in 1971, ridership on the route declined 75 percent.]

RAPID TRANSIT

Rapid transit is generally intended to refer to a collective method of moving groups of people in multiple vehicles capable of being operated by one person on an exclusive, grade-separated right-of-way not shared with other vehicles. The creation of such a right-of-way can be very expensive if none is readily available, and indeed some of the current projects exceed a billion dollars in some cities. However, where rights-of-way can be obtained readily or where travel volume is great, rapid transit is the most attractive, efficient, and least costly method of moving people in quantity. Little objective qualitative operational economic justification has been developed beyond the general idea that the cost of not providing it is greater than the cost of providing it.

DEMAND-ACTUATED TRANSPORT

At the opposite end of the spectrum, where there is little or no observable transit volume and no radial movement, demand-actuated urban transit is obviously the logical choice for economically maximizing service.

Thus, there are three general types of transit service: (a) demand-actuated, (b) conventional scheduled route (bus or trolley) on shared public rights-of-way, and (c) private right-of-way rapid transit (or commuter rail). Each has its own unique characteristics, but all three are capable of taking a nonmotorist from one point to another at a reasonable cost. Exclusive busways are a hybrid of conventional and private right-of-way transit and combine shared and exclusive rights-of-way. Their costs can be calculated the same way.

Notation and values of 1974 transit cost factors used are as follows (1 mile = 1.6 km):

A_b = annual operating cost per bus = $45,135;
A_c = annual operating cost per commuter rail car = $96,000;
A_r = annual operating cost per rapid transit car = $46,100;
A_t = annual operating cost per demand-actuated bus = $55,000;
C_b = capital cost per bus = $48,000;
C_c = capital cost per commuter rail car (diesel + $^1/_6$ locomotive) = $320,000;
C_r = capital cost per rapid transit car = $320,000;
G_b = capital cost of garage per bus = $20,000;
G_c = capital cost of shop per commuter rail car = $30,000;
G_r = capital cost of shop per rapid transit car = $25,000;
M = round trip mileage of route;
P = capital cost of rapid transit, at-grade alignment per mile = $4,000,000, aerial alignment per mile = $12,000,000, depressed alignment per mile = $20,000,000, and underground alignment per mile = $40,000,000;
R_b = capital recovery factor for bus = 0.100;
R_c = capital recovery factor for commuter rail car = 0.075;
R_g = capital recovery factor for garage or shop = 0.070;
R_p = capital recovery factor for right-of-way = 0.062;
R_r = capital recovery factor for rapid transit cars = 0.075; and
X = one-way peak-hour passenger volume for equal cost.

The various speed variables are as follows:

S_b = scheduled speed of bus (typical) = 10 mph,
S_c = scheduled speed of commuter rail = 30 mph, and
S_r = scheduled speed of rapid transit = 25 mph.

The speeds used are

1. Central business district peak bus speeds = 3 to 4 mph,
2. Suburban arterial bus speeds = 14 mph,
3. Commuter rail speed = 1 min/mile plus 1 min/stop, and
4. Rapid transit speed = 0.9 min/mile plus 0.9 min/stop.

(Variables pertaining to commuter rail are included although they are not specifically used in this paper.)

A comparison of exclusive busway and rail rapid transit involving 4 miles (6.4 km) of exclusive busway, 1 mile (1.6 km) of CBD streets, and 3 miles (4.8 km) of suburban streets is given below:

$$(A_b + C_bR_b + G_bR_g)MX/64S_b + PR_pM/2 = (A_rC_rR_r + G_rR_g)MX/150S_b + PR_pM/2 \quad (1)$$

where

1 mile (1.6 km) of busway costs \$10,000,000,
1 mile (1.6 km) of rail subway costs \$40,000,000,
4 miles (6.4 km) of rail aerial system cost \$12,000,000, and
2 miles (3.2 km) of busway cost \$4,000,000.

Therefore,

$$(\$45{,}135 + 48{,}000 \cdot 0.1 + 20{,}000 \cdot 0.07)16X/64 \cdot 16 + \$40{,}000{,}000 \cdot 0.062$$
$$= (\$46{,}100 + 320{,}000 \cdot 0.075 + 25{,}000 \cdot 0.07)14X/150 \cdot 25$$
$$+ \$56{,}000{,}000 \cdot 0.062 \quad (2)$$

and

$$X = 1{,}851 \text{ one-way passengers/peak hour to justify rail service at time value} = 0 \quad (3)$$

Following is a time value iteration for a 6-mile (9.7-km) average trip at 25 mph (40 km/h) for rail = 14.5 min and at 18 mph (29 km/h) for bus = 20 min:

$$\$536X = \$992{,}000 - 5X \cdot \$0.165 = 287 \text{ days} - 237X \quad (4)$$

and

$$X = 1{,}283 \text{ one-way passengers/peak hour to justify rail service at time value of } \$0.03/\text{min} \quad (5)$$

Equations 1 through 5 do not justify either an exclusive busway or rail rapid transit;

each mode must be compared with surface transit to determine basic justification.

Light rail service can be similarly treated. Taxi service could be called demand-actuated service but is not usually considered transit service because of its cost and its sporadic nature.

JUSTIFICATION OF TRANSIT MODE

Civic authorities often ask, At what volume of patronage is rapid transit justified and when is demand-actuated service the proper choice? There are no simple answers to these questions, but neither is the choice purely optional. Rapid transit operating costs per passenger-mile (kilometer) are normally the lowest, and the service attracts the highest ridership; however, investment is great, and this raises the question of economic justification. There is only a 25 to 33 percent operating cost difference between demand-actuated and scheduled route service (3), but the use factor causes great variation in unit passenger costs. The question of relative justification can be answered only if it is known how expensive a specific project will be and how heavily it will be used.

All forms of vehicular movement require expensive rights-of-way, but common practice has been to provide city streets without regard to economic analysis because they are considered necessary. Public transport using these streets is assumed to have no fixed cost, and the local fuel tax, if any, is the only charge for right-of-way. This cost varies on many public transport systems from 0 to $0.02 vehicle mile ($0.013/km) or 1.5 percent of operating costs. This charge is unrelated to the acquisition of the street or highway right-of-way, property taxes on its value, interest on its investment, snow removal, and police and traffic control cost, all of which are included in the traditional method of calculating rapid transit or commuter rail costs.

As a practical matter, street transit vehicles operating in the general traffic stream can share the public road for $0.02/mile ($0.012/km) or for free, provided the traffic volume does not become so large that an additional lane of traffic is required [the value of $0.02/mile ($0.012/km) is obtained by dividing the tax/gal (tax/liter) by the miles/gal (km/liter)]. For an exclusive lane, land must be acquired at great capital cost. There is seldom a necessity to measure the cost of single-unit street vehicles on an exclusive right-of-way. Their higher operating cost per passenger renders them incapable of amortizing the cost of their right-of-way at less than multiple-unit rapid transit service cost (Table 2). This is because the cost of acquisition and construction of a heavy-duty private right-of-way, whether at grade, subway, or aerial, is not much less costly per unit of bus capacity than the construction of a rapid transit line. The civil engineering costs are similar, but buses need no power supply and have no safety signal system and, therefore, save up to $2 million/mile ($1.2 million/km).

The actual fully allocated cost of rapid transit, although it is often lower per ride than for surface transit in a specific corridor, will vary widely depending on whether the specific type of right-of-way construction is on an existing right-of-way, at grade, or above or below grade and also depending on station spacing.

ECONOMIC JUSTIFICATION FOR RAPID TRANSIT SERVICE

Although rapid transit may be a necessity for many cities, including some that do not have it, far too little attention has been paid to its economic justification on an operational basis. Capital and subsidies are not unlimited even if traffic congestion is. Too many plans assume an unlimited need for subsidy and, in so doing, place rapid transit planning at the personal whims of the designer instead of under the self-policing, automatic, and accurately guiding steady hand of the marketplace (4).

This is not to suggest that private enterprise should undertake rapid transit development because that has become impossible under existing tax systems and public policies. It should be enough for the public to lend its full faith and credit, supplemented by public grants when the giving of the grant reduces the cost of living for the general taxpayer.

There is nothing wrong with tax support for a desirable and necessary public facility, but a nonelastic yardstick is necessary to measure the effectiveness of the planning and design work. Rapid transit must be built where it will do the most good, obviously, but this can be determined only after all the directly relevant factors have been converted into real dollars for realistic comparison. Although worthy of full consideration, indirect benefits other than travel time are not likely to weigh significantly in the proper choice; therefore, they are not included, not only for simplicity but also because few could agree on them. Time differentials can be equated to modal choice, resulting in a demonstrated value for time. This modal choice is the reciprocal of added revenue from the additional patronage generated by speed.

The economic relationships between rapid transit and surface street transit and between scheduled and demand-actuated service are expressed in equation 6. Equation 6 is simplified, for this purpose, on the sound assumption that rapid transit should always serve a relatively high traffic volume or it should not be built.

$$\underbrace{(A_b + C_bR_b + G_bR_g)MX/64S_b}_{\text{(bus model)}} = \underbrace{(A_r + C_rR_r + G_rR_g)MX/150S_r}_{\text{(rapid transit model)}} + PR_pM/2 - \$1{,}282.5(1/S_b - 1/S_r) \qquad (6)$$

[The fixed right-of-way cost per passenger, based on current high traffic volumes, will not vary greatly per incremental unit because of the high use. If there are only a few short trains per day, it would be necessary to treat right-of-way maintenance as a fixed cost, but rapid transit is never built for such low volume. This is more of a real problem with railroad operation for which low-volume operation is sometimes prudent.]

TRANSIT OPERATING COSTS

Review of transit operating costs in all urban metropolitan areas reveals that, with few exceptions, costs are reasonably consistent if equated to the vehicle rather than to the mile (kilometer) or hour as is usually done [Table 3 (1)]. Rapid transit construction costs are also reasonably consistent for similar types of construction. With this type of information, planners and transit authorities can set up the mathematics of the circumstances, work through the proposed formula, and thus obtain a preliminary but realistic determination of the merit of rapid transit for specific application (Figure 1).

For demand-actuated service at the other end of the spectrum, a use formula will be devised to assist in realistically determining where scheduled service should stop and where demand-actuated service should take over. Contrary to popular expectations, demand-actuated service seldom attracts more rides per capita than good scheduled service; therefore, quality of service is not a financial trade-off problem [Table 4 (5)]. Of course, where demand-actuated service enters new territory, it will increase the transit rides per capita, but, where there is a choice, the longer, uncertain waiting time and higher cost seem to more than offset the added convenience. For convenience alone, the taxi has already performed the necessary service.

Admittedly, economic considerations are not the sole criterion. It is usual for rapid transit to increase the number of transit riders per capita greatly so that traffic relief, property values, safety, and economic stimulation may have as much to do with rapid transit justification as the operational economy has to do with it. But one must be careful to avoid delusions in these unquantified areas of interest [Figure 2, Tables 1 and 5 (2, 6, 7, 8, 9)].

COST MODEL FOR TRANSIT TRAVEL

The many relevant facts for direct operating determinations as given above in the notation and explanation of the variables are readily available for use in substitution in an empirical but relatively accurate model.

Table 3. Urban transit operating costs for 1973-1974.

Area and Mode	Vehicles	Annual Cost (dollars) Total	Per Vehicle
Baltimore	1,000	45,000,000	45,000
Chicago bus	2,762	168,000,000	61,000
Chicago rapid transit	1,181	59,000,000	50,000
Chicago C&NW railroad	296	22,800,000	77,000
Cleveland bus	840	26,700,000	32,000
Cleveland rail	172	7,560,000	44,000
Detroit	1,114	47,000,000	42,300
Los Angeles	1,525	60,000,000	39,300
Philadelphia bus	1,650	67,320,000	40,800
Philadelphia rapid transit	490	22,100,000	45,000
Philadelphia railroad	446	42,816,000	96,000
Pittsburgh bus	915	43,371,000	47,400
Pittsburgh rail	95	5,629,000	59,250
St. Louis	824	23,500,000	28,500
San Francisco bus	1,300	55,705,000	42,850
Toronto bus	1,097	55,660,000	50,600
Toronto rapid transit	410	15,000,000	36,600
Washington, D.C.	1,353	60,000,000	44,500
Total bus	14,473	653,000,000	45,135
Total rapid transit	2,348	108,400,000	46,100

Note: New York, Boston, and Montreal were excluded to avoid unusual circumstances. Other omissions were caused by inadequate data.
Cost of transit operation has usually been simplistically calculated in terms of vehicle miles (kilometers) or somewhat more accurately in terms of the vehicle hour. The cost per vehicle is more consistent and equates to $1.46/bus-mile or $14.60/hour. The most accurate equivalent would be $11,000/bus plus $7.33/hour plus $0.36/bus-mile for 1974.

Figure 1. Investment versus traffic volume.

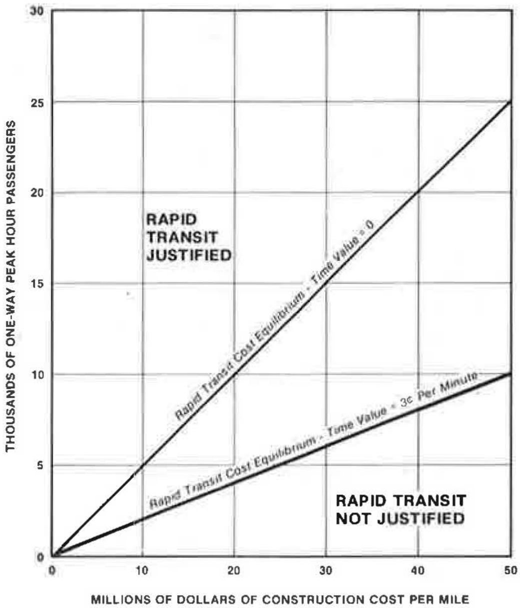


Table 4. Demand-responsive transportation systems.

Item	Regina	Buffalo	Bay Ridges	Haddonfield	Batavia	Ann Arbor	Columbus	Columbia	Davenport	Control PAT[a]	Harrisburg
Population served	15,200	7,000	14,000	25,000	18,000	13,000	37,000	17,300	125,000	100,000	170,000
Average daily fares	1,200	360	530	750	350	214	400	54	1,440	25,000	12,000
Annual ridership	305,000	120,000	193,450	225,000	105,000	64,200	127,700	13,500	480,000	6,750,000	3,600,000
Riding habit, annual per capita	20.0	17.0[b]	13.8	9.0	5.8	5.0	3.4	0.8	3.8	67.5	21.0
Buses including spares	6	7	5	12	5	4	5		40	95	60
Annual operating cost, dollars	217,770	245,000	83,000	500,000[c]	157,500	83,333	214,048		566,400	4,200,000	1,500,000
Annual revenue, dollars	61,000		41,000	120,000	53,000	29,000	25,540			2,950,000	1,440,000
Fare, dollars	0.35		0.25	0.50	0.40	0.50	0.20	0.50	—[d]	0.40	0.35
Cost per ride, dollars	0.71	2.02	0.43	2.20	1.50	1.35	1.68	2.50	1.18	0.62	0.42
Cost ratio over fare	2.0		1.7	4.4	3.7	2.7	8.4	5.0		1.5	1.2
Cost per passenger-mile, dollars	0.35		0.22	0.70	0.75	0.66	0.75			0.12	0.17
Annual cost per bus, dollars	36,295		16,600	40,500	31,500	20,875	42,810		14,160	45,000	25,000
1972 wage rate, dollars	4.38		3.64	4.75	3.00	4.00	—[e]			4.75	4.00
Passengers per mile	1.76		1.5	0.3	0.43	0.7	0.8			4.0	2.0
Passengers per hour	18.8[f]		16.5[f]	4.1	9.0	7.85	7.6	4.4		48.0	20.0
Many to one, percent	55		76	25		93	5			85	80
Miles per hour	10.6		11.0	13.7	20.0	11.2	9.5			12.0	10.0
Rank in trip generation	3	4	5	6	7	8	9	11	10	1	2
Rank in economy	4	9	3	10	7	5	8	11	5	1	2

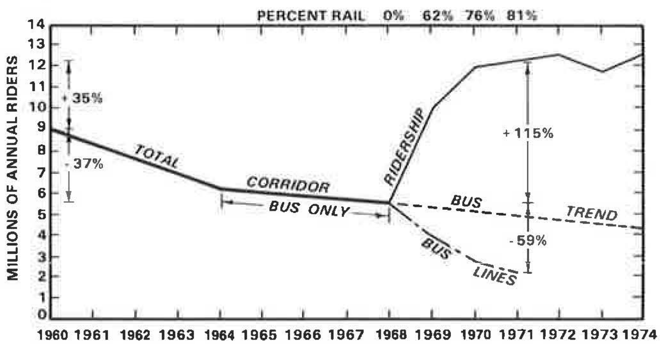
Note: 1 mile = 1.6 km.

[a]Port Authority Transit routes 35, 36, 37, and 38/42 in suburban Pittsburgh.
[b]Only population over 59 years eligible in model cities only.
[c]Excludes start-up costs and demonstration overhead.
[d]Taxi.
[e]High.
[f]Semifixed, scheduled peak-hour service feeding trunk transit lines.

Table 5. Rapid transit impact on ridership.

Area	Surface Transit Rides Amount	Surface Transit Rides Per Capita	Rapid Transit Rides Amount	Rapid Transit Rides Per Capita	Total Rides per Capita
Baltimore	117,136,000	56.5			56.5
Buffalo	36,983,730	28			28
Dallas	27,520,000	17.5			17.5
Detroit	94,343,800	22.5			22.5
Los Angeles	199,500,000	28			28
Minneapolis-St. Paul	59,000,000	32			32
St. Louis	52,180,000	22			22
Washington, D.C.	150,000,000	52.5			52.5
Median without rapid transit	76,500,000	34.5			34.5
Boston	81,000,000	29.5	73,000,000	26.5	56
Chicago	293,586,000	42	147,806,000	21	63
Cleveland	71,000,000	34.5	16,000,000	8	42.5
New York	821,220,000	71	1,122,456,000	97	168
Philadelphia	139,000,000	29	142,006,000	30	59
Pittsburgh	80,000,000	33	6,000,000	2.5	35.5
Toronto	238,000,000	90.5	118,000,000	45	135.5
Median with rapid transit	95,013,000	34.5	72,981,000	26.5	61

Figure 2. Ridership increase in southern New Jersey rapid transit system.



SOURCE: Wharton School, U. of Penna. Nov., 1972 DRPA - PAT Co.

Street transit costs depend on the annual cost of operation per unit A_b plus the annual increment of investment in rolling stock C_b, which is determined by multiplying the total by the capital recovery factor R (to reflect depreciation and interest costs), plus similar investment costs for fixed facilities such as garages (G_bR_g). The sum of these ($A_b + C_bR_b + G_bR_g$) constitutes the total annual cost per unit of rolling stock.

Surface Transit

The number of vehicle units can be determined by dividing the number of riders one way in the peak hour at the maximum load point by the scheduled capacity of each vehicle (64) [i.e., 40 × 8 = 320 ft^2/5 ft^2 (29.73 m^2/0.46 m^2)]. This will give the number of units required for a service for 1 hour. The actual number of vehicles, plus 10 percent for spares, will vary from this as the scheduled round trip and recovery time varies from 1 hour.

The annual cost of surface transit operation can be expressed by dividing the number of round trip miles M by the scheduled speed S_b in mph (km/h) and multiplying the result (M/S_b) by the predetermined number of vehicles (passengers/64). Thus, the annual cost of surface transit operation for a given route will be

$$(A_b + C_bR_b + G_bR_g)(MX/64S_b)1.1 \quad (7)$$

For demand-actuated service, the formula is similar except that the number of vehicles is determined by the ratio of one vehicle for each eight passengers per hour. This is the practical limit of achievement to date for unscheduled service without excessive waiting time.

Rapid Transit

Rapid transit operating costs can be determined the same way, except that the private right-of-way adds capital cost and permits the passenger loading to be increased from 64 per unit to 150 [i.e., 75 × 10 ft = 750 ft^2/5ft^2 (≈ 69.97 m^2/0.46 m^2)] with larger vehicles if 5 ft^2(0.46 m^2) of vehicle size [4.5 ft^2(0.42 m^2) of interior space] are allocated to each passenger. This is the practical limit of loading if each passenger is to have unfettered access to a door at his or her stop and a handhold or a seat while riding. The cost of the exclusive right-of-way will be called P, multiplied by the capital recovery factor R_p times the length of the route M/2. The total cost per year then becomes

$$(A_r + C_rR_r + G_rR_\phi)\ MX/150S_r + PR_pM/2 \quad (8)$$

By equating this rapid transit cost with the surface transit cost, X becomes the number of passengers one way per peak hour that determines the break-even point of rapid transit economy as compared with surface transit service.

The formula becomes practically meaningless at volumes above 6,000 passengers/peak hour/artery because surface transit above this figure requires either trolley trains or an exclusive pair of street lanes for bus loading and passing. The delays of high-volume street transit at loading zones usually limit CBD speeds to 3 or 4 mph (4.8 or 6.4 km/h). This idea is difficult to sell to passengers, and the delays make operation very expensive. When the full cost of providing two more lanes of city street is considered, rapid transit will likely be more economical and more expeditious and attractive for high-volume travel.

Demand-Actuated Model

The economic justification for demand-actuated service arises from the ability of one vehicle unit to cover more territory, even though it serves few passengers. It is the low-load factor of scheduled service that justifies substitution of demand-actuated service rather than line loading at capacity. The added dispatching and control costs for demand-actuated service add 25 to 33 percent to operating cost (3), and the eight passengers per hour limit the efficiency of the service. The equation for substitution of demand-actuated service for scheduled service is, thus, quite simple. A demand-actuated bus will serve eight peak-hour riders per hour at a cost of 1.25 times the cost of scheduled service. Thus, when a scheduled-service bus is serving less than six and one-half peak-hour passengers per hour or when two buses are serving less than eight passengers per hour, demand-actuated service is prudent. Urban area scheduled transit service in 1974 is costing an average of \$14/hour (Note, Table 3) at nominal \$5.50/hour wage scales. Therefore, the most realistic cost estimate for demand-actuated service will be about \$17.50/hour or \$2.20/passenger minimum when the service is fully demand-actuated and unscheduled and based on current metropolitan wage rates. Table 4 gives some demand-actuated services at less than current wage scales.

COMPARISON OF URBAN TRANSIT EXPENSES

Table 2 gives operating expenses that are typical except for New York City and Boston where unusual restraints apply for all urban transit modes.

These costs have been developed from the average of the fast, low-volume, newer system in Cleveland, the older, higher volume, more extensive system in Philadelphia and the newest, high-volume system in Toronto. All three systems have similar modern surface vehicles, although in Cleveland conventional rapid transit is supplemented by surface rail vehicles used for light-volume rapid transit service (Table 3).

The interest used to compute the costs is based on the local government rate of $5\frac{1}{2}$ percent. Federal funds, particularly highway funds, are in part on a cash-flow basis devoid of interest, but the federal debt precludes debt-free capital without interest. It is assumed that private capital will no longer be used to build highways or rapid transit lines.

Substituting the standard proved values in the equation yields

$$(A_b + C_bR_b + G_bR_g)MX/64S_b = (A_r + C_rR_r + C_rR_g)MX150S_r + PR_pM/2 \qquad (9)$$

Based on equation 9, X = 2,100 passengers on an abandoned converted railroad right-of-way, 2,100 in an expressway median, 6,300 on an aerial line, 10,500 in a depressed open alignment, and 21,000 in a full subway. In most cases, a single rapid transit line will include several of these different elements, and the calculations will be modified to reflect the variation. For commuter rail service, the break-even point comes at 943 passengers/peak hour for diesel service requiring \$1 million/mile (\$0.6 million/km) for track upgrading and stations.

For example, given 18 miles (29 km) of railroad on which commuter passenger service is being considered, the break-even point for commuter rail can be determined as follows:

$$(A_b + C_bR_b + G_bR_g)MX/64S_b = (A_r + C_rR_r + G_rR_g)MX/150S_b + PR_pM/2 \qquad (10)$$

where the suburban bus schedule speed into city with recovery time = 14 mph (23 km/h); all passengers are seated at peak, 64 is reduced to 53 and 150 is reduced to 104; and commuter rail right-of-way embellishment costs $1 million/mile ($0.6 million/km). Therefore,

$$(\$45{,}135 + 48{,}000 \cdot 0.1 + 20{,}000 \cdot 0.07)\ 36\ X/53 \cdot 14 = (\$87{,}500 + 320{,}000 \cdot 0.075 + 30{,}000 \cdot 0.07)\ 36X/104 \cdot 30 + (1{,}000{,}000 \cdot 0.062)36/2 \tag{11}$$

and

$$X = 943 \text{ one-way passengers in peak hour justify rail service at time value} = 0 \tag{12}$$

Following is a time value iteration for 943 one-way passengers in peak hour that typify 3,772 average daily two-way passengers, each saving an average of 23 min worth $0.69 at $0.3/min as derived. The annual time saving has a value of $2,603/day or $728,000/year to be applied against construction cost. Thus,

$$\$2{,}490\ X = \$1{,}306\ x + 1{,}116{,}000 - 4X \cdot \$0.69 \cdot 281 \tag{13}$$

and

$$X = 570 \text{ one-way passengers in peak hour justify rail service time value} = \$0.03/\text{min} \tag{14}$$

Many planning studies also include the value of time saved, which will reduce the break-even volumes of travel to much lower levels. It will also reflect the superior elasticity of a more competitive service in making comparison with other alternatives. Mathematical analysis of traveler choice indicates that modal split and traffic assignment techniques are most accurate when a derived value is put on travel time [$0.0167/min in 1960 (10)]. When this value is updated to 1974, approximately $0.03/min will most realistically reflect travel patterns. Since surface transit averages 6 min/mile (3.7 min/km) in urban centers and rapid transit averages about 2.5 min/mile (1.6 min/km), the saving of 3.5 min is worth $0.105 in offsetting capital cost of construction. Accordingly, the expression $-85{,}500\ (1/S_b\ 1/S_r)(\$0.03XM/2)$ should be appended to PRM/2 in equation 9. This will reduce the subway break-even cost from 21,000 one-way passengers/peak hour to 5,825 at $0.03/min saved. Because there are excellent time savings on at-grade rights-of-way, the cost can become zero or less. This means that the project rate of return exceeds the amount calculated. Since most of the federal highway program has been justified on time savings, balanced transportation planning requires similar assumptions for public transit.

Wherever the speed and regularity of rapid transit service will attract volumes of peak-hour travel that are greater than the values of X calculated by the model in this paper, investment and construction are likely to be justified.

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ENERGY OPTIMIZATION FOR RAIL PUBLIC TRANSIT SYSTEMS

Norman H. Danziger, Parsons, Brinckerhoff, Quade and Douglas, Inc.

Energy optimization for rail public transit systems is discussed from the viewpoint of an integrated systems approach. This approach considers the interaction of all the major subsystems of a total rapid transit system rather than each subsystem independently as has often been done previously. Some of the major subsystems examined include vehicles and their major propulsion, braking and auxiliary systems, train operations, environmental control facilities, and civil and structural facilities. The major factors that may significantly affect an overall energy evaluation are identified, and the ways in which each of these factors may be controlled to effect overall maximum efficiency of energy use are discussed. Energy evaluation techniques include a new strain performance simulation computer program developed by Parsons, Brinckerhoff, Quade and Douglas, Inc., as part of a 4-year subway environment research project. This paper notes that the procedures for evaluation on a total systemwide basis are applicable for any rail transit system and can be used to extend or modify existing rail transit systems and the design of new systems.

•UNTIL fairly recently, discussing the optimization of energy in rail public transit systems would have been considered quite irrelevant. Considering the absence of new construction, the need for energy optimization might have been questioned, and, considering the many variables involved, the ability to perform a meaningful analysis would have been doubtful.

It has become clear, however, that these objections are no longer valid. The growing need for rapid and comfortable urban public transit is widely regarded as one of the outstanding technological challenges of the last half of the twentieth century. Today, more rapid transit systems are being thought about, planned, designed, or built than ever before. It has been estimated that, in cities in the United States, expenditures on new, expanded, or improved rapid transit facilities will amount to $25 to $35 billion over the next 10 to 15 years. Cities expanding existing systems or planning new systems include Atlanta, Baltimore, Boston, Buffalo, Chicago, Cleveland, Honolulu, Los Angeles, Miami, Minneapolis-St. Paul, New York, Pittsburgh, St. Louis, and Washington, D.C. In other countries, planning or construction of transit is under way in Toronto, Montreal, Mexico City, Vienna, Munich, Frankfurt, Budapest, Caracas, Hong Kong, and Sao Paulo; transit studies are being done in Singapore; Japan is planning to almost double its existing 82 miles (132 km) of rapid transit in Tokyo, Osaka, and Kobe; and Brussels, Helsinki, Turin, and Amsterdam are among the European cities planning entirely new rapid transit systems. The population growth in urban areas demands a greater frequency of rapid transit service at higher speeds. Since the increase in power to provide faster and more frequent train service varies as the square of the increase in speed, power requirements may be expected to increase at an equal rate.

EVALUATION OF ENERGY BALANCE

The need for an integrated systems approach deserves particular emphasis when requirements or problems related to a transit system energy balance are to be evaluated. Because of the transient nature of subway system characteristics, few, if any, phenomena or parameters are truly independent. Variations in design average and maximum train speeds, for example, will have a profound effect on many aspects of a transit system. These include operation concepts, required number of trains for the system, vehicle propulsion and braking system characteristics, radii of track curvature, environmental control systems, and traction power and auxiliary power distribution systems. The energy balance for the entire transit system must therefore consider all of its physical, geometrical, operational, and physiological parameters. After an energy evaluation has been made, energy and cost trade-off evaluations can be accomplished to provide guidance on alternative system concepts.

The methodologies for performing cost trade-off evaluations are familiar to most engineers. They should consider, in their evaluations of alternatives, capital costs, operating costs, life of equipment, and the financing costs. Because of the various funding factors and the variations in their application to both the capital and operating costs of a transit system, the highest priority cost factor cannot be established in a generalized way. The planner should take into account current federal, state, and local funding options before a meaningful trade-off evaluation is made.

Before one can evaluate the energy balance that is obtained in a rapid transit system, it is necessary to understand the characteristics and behavior patterns of the various interrelated parameters. To begin, one must identify and quantify the power loads. The most important loads, of course, are those associated with train operations. They account for approximately 85 to 90 percent of the system energy demands. When one examines the most significant load contributor, the vehicle, several factors are apparent. Power required within line sections by trains for their propulsion system and air-conditioning equipment will be substantially higher in systems now under construction or being planned for the future than most present systems. The higher speed and acceleration requirements of future trains necessitate significantly higher power input and resultant power losses.

Approximately 50 percent of the total vehicle energy input is dissipated in the train braking cycle. When current dynamic or friction braking systems are used, this energy loss is converted to heat. Recent studies (1) indicate that, in subway sections of rapid transit systems, the average annual energy requirements for mechanical cooling and ventilating systems necessary to maintain desirable environmental conditions can amount to as much as 50 percent of the traction energy requirements.

On-board vehicle auxiliaries, most notably the air-conditioning equipment but also the lighting systems and air compressors, are the major power loads of the vehicle. Lighting and miscellaneous power loads for the fixed facilities of a rapid transit system normally account for the remaining 10 to 15 percent of the system power demands. These power loads primarily include escalators and environmental control systems (ventilation and mechanical cooling).

An understanding of the characteristics of a vehicle, as they may interact with overall energy considerations, is appropriate. Table 1 gives various vehicle characteristics for several systems in the western hemisphere (1).

Table 1. Vehicle characteristics.

System	Cars/Train		Maximum Passengers/Car		Motors		Tare Weight (lb)	Speed (mph)	
	Minimum	Maximum	Seated	Standing	hp/Motor	Motors/ Powered Car		Average	Maximum
New York	10	10	50	250	100	4	76,500	18	50
Chicago	2	8	50	75	55	4	42,700	24	55
Philadelphia	2	6	54	71	100	4	51,000	18	42
Boston	2	4	54	254	100	4	70,500	26	50
San Francisco (BART)	2	10	72	144	150	4	56,500	35	80
Toronto (TTC)	4	6	83	217	125	4	59,000	17	50
Montreal (MUCTC)	3	9	40	120	155	4	60,000	20	50
Washington, D.C. (WMATA)	2	8	81	94	175	4	70,000	35	75

Note: 1 lb = 0.45 kg. 1 mph = 1.6 km/h. 1 hp = 746 W.

The kinetic energy of the vehicle is primarily a function of its weight and operating speed ($K = mV^2$). The weight is a consequence of the physical characteristics. The weight and operating speed are generally influenced by the anticipated passenger loadings or traffic density and by other parameters such as length of the system; alignment, profile considerations, and constraints; vehicle structural design requirements; and distance between stations. Some of the major systemwide features and their range of variations are described below.

Vehicle Length and Weight

The consist (number of cars) varies as a function of system operating requirements and will generally vary from 2 to 10 cars. These requirements are usually influenced by peak versus off-peak traffic demands. Often, cars are semipermanently coupled in married pairs, which consist of two cars that share certain auxiliaries such as air compressors and communication systems. Although this provides certain economies in car construction and maintenance, the two cars may only be operated as a pair. Some systems, such as the MUCTC in Montreal, operate a three-car consist. Large transit systems may operate trains 600 ft (183 m) long or longer and use 10 or 12 cars during peak traffic periods.

Weight will vary with the size of the vehicle; however, it will also vary as a function of construction materials. Cars with aluminum bodies, for example, are generally regarded as lightweight when compared with stainless steel bodies. Vehicle tare weights for rapid transit service will generally range from 50,000 to 80,000 lb (22 680 to 36 288 kg).

Vehicle and Wheel Type

The most common type of vehicle truck is a two-axle, four-wheel type. The wheels are steel-flanged for operation on steel rails. Because of the steel wheel-steel rail noise problem in the older portions of the Paris Metro, which contains short radius curves, the French developed a pneumatic rubber-tired truck. This design concept is now in use in some parts of the Paris Metro and in the new Metros in Montreal and Mexico City. Two rubber-tired wheels are mounted on each of the two axles per truck. The wheels ride on a concrete or steel track. The trucks include horizontally mounted, rubber-tired wheels operating against sidewalls of the guideway to steer the vehicles.

Advantages claimed for the rubber-tired systems are reduced noise on short radius turns and the ability to operate on steeper grades than with flanged steel wheels. Because of the construction features and number of components of the pneumatic rubber-tired trucks, their weight and rotational inertia are significantly higher than for flanged steel-wheel trucks. In addition, the limitations of load-bearing capacity of the rubber tires result in significantly shorter car lengths than the allowable maximum for steel-wheeled cars. Another disadvantage of rubber-tired trucks is the higher rolling friction and hysteresis losses common to any rubber-tired vehicle. Collectively, these losses, together with a greater car weight per passenger, result in total system traction power requirements that may be more than 50 percent greater than for steel-wheeled vehicles per passenger carrying capability for systems with similar track profiles (2). Therefore, it should be evident to system designers that many site and system factors must be taken into account in selecting the most appropriate truck-vehicle concept.

Propulsion System

Most rapid transit system cars are driven by electric traction motors that are contained on each car. The source of energy is wayside electric power distributed through a third rail or overhead catenary wire. Contact shoes or pantographs, as appropriate, function as the power pickups for the car. The traction motors are generally mounted within the vehicle truck and there may be one or two motors per truck, or two to four per car. Four motors up to 150 hp each per car are possible. Motors may be ac or dc, although most transit systems use dc. The motor sizes are determined as a function of car weight, design speed criteria, and design acceleration rate requirements.

Braking System

For safety considerations, most rapid transit cars have multiple braking systems. These include friction shoe or disc brakes and usually some form of electric braking. In electric braking (dynamic or regenerative), the traction motors are switched to function as generators during the braking mode. Where dynamic brakes are used, the electric energy generated by the conversion of the train's kinetic energy in bringing the vehicle to a stop is discharged to on-board resistor grids. In the process, these resistor elements are heated up to 500 or 600 F (260 or 315 C) or even higher. Thus, the braking energy is ultimately all dissipated as heat, either at the wheels as a result of the friction brakes or at the resistor grids.

One of the more recent advances in transit vehicle propulsion-braking systems is the use of a regenerative braking system. Although this system is similar to a dynamic braking system insofar as the switching of the traction motors to operate as generators is concerned, part of the generated energy is then used by on-board auxiliaries. An alternative system permits return of the electrical energy to the contact rail for possible use by other trains. Regeneration can reuse 25 percent or more of the available braking energy of trains. Since, on the average, the braking energy accounts for almost 50 percent of the total energy lost in a rapid transit system, reuse of some of that energy and resultant reductions in heat dissipation can be effected. Therefore, a regenerative braking concept is highly desirable for energy conservation. The effective use of a regenerative braking system is limited only by present technology. Further advances in compatible electrification and power control systems are necessary before the full benefits of regeneration can be realized.

Air Conditioning

Most transit agencies building new systems or replacing outmoded rolling stock are purchasing air-conditioned vehicles. Since the power required per car for air conditioning may be as much as 50 kW, the energy and heat dissipation loads of the air conditioners are significant contributors to the overall load side of the transit system energy balance. This is particularly true during hot summer months when they operate almost continuously, even when the train is stopped and no propulsion power is drawn. In addition, the weight of vehicle air conditioning adds to the overall propulsion system energy requirement.

Operational Requirements

Since the kinetic energy of a vehicle varies as the square of its speed, it is apparent that operational requirements of vehicles can significantly affect the vehicle power demands. Higher speeds for vehicles are generally desired by transit system planners because they influence the travel time of the passengers and are a factor in determining rolling stock inventory requirements. However, in downtown subway systems, relatively close spacing of stations [within 0.5 mile (0.31 km)] will limit maximum operating speeds that might be achieved, since criteria for accelerating and decelerating rates will govern the operating conditions. In some instances, close station spacing may result in a train shifting from a maximum acceleration mode to maximum deceleration mode without any operation at a steady cruising or diminishing coasting speed. Consequently, if an increase in running time of trains can be accepted (usually measured in seconds for a downtown station-to-station run), the resultant reductions in energy demand could be significant. In many cases, the maximum cost effectiveness can be achieved where a slight increase in headways due to coasting can be tolerated without overloading the system.

Although newer systems are using semiautomatic or fully automatic train control systems, existing systems are predominantly manually controlled. In such a system, the train operator or motor person manually controls the starting, running, and stopping of the train and the opening and closing of the train doors in stations. The motor person operates the train by varying a control lever in the cab. On most systems, through a device known as a cam controller, appropriate parts of the vehicle propulsion motor circuitry are mechanically switched to accelerate, cruise, and decelerate the train.

Recent applications to new systems use chopper controls instead of cam controllers. Fundamentally, a chopper is a solid-state switching device that accomplishes similar end results as the cam controller but does this much more efficiently and smoothly by eliminating mechanical cam contactors. Chopper controls can reduce the traction power energy requirement in the acceleration mode by as much as 10 percent compared with that for cam controllers. In a chopper system, the motors do not operate at full voltage during initial acceleration, but the voltage increases as the ratio of the chopper off time to on time decreases. Because the motors do not operate at full voltage, there is a reduction in power consumption.

Since the kinetic energy of the train relates in part to its weight, the transit system planner may endeavor to specify vehicles that result in the lowest tare weight per passenger carried. Factors that the planner should consider, however, are numerous, and many decisions about the physical characteristics of the vehicle can have a significant impact on energy consumption. In general, the greater the length of a vehicle is, the lower the car weight per passenger will be. Although this would appear to be an obvious advantage, it may limit the operating flexibility for a given system (economical number of cars per train) or provide constraints on minimum track radii. These situations may require enlarged tunnels and may conflict with track routing and alignment considerations. Similarly, local topographic or right-of-way construction considerations may warrant the use of steeper grades, which may be more suitable for rubber-tired vehicles on concrete or steel guideways than for steel-wheeled vehicles on steel rails. When designers understand the characteristics of the major vehicle parameters, they will be able to evaluate the impact and interaction of those characteristics and the overall energy balance.

Track Profile

For a fixed-guideway rapid transit system, the alignment or routing of the system trackways and the locations of stations are determined by transportation planners as a function of the anticipated passenger traffic densities in the various transportation corridors.

Having established an acceptable alignment, transportation system designers then proceed to develop a track profile. Usually at this point determinations are made with regard to those segments of the system that should properly be located above, at, or below grade. Very often these determinations involve an iterative process that takes into account alternative alignments. The objective is to establish an overall system layout that best serves passenger traffic needs and that results in the most economical system construction costs. Subway, or below-grade, construction will be the most costly compared with at-grade or above-grade configurations. [In April 1974, the New York Times reported New York City construction costs of $30 million/subway mile (kilometer)]. Decisions relating to the determination of the track profile may significantly affect and interact with total energy considerations.

The development of the track profile will also consider the grade changes. Construction and other local site conditions may result in varying requirements. Vehicle characteristics will impose constraints on grades and on vertical radii of curvatures where changes in grade are necessary. Where possible, it would be desirable for trains to travel on a downgrade when leaving a station so that it would be assisted in the accelerating mode, and this would reduce the input power requirements. Similarly, it would be desirable for trains to approach a station on a rising grade so that the braking energy requirements may be reduced. A humped track profile can result in energy conservation by using the potential energy capabilities of the trains.

Conclusions About Subsystems of Rapid Transit

Since the major contributor to the total energy load is the energy used by the vehicle, it is the characteristics of the vehicle and of the system operating concepts that should primarily be addressed to effect energy reductions. Naturally, the cost effectiveness of energy operating costs can be evaluated against amortizing the cost of capital investment. It remains for the owners of a given system, however, to ascertain the additional intangible values of energy conservation that might be achieved with still additional capital investment. In any event, unless a totally integrated transit system design approach is used, opportunities for reducing capital investments and concurrently conserving energy might not even be realized. However, the following factors may be used to achieve these goals:

1. Most transit vehicles have a service life of approximately 20 to 30 years; therefore, the decisions relative to the vehicle component characteristics will have a long-term effect in regard to energy control factors. To affect load reductions, several objectives, such as reduced weight of the vehicle and operating speed constraints, should be sought, and the most efficient propulsion systems should be obtained. Braking systems that reduce energy losses are highly desirable. Thus, from an energy viewpoint, chopper controls and regenerative braking systems with maximum line receptivity are the most desirable objectives.
2. Steeper downgrades for trains leaving a station and greater upgrades approaching the station can significantly reduce the power loads. Where grades can be made greater than those capable of being used for steel wheel-steel rail systems, the benefits may be significant enough to favor consideration of pneumatic rubber-tired vehicles.

ANALYSIS OF ENERGY BALANCE DESIGN PROCESS

Overview

The analysis phase of the energy balance design process, however, is not a singular cycle of events. On the contrary, it is more of a repetitive process that continues as appropriate to the nature of the overall rapid transit system design decisions under consideration. In this iterative approach, the intensity of investigation and evaluation must be in proper relationship to the other systemwide investigations.

Given a set of input parameters and an ability to make the evaluation of the simultaneous interaction of all these parameters in a dynamic system, the engineer or planner can then ultimately determine the overall energy requirements and ascertain the system cost. What then becomes most important for the system planner is the ability to quickly estimate the total system cost variations as a function of varying some of the controllable input parameters. There could be several hundred significant alternatives resulting from the possible major variations in the controllable input parameters that would be a result of these permutations and combinations.

The preoperational computation of train velocity, acceleration, and position in a given system has long been carried out by rail transit engineers using a classical computational procedure based on track profile and alignment (grade and curvature), train weight, and propulsion system characteristics. The tedious nature of these computations eventually prompted a number of motor manufacturers and engineering consultants to create computer programs for determining train performance. Although these computer programs vary in their ability to simulate complex operating schedules, all use a computational procedure that follows closely that used in classical hand calculation.

Subway Environment Simulation Computer Program

One of the major products of a recently completed subway environmental research project (1) was the development of a subway environment simulation (SES) computer program. The program was developed by Parsons, Brinckerhoff, Quade and Douglas, Inc. and reflects inputs from Kaiser Engineers, De Leuw Cather and Company, the Graduate Aeronautical Laboratories of the California Institute of Technology working with the Jet Propulsion Laboratories, the aerospace technology division of the Developmental Sciences, Inc., and from every operating rapid transit authority in the western hemisphere (these data were received through the offices of the Transit Development Corporation). The Urban Mass Transportation Administration provided most of the funding for the project, and the operating rapid transit agencies of the United States and Canada provided additional funding.

The research project that led to the development of the SES program came about when it was recognized that there was a long-standing need for analytical tools with which the environmental characteristics of a proposed rapid transit system subway design could be evaluated before construction. To achieve this objective, the computer program was developed to provide a dynamic simulation of the operation of multiple trains in a multiple track subway and to permit continuous readings of the air velocity, temperature, and humidity throughout any arbitrary arrangement of stations, tunnels, ventilation shafts, and fan shafts. The SES program comprises four interdependent computation sequences: a train performance subprogram, an aerodynamic subprogram, a temperature/humidity subprogram, and a heat sink subprogram. These subprograms operate simultaneously by using a mutually shared set of system descriptive parameters. The computations in the program of the aerodynamic and thermodynamic phenomena integrate the various differential equations by using a modified version of the Runge-Kutta numerical integration technique.

The new SES train performance subprogram differs from most conventional train performance programs in two important respects: (a) It has been designed specifically to accomodate accurate, continuous computations of the total heat (energy) released by trains, passengers, and ancillary equipment such as air conditioning; and (b) it permits the direct computation of the aerodynamic drag acting on each of the trains in the system by using continuously computed aerodynamic parameters (3). This is particularly important in an overall energy analysis because the aerodynamic drag on vehicles resulting from air motion relative to the trains affects the power consumption of the vehicle motors. In evaluating vehicle aerodynamic drag, conventional programs ordinarily settle for a semiempirical relationship based on train velocity and blockage ratio (the ratio of the train frontal area to that of the tunnel cross section). In practice, the aerodynamic drag on a train fluctuates continuously as it encounters variable annular airflows resulting from changes in tunnel diameter, ventilation shaft location, mechanical ventilation, and the piston-action airflow from other trains. Therefore, the continuous computation of vehicle aerodynamic drag in the SES program represents a significant advance in the state of the art.

The air velocities computed in the aerodynamic subprogram are recycled to the train performance subprogram, and there they are used to determine the airflows adjacent to the trains and provide a means to compute the vehicle aerodynamic drag. The aerodynamic drag is a function of the air velocity in the tunnel relative to the train, the train blockage ratio, tunnel wall friction, and the configuration of the cars.

As noted earlier, the computation of aerodynamic drag is an essential component of the subway simulation because this factor determines both the air resistance trains must overcome to accelerate and the amount of energy imparted by the moving trains to the surrounding air. In general, the drag experienced by a train in a single-track tunnel increases as train speed increases and decreases as the frequency of train operation (shorter headway) decreases.

The train performance subprogram can be operated independently to evaluate the comparative performance of transit vehicles or propulsion motors by suppressing the computation and printing of environmentally related information. The airflows and air velocities of the aerodynamic subprogram would still be computed because these data would be necessary to compute aerodynamic drag for the train performance subprogram.

The most important train-related energy release to the system occurs during the vehicle braking cycle. For a train using a dynamic braking system, the speed reduction of the vehicles is brought about by using the motors as generators to produce electrical power. This power frequently is dissipated to a grid of undercar resistors. The rate at which energy is dissipated is approximately equal to the net rate of the decrease in kinetic and potential energy of the braking train. The SES program computes this energy loss directly from vehicle deceleration rates, velocities, and total mass. Some of the braking energy is absorbed by friction brakes and by friction, windage, and bearing losses of the wheels and generators.

The SES program has been validated by field tests conducted on the rapid transit systems in the San Francisco Bay area, Chicago, and Montreal. It is currently being widely used in numerous environmental systems analyses for various rapid transit systems. Its extension to overall transit system energy optimization studies is now under consideration.

CONCLUSIONS

Examining energy problems leads to a consideration of all the major components of a rapid transit system, such as the vehicles, the fixed facilities, and the environmental control systems in the subway stations and line sections through which a transit system operates. As the various transit system specialists, including planners, engineers, architects, and others, investigate the interfaces between the energy problems and the various component subsystems of which a rapid transit system is composed, significant areas may be identified where overall optimizations of cost of construction and operation can be achieved.

To optimize construction costs, the transit system specialists must first recognize those elements for which alternatives are available. Various combinations of train lengths, headways, and speeds, for example, may satisfy the same traffic demands and yet have significantly different operating energy requirements. Conventional cost estimating techniques for both capital and operating costs may be developed after the trade-off alternatives have been established. The decisions relating to these alternatives are normally made in the early phases of planning a new subway system or extension to an existing system. Such decisions may have a profound effect on the overall energy requirements.

The importance of an overall integrated systems approach in the design of rapid transit systems cannot be overremphasized, if true optimization of energy use is to be achieved. The optimization of the vehicle itself or of the operating conditions of the system may be contrary to the achievement of energy conservation objectives. In a recent design study for a new downtown subway rapid transit system, the operating conditions established in the relatively closely spaced stations [approximately 2500 ft (762 m) apart] would have resulted in trains accelerating from one station and having to initiate a braking cycle when they approached the next station while they were still in an accelerating mode with the throttle wide open. From an operating design viewpoint, this ensured the fastest run time for a train from terminal to terminal. In addition, it minimized the total number of trains required for the system to meet the peak rush hour passenger traffic demands. Consequently, the operating system was thought to have been optimized.

An examination of this operating plan in the interest of reducing the environmental cooling load resulted in a cruising or coasting operating mode being introduced between each accelerating and braking cycle for each station-to-station run. As a result, the total station-to-station run times were each increased by several seconds. The total travel time from terminal to terminal was increased by approximately 5 percent. Two additional trains had to be purchased (at about $1 million each) to satisfy the peak rush hour traffic demands. However, the following were accomplished:

1. Traction energy requirements were reduced by 25 percent,
2. Capacity and operating energy requirements for environmental control equipment were substantially reduced, and
3. Capital cost savings for the systemwide environmental control equipment and facilities were approximately equal to twice the purchasing cost of the two additional trains.

Application of energy optimization analyses to total rapid transit systems designs may be rewarding in conserving energy and total system costs. Engineers now have all the tools and data normally required to perform these energy optimization analyses. It remains for energy engineers to apply their imagination and ingenuity in collaboration with all the other members of the transit system design team, such as the planners, vehicle designers, power engineers, environmental engineers, civil and structural engineers, and subsystem hardware component designers and fabricators, to create the optimum system design.

ACKNOWLEDGMENT

I wish to acknowledge the contributions of my colleagues, in particular, Woodrow W. Hitchcock and Werner W. Metsch, at Parsons, Brinckerhoff, Quade and Douglas, Inc.

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TOTAL ENERGY REQUIREMENTS OF THE BAY AREA RAPID TRANSIT SYSTEM

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The paper concerns the energy requirements of the Bay Area Rapid Transit system in five areas: traction energy, station energy, maintenance energy, construction energy, and impact energy. Vehicle traction energy is bounded by a probable lower bound of 3.2 kW-h/car-mile (7.2 MJ/km) and a probable upper bound of 5.5 kW-h/car-mile (12.4 MJ/km). When the station and maintenance energies are added, it is expected that the eventual total operating energy cost will lie between 6 and 7 kW-h/car-mile (13.5 and 15.7 MJ/km). The construction energy is calculated through the use of energy input-output analyses and is approximately equal to the total operation energy over a 50-year projected system life. The impact energy of Bay Area Rapid Transit, that is, the energy associated with other systems built because of the existence of Bay Area Rapid Transit, is discussed. There are not as yet sufficient data available to make an estimate of this energy. The important problem of energy dependence on loading is studied, and it is found that there is a nearly inverse (hyperbolic) relation between energy intensity [kW-h/passenger-mile (joule/kilometer)] and the vehicle loading factor.

•THE objective of this study is to determine as completely as possible the total energy requirements of the Bay Area Rapid Transit (BART) system. Energy is directly or indirectly used in a variety of ways in connection with the BART system. Five energy uses are identified: traction, station, maintenance, construction, and impact. These energy uses are defined, and the original projected traction, station, and maintenance energies made prior to construction of BART are given. Actual energy use by BART, as of the summer of 1973, is also given, and the extremely important relation of energy use to the loading factor is developed. In addition, a methodology for obtaining indirect energy costs of construction is discussed, and preliminary estimates of these costs are made. The concept of impact energy is also briefly discussed, and energy costs of BART are compared with those of other systems, such as the automobile and bus.

TERM DEFINITION

This paper identifies five energy use forms that are not uniformly defined in the literature. The purpose of this section is to define the terms used.

Traction Energy

Traction energy is provided to the vehicle through the 1,000-V dc third rail. It includes energy for vehicle propulsion, lighting, heating, air conditioning, and various other minor energy demands within the vehicle.

Station Energy

Station energy is used to operate passenger stations, associated parking lots, and the main administration building. It includes lighting and heating of the administration building. Stations are not heated.

Maintenance Energy

Maintenance energy is required to repair and maintain vehicles and other equipment and to provide heat and light for maintenance facilities.

Construction Energy

Construction energy is used to build the BART system, including vehicles, stations, roadbeds, the administration building, and other associated facilities.

Impact Energy

Impact energy is used in building or operating systems, structures, or devices that are developed because of the existence of BART. By nature, it is energy that is difficult to define and to determine.

PREDICTED ENERGY LEVELS

The BART system is not as yet complete, and some prediction of final energy demand is necessary to obtain an estimate of eventual total energy requirements. Comparative historical data from other systems are included in this section, and all electric power and energy requirements in this section and through most of the paper are in terms of demand at the point of use. Only in the last section will these demands be referenced to the energy required at the input to the power plant.

BART Annual Energy Demand Estimates

It was estimated in 1972 (based on the 1967 power estimate and scaled down from a 450- to 250-car system) that the final system electric energy requirements would be 90 million kW-h (324 million MJ) for traction and 130 million kW-h (468 million MJ) for station and maintenance. In addition, some natural gas, gasoline, and diesel fuels were expected to be used. We will not consider these in detail here since they are relatively small. The natural gas energy [65 billion Btu (68.5×10^{12} J)], used for administration building heating, maintenance heating, and car washing, is equivalent to about 21 million kW-h (76 MJ). The liquid fuel energy needs are much smaller than this.

The figures above indicate an initial estimate of 40 percent energy for traction and 60 percent for station and maintenance. As we shall see below, it now appears that, in practice, these percentages may be nearly inverted.

Existing Rapid Transit System Energy Requirements

A survey of existing systems indicates an approximate energy demand range into which the BART system might fall. Table 1 gives the energy and power requirements of five such systems. For comparison purposes, the BART traction energy estimate is bracketed by a probable lower bound [3.2 kW-h/car-mile (7.2 MJ/km)] and a probable upper bound [5.5 kW-h/car-mile (12.4 MJ/km)]. These terms and their justification are discussed in detail later.

From Table 1, we can learn a number of things about what to expect from electric public transit systems. Unless radically new and different systems are proposed or developed, we should be able to use the figures from Table 1 to make at least approximate estimates of power and energy use.

The energy demand per car-mile (kilometer) should be somewhere near 5 kW-h/car-mile (11.3 MJ/km). A particularly light or streamlined car or one that makes relatively few stops or effectively uses regenerative braking should demand less energy. Opposite characteristics would lead to higher figures.

Table 1 also gives perhaps the most important factor for passenger systems, the energy demand per passenger-mile (kilometer), assuming that each seat is filled and there are no standees. This is an idealized condition. The dependence on percentage of seats occupied will be discussed in detail later in the paper. A value of 0.06 to 0.10 kW-h/passenger-mile (0.02 and 0.14 MJ/km) should be reasonable for approximate planning purposes.

Electric motor power per tons (kilograms) of vehicle is an important factor because of its relation to the ability of the vehicle to accelerate. For example, the BART system has a maximum acceleration of 3 mph/sec (1.34 m/s/s). This is a high rate, close to the limit of comfort. Hence, BART vehicles require rather high-powered motors. Fast acceleration is necessary if a high average speed is to be maintained and stations are fairly close to each other. [BART has a peak speed of 80 mph (129 km/h) and an average design speed of 45 mph (72 km/h)].

Energy demand also depends on station spacing and average speed. Note the fairly strong correlation between traction power and traction energy (Table 1). Trains that make frequent stops and maintain a high average speed must be high-powered and will consume more energy per ton-mile (kilogram-kilometer) than slower trains with less frequent stops. But trains that make frequent stops have a good potential for making effective use of regenerative braking.

From an energy use standpoint, it is desirable to keep the ratio of seat density per ton (kilogram) high. However, other factors, including safety and comfort of ride, tend to favor greater weight. The designer has a compromise to make here. The high ratio of seat density per ton (kilogram) for the BART system reflects, to some extent, the availability of new lighter and stronger vehicle construction materials and new design techniques.

ENERGY USE BY BART

In that the BART system is not completely operational as yet, the data on actual energy being used by BART will certainly differ somewhat from final energy data. This might suggest that we should wait until the system is operating normally to obtain data. There are two reasons for proceeding at this time with only preliminary data. First, there is a need today for information about energy costs of transportation systems. Planning of future systems cannot wait for final, normal-operating data. Second, the process of evaluating the preliminary data with respect to weaknesses sheds light on the way in which energy is used in various ways in the system. This also provides a logical background for our discussion of load factor effects.

At least four factors operate to make the data incomplete as of July 1974: (a) BART is incomplete (not all tracks are in use), (b) more trains will be added, (c) the system is in a check-out period, and (d) the automatic control system is not fully operative.

The data for daily traction, operation, and maintenance energy used by BART during June 1973 were used as the basis for this analysis. We have reduced these raw data (2) in a number of ways to facilitate evaluation. In the following, we distinguish between revenue periods, when the system carries passengers (5 a.m. to 8 p.m., Monday through Friday), and nonrevenue periods.

Table 2 gives the way in which the various energies contributed, on a percentage basis, to the total monthly energy use. The first observation from Table 2 is that the energy split between traction and station and maintenance is nearly 50-50 (early estimates suggested a 40-60 split). Since station and maintenance energy is almost fixed (independent of traction mileage or passenger numbers), an increase in car-miles (kilometers) will tend to cause an even greater percentage increase in traction energy. Hence, it is now anticipated that, when BART becomes fully operational, traction energy will exceed that of operation and maintenance and perhaps will have a split greater than 60-40, the inverse of the original estimate. Table 3 gives a recent updated BART estimate of annual energy use based on early data (Figure 1).

If the current (1973) estimate is compared with the 1972 estimate, we find that the traction energy estimate is up by 22 percent and that station and maintenance energy estimates are down by 35 percent.

The estimation error in the case of station and maintenance energy is not difficult to understand. Little is known about these energy requirements. We are not aware of the availability of any station and maintenance statistics analogous to the national traction statistics given in Table 1. The original estimates of station and maintenance energy, made with few data, were conservative. We also observed that station energy is quite dependent in general on geographic and climatic factors, which determine heating, cooling, and lighting needs.

There is a dramatic increase in percentage of energy used for traction when 250 cars are compared with 450 cars (Table 3). The reason is obvious: Fixed costs (station lighting, administration, escalators, maintenance facilities) when established change little, but traction energy goes up proportionately, as cars are added. The net effect is that the total energy per car-mile (kilometer) goes down as car-miles (kilometers) go up. The more the system is used, the less it costs per unit of use.

Another interesting set of data obtainable from the raw data is the current energy required per car-mile (kilometer) and passenger-mile (kilometer). These data are given in Table 4. These data are based on operating periods early in the life of the system. As system use increases substantially, the energy cost per car-mile (kilometer) will decrease quite significantly. This effect is discussed in some detail at the end of this section.

Why do nonrevenue periods tend to require so much energy? One might expect the system would be turned off during these periods. In fact, the system remains mostly turned on for 93 of 168 hours of the week when the system is not operating. The raw data show that the ratio of revenue period station and maintenance energy to total station and maintenance energy is nearly equal to the ratio of revenue hours to total hours in the week. Station lighting stays on for security and maintenance reasons. At least, partial parking lot lighting comes on or stays on at night. Other facilities remain activated for testing, security, and maintenance.

The traction energy demand during nonrevenue periods represents 17.6 percent of all energy used by BART (Table 2). Nonrevenue period traction energy is used for vehicle testing and for lighting and heating or cooling vehicles not in service. Data from BART indicate an almost constant nonrevenue period power load of about 4 MW. Since this load is consistent 24 hours a day on Saturday and Sunday and during week nights, we deduced that little of it can be for testing. At this time, almost all cars are left in an energized mode with third-rail power on. Vehicles are heated and lighted, and some pumps are run continuously. This load per car is near 20 kW.

It is not entirely clear why cars are left hot while they are not in use. At least two factors contribute to this mode of operation. The air conditioner compressor pump-down cycle is 15 min. Apparently it would be necessary to have personnel monitor this process. In addition, during initial testing of vehicles, a number of problems were encountered that made it desirable to keep the vehicles hot. It is not clear at this time whether this mode is a permanent necessity or whether it can be phased out as the system approaches full operational status. It certainly seems reasonable that planners of future systems should ask design engineers whether live storage is actually necessary or desirable.

Traction energy is all the energy supplied to the 1,000-V dc third rail. It supplies pure traction or vehicle propulsion energy and auxiliary energy for vehicles in operation (heating, cooling, lighting) and for stand-by vehicles not in operation. The

Table 1. Factors relating to electric transit vehicle propulsion.

System	kW-h/ Car-Mile	kW-h/ Passenger-Mile[a]	HP/Ton	kW-h/ Ton-Mile	Seats	Weight (lb)	Seats/ Ton
Philadelphia[b]	5.9	0.105	13.6	0.200	56	48,500	2.3
Chicago[b]	4.5	0.090	8.1	0.166	51	42,000	2.4
New York[b]	5.4	0.115	8.7	0.118	47	79,000	1.2
Cleveland[b]	3.6	0.067	6.7	0.109	54	54,600	2.0
Toronto[c]	5.2	0.084	5.4	0.108	83	58,000	2.9
BART							
Probable lower bound	3.2	0.045	18.7	0.112	72	57,000	2.5
Probable upper bound	5.5	0.076	18.7	0.193	72	57,000	2.5

Note: 1 kW-h/mile = 2.25 MJ/km. 1 HP/ton = 0.8255 W/kg. 1 kW-h/ton-mile = 2470 J/kg-km. 1 lb = 0.45 kg. 1 ton = 907 kg.
[a]Assumes all seats occupied. [b](1). [c](1, 2).

Table 2. Contribution of various energies to total monthly energy use in June 1973.

Energy Type	Energy Use per Month (percent)
Traction	
Revenue periods	36.6
Nonrevenue periods	17.6
Subtotal	54.2
Station	
Revenue periods	16.0
Nonrevenue periods	21.5
Subtotal	37.5
Maintenance	
Revenue periods	3.4
Nonrevenue periods	4.9
Subtotal	8.3
Total	100

Table 3. 1973 estimate of annual BART energy.

System	Energy (kW-h)	Percent
250-car		
Traction	110,000,000	56
Station and maintenance	85,000,000	44
450-car		
Traction	198,000,000	70
Station and maintenance	85,000,000	30

Note: 1 kW-h = 3.6 MJ.

Table 4. Average energy use in June 1973.

Energy Type	kW-h Per Car-Mile	kW-h Per Passenger-Mile
Traction		
Revenue periods	5.680	0.209
All periods[a]	8.411	0.309
Total		
Revenue periods	8.676	0.319
All periods	15.513	0.571

Note: kW-h/mile = 2.25 MJ/km.
[a]Includes night and weekend use.

stand-by vehicles are in live storage and draw about 20 kW in this condition. If auxiliary energy for operating vehicles or for vehicles in live storage is discounted, then the 5.680-kW-h/car-mile (12.78-MJ/km) value given in Table 4 decreases. If regenerative braking is effective in returning energy to the system, net traction energy will be further reduced.

To quantify these effects, we first performed a calculation that eliminated the energy supplied to vehicles in live storage. This reduced traction energy to about 4.5 kW-h/car-mile (10.1 MJ/km). Since auxiliary power demand for operating vehicles is about 20 kW and average train speed is 45 mph (72 km/h), we assume an auxiliary energy demand of approximately 0.5 kW-h/car-mile (1.1 MJ/km). Discounting this demand further reduces traction energy to about 4.0 kW-h/car-mile (9 MJ/km). Therefore, our best estimate is that the pure propulsion energy requirement of a BART vehicle, discounting auxiliary energy and possible regenerative energy return, is 4.0 kW-h/car-mile (9 MJ/km).

It is anticipated that some fraction of this pure propulsion energy can be recovered by the regenerative braking system. An energy return from regenerative braking of 20 percent is probably a reasonable upper bound. The degree of success of regenerative braking will not be clear until the BART system is fully operational.

From the discussion above, it is clear that three energy factors could increase or decrease the stated traction energy based on the pure propulsion energy demand of 4.0 kW-h/car-mile (9 MJ/km). These factors are as follows (1 kW-h/car-mile = 2.25 MJ/km):

Factor	Energy Range (kW-h/car-mile)	Effect
Regenerative braking	0.0 to 0.8	Energy saved
Auxiliary energy for operating cars	0.5	Additional energy used
Auxiliary energy for live storage	0.5 to 1.0	Additional energy used

Hence, the traction energy can range from a probable lower bound of 3.2 kW-h/car-mile (7.2 MJ/km) to a probable upper bound of 5.5 kW-h/car-mile (12.4 MJ/km). The correct value to use depends on the assumptions the planner wishes to make and on the eventual degree of success of regenerative braking. If the planner or evaluator believes that auxiliary energy for operating cars is a part of traction energy, then 0.5 kW-h/car-mile (1.1 MJ/km) will be added. If the planner believes it is a convenience, analogous to the convenience of a station, then it may be accounted for another way, perhaps as an element of nonpropulsion operating costs. Of course, it must be accounted for eventually as some part of the total system energy.

The live storage factor is even more difficult to account for, and it may be possible to eventually eliminate live storage in the system. Or, if live storage is necessary, it may be desirable to account for it other than as an element of traction energy.

All of the above assumptions or accounting choices are necessarily left to the planner.

For our analysis of passenger loading effects in the next section, we assume traction energy to be 5 kW-h/car-mile (11.3 MJ/km). For purposes of comparing BART with buses and automobiles, we consider both the probable upper bound and the probable lower bound.

Next we consider the relation of energy use to annual car-miles (kilometers). Table 4 shows the energy required by BART cars in June 1973. As time passes, this energy will decrease for a number of reasons. Fixed operation and maintenance costs will be averaged over more car-miles (kilometers) and the opportunity for regenerative braking will increase. The relative amount of live storage should also decrease. The result is a roughly inverse (hyperbolic) relation of energy intensity to annual car-miles (kilometers). Some of the above factors have been considered in a recent projection of future energy costs made by BART (2).

We are now in a position to reconsider the power demands of BART. Figure 1 gives an estimate of power demand based on the data available at this time. The base power demand of about 16 MW is required for stations and maintenance (8 MW) and for auxiliary power to an assumed 400 operating and live storage cars. The peaks are estimated from anticipated train use when the system is fully operational. The major change in the 1973 estimate when compared with the 1967 estimate is that station and maintenance energy is somewhat less than had been originally estimated. In addition, the peak power demand is about 0.5 percent of the capacity of the area's power plant, the Pacific Gas and Electric Company.

A brief review of the way in which nonpropulsion energy is used for BART shows that, on the average, a BART car uses about 20 kW of power for nontraction purposes. About 1 kW is used in lighting, 10 kW for air conditioning, 20 kW for heating, and about 25 kW for other miscellaneous purposes such as fans, blowers, pumps, controls, and convenience outlets. Not all of these are on at the same time of course. The average demand is about 20 kW.

EFFECTS OF VEHICLE LOADING ON ENERGY USE

Vehicle loading or the number of passengers on a vehicle affects energy use in two ways: It usually has a small effect on the weight and, hence, the energy use per car-mile (kilometer), and it has a major effect on energy use per passenger-mile (kilometer). This latter measure is almost inversely proportional to the number of passengers carried.

Effect of Passengers on Vehicle Weight

Before discussing the important problem of energy use per passenger-mile (kilometer), we must briefly consider the effect that passengers have on vehicle weight. The weight of a vehicle is

$$W = W_0 + pW_p \qquad (1)$$

$$= W_0 + f_L S W_p \qquad (2)$$

where

W_0 = weight of the vehicle without passengers,
p = number of passengers,
f_L = loading factor (fraction of seats with passengers),
S = number of seats per vehicle, and
W_p = average weight of passenger = 150 lb (68 kg).

For most motorized vehicles, $f_L S W_p$ in equation 2 tends to be fairly small. In the case of BART, $W_0 \approx 57{,}000$ lb (25 855 kg) and $S = 72$. Therefore, equation 2 becomes approximately

$$W = 57{,}000 + 10{,}000\, f_L \qquad (3)$$

The loading factor can vary from 0 to about 2 ($f_L > 1$ indicates standees). Hence, a BART vehicle with every seat occupied has a total weight of 19 percent greater than its zero-passenger weight. [A 4,000-lb (1814-kg) automobile with 5 seats has almost exactly the same percentage increase in weight, when fully loaded, as the BART vehicle.]

Effect of Loading on Energy Intensity

As we noted previously, passenger loading does not have a great effect on the weight of a vehicle. Hence, one approach to determining the effect of passenger loading on energy intensity in units of energy per passenger-mile (kilometer) would be to assume the weight to be constant. For the time being, however, we will include the effect of loading on weight. We will assume there is a BART vehicle that requires 5 kW-h/car-mile (11.3 MJ/km) and that $f_L = 0$ (no passengers). We further assume that traction energy increases by a proportionality factor of 0.8 times the weight. (This means that about 20 percent of traction energy is not weight dependent. This includes aerodynamic drag, for example.) Based on the above assumptions, the energy required per car-mile (kilometer) is (CM = car-mile, PM = passenger-mile)

$$E_{CM} = 5 \times \frac{57{,}000 + 8{,}000\, f_L}{57{,}000} \qquad (4)$$

The energy per passenger-mile (kilometer) is

$$\begin{aligned} E_{PM} &= \frac{E_{CM}}{p} \\ &= \frac{E_{CM}}{72 f_L} \\ &= \frac{5}{72}\left(\frac{1}{f_L} + 0.14\right) \\ &= \frac{0.07}{f_L} + 0.01 \qquad (5) \end{aligned}$$

It is clear from equation 5 that, for typical loading factors near 0.25, the effect of passenger weight (the second term in equation 5) is not very important. It does, however, become quite important for load factors in the range from 1 to 2. Figure 2 shows the loading effect given by equation 5.

Loading Factor Versus Comfort and Convenience

Figure 2 shows the important relationship between energy cost per passenger-mile (kilometer) and passenger loading. It is clearly desirable from an energy standpoint to have as high a load factor as possible. However, two other important considerations argue against high load factors. The first is comfort. If $f_L > 1$, some passengers are standing. If f_L approaches two, the vehicle becomes crowded and even more uncomfortable. This decreases the quality of the ride and will probably discourage some passenger use.

The second consideration is convenience. Passengers usually wish to wait as short a time as possible for a train. This means frequent train service and lower load factors. It is not clear, however, that doubling the train frequency will halve the load factor. Doubling the train frequency will probably result in a more attractive system, and the result will be that the new load factor should fall somewhere between the original

Figure 1. Estimated BART power requirements for typical weekday.

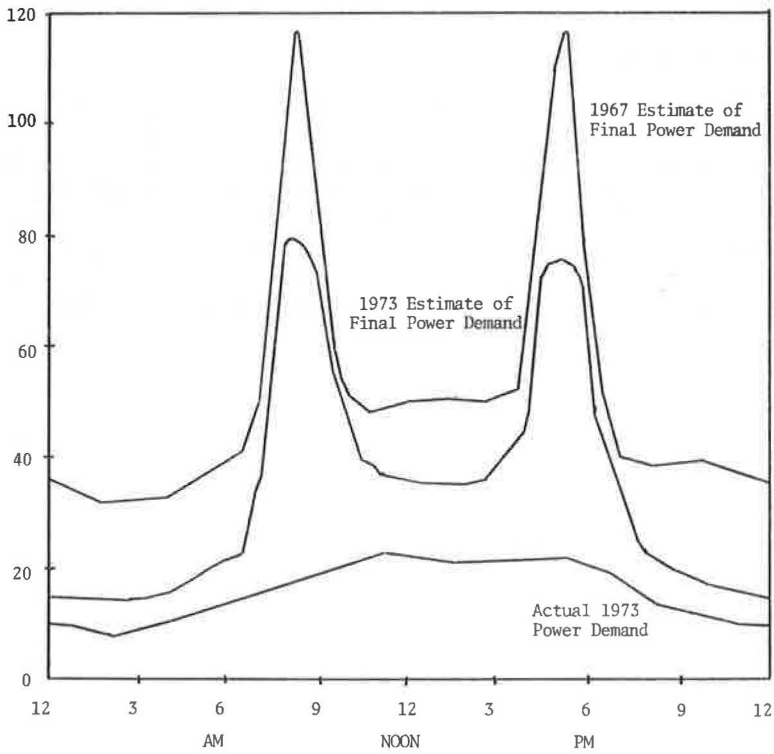
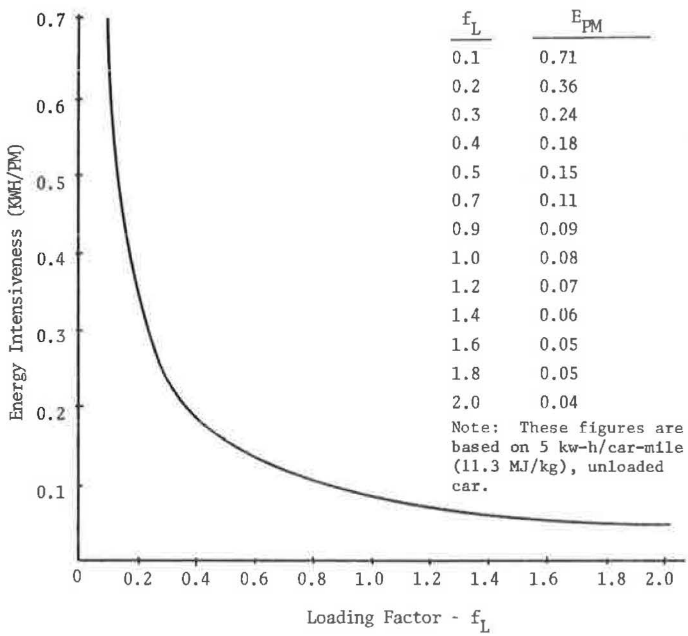


Figure 2. Dependence of energy intensiveness on loading factor.



f_L	E_{PM}
0.1	0.71
0.2	0.36
0.3	0.24
0.4	0.18
0.5	0.15
0.7	0.11
0.9	0.09
1.0	0.08
1.2	0.07
1.4	0.06
1.6	0.05
1.8	0.05
2.0	0.04

Note: These figures are based on 5 kw-h/car-mile (11.3 MJ/kg), unloaded car.

load factor (before doubling the train frequency) and half that original load factor. We can generalize this relation by writing

$$f_{L1} = \frac{kf_{L0}}{f} \quad (6)$$

where

f_{L0} = original load factor,
f_{L1} = new load factor,
f = factor by which the frequency of trains is increased, and
k = factor by which total ridership increases.

The factor k probably lies roughly between 1 and 2, depending on the increased attractiveness of the new system. We are essentially stopped at this point by a lack of knowledge about how k varies with f. Availability of such a relation would allow us to select a train frequency that maximizes f_{L1} and hence minimizes energy per passenger-mile (kilometer). This may or may not, of course, be perceived as a desirable decision criterion. Eventually the conflicting goals of energy efficiency and comfort and convenience must be studied in more detail.

ENERGY COSTS OF BART CONSTRUCTION

Input-Output Analyses

The amount of energy consumed as a result of a given final demand placed on the economy must be determined. Let X be an n-dimension vector of total outputs of the economy, each element of which represents the value of output of a given sector. In particular, each element x_i is the output of sector i and consists of the sales to all other sectors in which the output of i is used as an intermediate good plus the sale of the output of i, which is used in final consumption. Symbolically,

$$x_i = \sum_{j=1}^{n} a_{ij}x_j + y_i \quad (7)$$

where

x_j = output of sector j,
a_{ij} = technical coefficient representing the amount of the i th output needed for production of one unit of j th output, and
y_i = amount of x_i used as final consumption.

If there are n sectors in the economy, then i can take any value from 1 to n and make a total of n equations in the form of equation 7. This set of equations may be represented in matrix form as follows

$$X = AX + Y \quad (8)$$

where X is an n-dimension column vector of gross outputs; A is an n × n matrix of input-output coefficients, the ij th element of which tells how much output of sector i is needed to produce one unit of output j; and Y is an n-dimensional column of final demands. A more interesting form of equation 8 to solve for gross output X as a function of final demand Y is

$$X = (I - A)^{-1} Y \tag{9}$$

where I is an n × n identity matrix. This form of equation 9 is interesting because it tells us what gross output throughout the economy is required to sustain a final demand of Y. Using equation 9, we can determine what gross production ΔX is necessary to sustain a final demand ΔY, which is the construction of, for example, the BART system.

The task of determining the energy content of the output has been undertaken by the Center for Advanced Computation (3) whose analysis follows. Take row i from A and denote it by a_i. If i is an energy sector, for example, coal, then the typical element of $(a_i = a_{i1}, a_{i2}, \ldots, a_{in})$, which is a_{ij}, represents the value of coal needed to support \$1 of production of the j th output. If p_i is the price of the i th output (coal), the $(1/p_i)\, a_i = \gamma_i$ gives the physical quantity of coal needed in production. Therefore, let

$$\gamma_i = \left(\frac{a_{i1}}{p_i}, \frac{a_{i2}}{p_i}, \ldots, \frac{a_{in}}{p_i}\right) = \left(\gamma_{i1}, \gamma_{i2}, \ldots, \gamma_{in}\right) \tag{10}$$

Each γ_{ij} gives the physical quantity of coal needed to sustain the output of \$1 worth of the j th sector. Since the typical element of $(I - A)^{-1}$, which we denote as A_{ij}, gives the value of production in sector i necessary to sustain final demand of \$1 of output in sector j, we can proceed to interpret $\gamma_i(I - A)^{-1} = t_i$. Each element of the row t_i, $t_{ij} = \sum_{j=1}^{n} \gamma_{ij} A_{ji}$, is the total physical amount of coal (output of energy sector i) needed by all sectors to sustain \$1 of final demand in sector j.

Given that there are m energy sectors, there will also be m vectors of the type γ_i or

$$R = \begin{bmatrix} r_1 \\ r_2 \\ \cdot \\ \cdot \\ \cdot \\ r_m \end{bmatrix} \tag{11}$$

where R is an m × n dimension matrix. Thus,

$$R(I - A)^{-1} \begin{bmatrix} t_1 \\ t_2 \\ \cdot \\ \cdot \\ \cdot \\ t_m \end{bmatrix} = T \tag{12}$$

where T is an m × n matrix whose typical element t_{ij} gives the physical quantity of energy sector i (coal, gas, oil) needed to sustain \$1 of final demand in sector j.

To compute the amount of primary energy sources necessary to sustain Y, write

$$E = TY \quad (13)$$

where E is an m × 1 dimensional vector of total quantities of energy sources required by the final demand Y. If Y_1 represents the final demand placed on the economy by a transit system, then $E_1 = TY_1$ is the total quantity of energy sources required throughout the economy to sustain its production. It is easy to convert the quantities of coal and oil to any desired conventional energy unit such as Btu (J), and this is what the elements of E tell us.

There are some caveats in using the input-output approach in estimating energy use. The lag with which input-output matrices are published is very long. For example, the 1963 input-output matrix of the U.S. economy was published by the Bureau of Economic Analysis, U.S. Department of Commerce, in 1969. With this kind of lag time, the structure of the economy, in the sense of how much of what is needed to produce any given item, will have changed during the interim. If the 1963 matrix had been applied to energy problems when it first was published in 1969, there certainly would have been errors in the analysis. This is the problem that cannot be overcome.

As with any empirical work, the input-output matrix is sensitive to the conventions used in data collection. A change in conventions in gathering the data or in assigning or categorizing the output of a given subsector will change the input-output matrix and not cause a corresponding change in real structure of the economy.

The input-output matrix is built in value terms (prices times quantities). This means that some price level is used in its construction. Use of a different price level in calculating the value of final demand at a time other than the time the matrix was constructed will result in an error being introduced into the results. A correction for changing price levels must be included to eliminate this source of error; this is something the user of input-output techniques can do.

Approximate Estimate of Energy Requirements of BART

An approximate estimate of the energy required by the vector of final demands given in Table 5 can be derived as follows. Take the total amount of energy consumed in the United States for a given year and divide that amount by the total final demand, or gross national product, of that year to get the average energy per dollar of final demand. In 1965 this figure was 78,800 Btu (83 million J) per dollar output (4). Then, simply multiply the total dollar final demand generated by BART by this figure (5). (Because 1963 is close to 1965, the energy structure of the economy will not be too dissimilar at these dates.) From Table 5, the total classified by input-output sector as of the fall of 1972 is approximately $808 million. The total BART cost is more like $1.4 billion, but the balance has yet to be classified by input-output sector. For the purposes of this comparison, the smaller figure is used. By multiplying, we find that 63,649,360.4 MBtu (67×10^{15} J) are required if each dollar used the energy that the average final demand dollar required.

Input-Output Estimate of the Energy Requirements of BART

If we take the T-matrix of equation 12, convert it to energy units instead of quantity of energy sources [i.e., tons (kilograms) of coal, gallons (liters) of oil], and finally sum T over its rows element by element, we get a row T** (3). Each element t_j^{**} gives the total amount of energy (both direct and indirect) in energy units [Btu (J)] needed to sustain $1 in final demand in sector j. Taking the product of the row T** with the column Y (Table 5), we get

$$T^{**}Y = 62{,}684{,}232.625 \text{ MBtu } (66 \times 10^{15} \text{ J}) \quad (14)$$

This estimate is within 1 million MBtu (1055×10^{12} J) or 1.5 percent of the preliminary estimate using only the average energy intensity for 1965.

If we extrapolate these results to the total anticipated capital cost of about $1.4 billion for BART, we obtain a total capital energy cost of about 109 million MBtu (115×10^{15} J). The credibility of such an extrapolation is discussed later.

Next, we compare the energy required to build the system with the energy required to operate it. As stated earlier, BART currently anticipates annual energy demand by a 450-car system to approximate the following: (a) 198 million kW-h/year (712 million MJ/year) for traction, and (b) 85 million kW-h/year (306 million MJ/year) for station and maintenance.

This is electric energy at the point of use. To estimate the thermal energy [in Btu (J)] into the power plant to provide this electric energy, we multiply by 10,000 Btu/kW-h (2.93 J/J). This accounts for thermal power plant inefficiencies and transmission/distribution losses. Furthermore, to compare initial capital energy costs with operating energy, we assume that the system operates for 50 years and multiply by this factor also. The total energy demand over the 50-year assumed lifespan is given in Table 6.

Thus, we see that, with the assumptions made here, traction energy is about 40 percent of the total energy used by BART. In comparison Hirst (5) has found that 50 percent of the energy used in building and operating automobiles each year is propulsion energy from gasoline.

Evaluation of Input-Output Results

We now evaluate the extraordinary agreement between the construction energy costs obtained by the approximate method and those obtained by the input-output approach. In view of the assumptions made in both methods, the level of agreement is surprising. The obvious question is whether this is mere chance or whether the approximate method is actually highly accurate for this type of system. If the latter is true, then the analysis is simplified considerably. Unfortunately, the scope of this study does not permit the necessary in-depth evaluation required to answer this question.

A related question is whether it is accurate to extrapolate from the $808 million data to an energy figure for $1.4 billion as we did in the previous section. The answer is yes if the $808 million worth of work is representative of the energy intensiveness of the entire project. We do not have the data to answer this question; therefore, the results in the previous section may be slightly erroneous.

BART IMPACT ENERGY

BART impact energy is used in building and operating systems related to BART or that exist because BART exists. This includes new office buildings constructed along BART corridors because of the convenience of BART. It also includes, on the negative side, the decrease in energy because of a shift from existing automobiles and buses to BART, and, on the positive side, the generation of new trips by new business and industry generated by BART. It is sometimes thought that BART will lead to less cars on the bridges or result in a net savings of energy. Probably neither of these assumptions is correct. BART's impact on the community in stimulating growth may well add more automobile trips than it replaces and lead to a net increase in energy use. This should not be construed as inferring that BART is thus a failure. On the contrary, it might be interpreted as evidence that BART has succeeded in stimulating the economy of the region, including some urban areas that might otherwise have deteriorated significantly.

Unfortunately, a detailed analysis of impact energy would be quite complex and well beyond the scope of this study. It may be that the Metropolitan Transportation Commission's BART impact study will provide sufficient data to carry out a partial energy impact study sometime in the future. Such a study would make use of trip replacement and generation studies and new building costs, within the approach used in the previous section.

COMPARING BART WITH OTHER SYSTEMS

In this section, the energy demands of BART are compared with other systems, specifically buses and automobiles. A decision must be made at the outset about what components of energy cost will be compared. To compare only propulsion (or traction) costs is somewhat limited and perhaps misleading. However, the inclusion of factors such as operation, maintenance, and construction costs makes the analysis more complex and speculative. For example, although construction energy for BART can be estimated, how does one estimate energy used to build the freeways, roads, parking lots, garages, and driveways required by buses and automobiles? Two comparisons are made, and a series of assumptions is made in each case. First, propulsion energies only are compared. Then total energies are compared.

For BART traction energy, we use the probable upper and lower bounds introduced earlier in the paper. We assume a load factor of 25 percent or 18 passengers per vehicle and an energy conversion heat rate of 10,000 Btu/kW-h (2.93 J/J) (corresponding to a power plant/distribution system efficiency of 34 percent). For buses we assume 5 miles/gal (2 km/liter), a gasoline conversion rate of 136,000 Btu/gal (3.7×10^7 J/liter), a 50-seat vehicle, and a load factor of 25 percent or 12.5 passengers/vehicle. For the automobile we assume 12 miles/gal (5 km/liter), 136,000 Btu/gal (3.7×10^7 J/liter, and 1.4 passengers per vehicle. The resulting propulsion energy intensities are given in Table 7 on a passenger-mile (kilometer) basis.

A number of facts should be kept in mind. First, the loading factors are assumed somewhat arbitrarily, although they tend to approximate national averages. Different loading factors could drastically change these comparisons. A fully loaded automobile (car pool) could be about as efficient as BART or a bus that is 25 percent loaded. However, a fully loaded bus or BART with standees could be as much as 10 to 15 times more energy efficient than the average automobile. The great sensitivity of energy comparisons to loading should be kept in mind at all times in transportation energy studies.

A second important fact is that, even though we have referred propulsion energy to power plant input energy, it is not obvious that the resulting comparison is completely fair. The energy source for the power plant could, in general, be coal, oil, natural gas, uranium, or hydroelectric power, each with different processing energy requirements. Gasoline must also be processed in a refinery and is about 85 percent efficient. Hence, comparing fuel energies at the input to the power plant with energy into the automobile has some real limitations.

Finally, we consider the question of comparative total energy use. As stated previously, in the case of BART and automobiles, propulsion energy tends to be about 50 percent of total energy. Although these data are probably fairly accurate for automobiles, BART must reach completion and experience some months of normal operation before comparative total energy use can be tested for BART. A similar analysis has not been made for buses. If buses have about the same 50-50 energy split and if the data for BART and automobiles are reasonably accurate, then we can obtain an estimate of total energy comparison by simply doubling the propulsion energy figures given in Table 7. This is fine for buses and automobiles but is ambiguous in the case of BART since we have two bounds. The traction estimates used previously assume that auxiliary energy is accounted for as traction energy and that regenerative braking is partially successful. On the basis of these assumptions, we assume a traction energy of 4.7 kW-h/car-mile (10.7 MJ/km) for purposes of calculating total BART energy.

Again, the reader must be cautioned that these results are based on some major assumptions: The extensive use of light, compact automobiles could reduce automobile energy use by more than two times; the allotment of energy costs to roads and garages is quite arbitrary; and the impact energy for BART and for other vehicles has not been considered quantitatively.

Table 5. Final demand placed on the U.S. economy (input-output sector) by energy requirements of BART.

Bureau of Economic Analysis Input-Output Sector	Final Demand (current dollars)[a]	Bureau of Economic Analysis Input-Output Sector	Final Demand (current dollars)[a]
400	2,690,000	5303	3,477,000
1102	139,259,000	5308	10,319,000
1103	46,000	5502	30,000
1104	88,983,000	5603	798,000
1105	487,923,000	5604	197,000
1202	3,357,000	5703	84,000
2008	132,000	5805	231,000
3611	2,657,000	5903	9,000
3808	8,551,000	6104	20,304,000
4004	27,475,000	6411	314,000
4102	14,000	6412	179,000
4203	50,000	6600	2,000
4601	5,723,000	6801	23,000
4704	275,000	6802	1,000
4901	76,000	6803	134,000
4903	795,000	7303	5,000
4907	2,786,000	Total	807,733,000
5201	834,000		

[a]These expenditures occurred over a 20-year period. Expenditures in the same sector that occurred at different times are lumped into the sector total and are not corrected for price increases. Thus, the sector totals are not, for example, in 1963 constant dollars.

Table 6. Total BART energy requirements.

Energy Type	Btu ($\times 10^{12}$)	Percent
Construction	110	44
Traction	100	40
Operation and maintenance	40	16
Total required	250	

Note: 1 Btu = 1055 J.

Table 7. Comparative propulsion energies.

Vehicle	Propulsion Energy (Btu/ passenger-mile)	Total Energy (Btu/ passenger-mile)
BART		
Probable lower bound	1,800	5,200
Probable upper bound	3,600	
Bus	2,200	4,400
Automobile	8,100	16,200

Note: 1 Btu/passenger-mile = 659 J/km.

Based on the assumptions made here, we conclude that there are not sufficient data to favor BART over buses or vice versa on an energy basis, but that both BART and buses are more energy efficient than the automobile.

CONCLUSIONS AND IMPLICATIONS

1. BART traction energy will range from 3.2 to 5.5 kW-h/car-mile (7.2 to 12.4 MJ/km), depending on how certain auxiliary energies are accounted for and on the degree of success of the regenerative braking system. The additional energy per car-mile (kilometer) resulting from system operation and maintenance should range from about 1.0 to 1.5 kW-h/car-mile (2.3 to 3.4 MJ/km) when the system is fully operational.
2. BART is in a transition or break-in stage at this time. Although final energy levels can be estimated, these should be checked from real data when BART is fully operational.
3. BART traction energy, as with any system, is highly sensitive to load factors. Traction energy per passenger-mile (kilometer) is almost inversely proportional to the number of passengers.
4. If the BART system is used for 50 years, the energy required for propulsion will be roughly 40 percent of total energy. The other 60 percent is for construction and operation and maintenance.
5. The approximate method used to find construction energy and the complex input-output approach yield almost exactly the same result. This is surprising, considering the assumptions that must be made in both cases. Some attempt should be made to determine if this relation is consistent.
6. Although it is believed that impact energy is significant, no attempt is made here to quantify it. The Metropolitan Transportation Commission's BART impact study may greatly facilitate this analysis.
7. A comparison of BART with buses and automobiles suggests that the propulsion energy and total energy demand of both buses and BART are about 2 to 3 times lower than that for automobiles (assuming an average size car and a loading factor of about 25 percent for all vehicles). Such comparisons are highly sensitive to the assumptions made.

On an energy basis, BART is more efficient than automobiles but not necessarily more efficient than buses. A number of steps could be taken in private or public transit to reduce energy use. More detailed data should be obtained on BART and other new systems as they become operational. Construction energy and impact energy are significant but have not as yet been studied in sufficient detail to provide conclusive results. Comparing energy costs of transportation systems depends on the nature of the systems and the assumptions made about their operation.

ACKNOWLEDGMENT

This paper is based on a study performed in cooperation with Business and Transportation Agency, California Department of Transportation. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the state of California. This report does not constitute a standard, specification, or regulation.

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