

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.

^aAssumes 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	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.

^aIncludes 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):

<u>Factor</u>	<u>Energy Range</u> (kW-h/car-mile)	<u>Effect</u>
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

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

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

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

$$W = 57,000 + 10,000 f_L \quad (3)$$

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)

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

The energy per passenger-mile (kilometer) is

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

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.

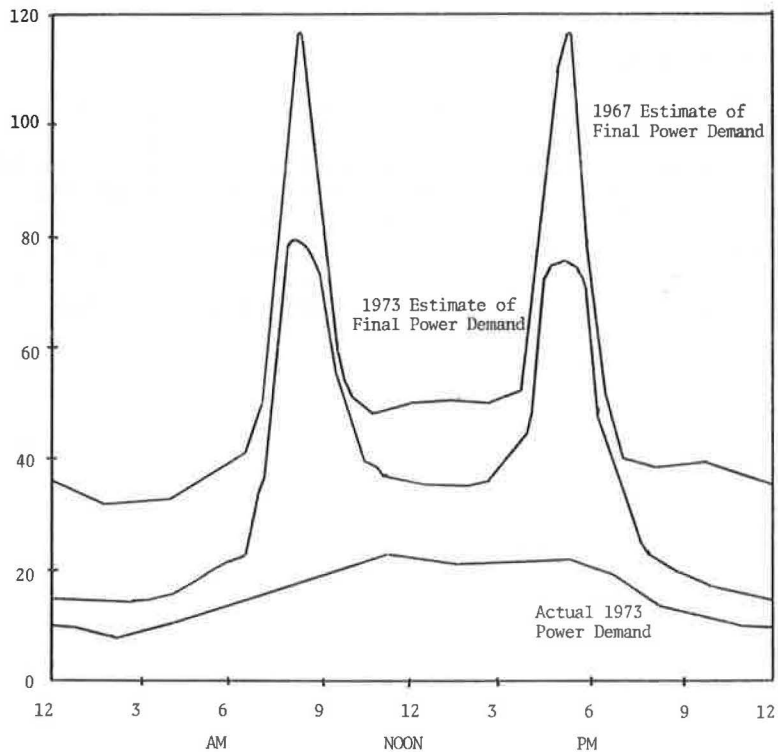
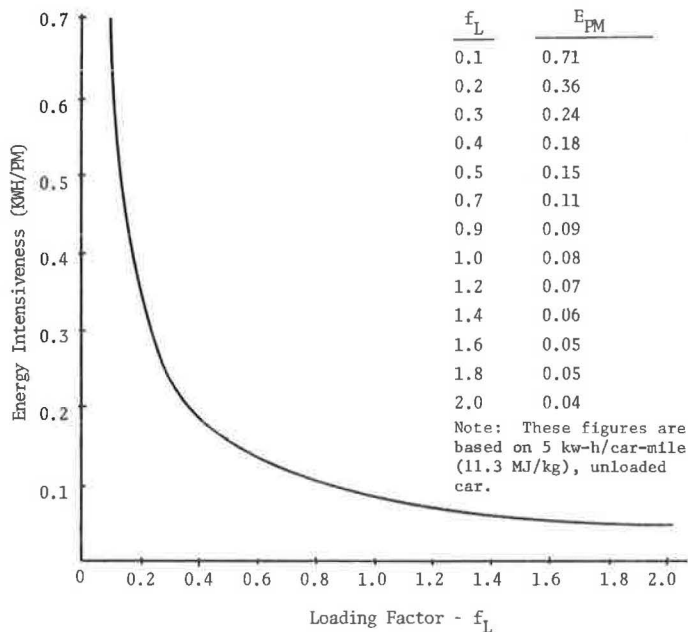


Figure 2. Dependence of energy intensiveness on loading factor.



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 $n \times n$ 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

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

where I is an $n \times n$ 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 $(a_i = a_{i1}, a_{i2}, \dots, a_{in})$, 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

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

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 ,

$t_{ij} = \sum_{j=1}^n \gamma_{ij} A_{jt}$, 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

$$R = \begin{bmatrix} r_1 \\ r_2 \\ \cdot \\ \cdot \\ r_m \end{bmatrix} \quad (11)$$

where R is an $m \times n$ dimension matrix. Thus,

$$R(I - A)^{-1} = T \quad (12)$$

where T is an $m \times n$ 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

$$E = TY$$

(13)

where E is an $m \times 1$ 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

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

(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 ($3.7 \times 10^7 \text{ J/liter}$), 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 ($3.7 \times 10^7 \text{ J/liter}$), 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)*	Bureau of Economic Analysis Input-Output Sector	Final Demand (current dollars)*
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		
5201	834,000	Total	807,733,000

*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.

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