mated in this study for mode shifts to transit at the least added cost to the transit agency but will also cause additional energy conservation attributable to increased car and van pooling, shortened trip lengths, and trip elimination.

Increased coverage and frequency of transit service are particularly effective in inducing mode shifts; this, however, is the one otherwise useful strategy that, when applied alone under the wrong circumstances, can increase net energy consumption. To conserve energy, increased coverage and frequency are best provided in connection with fare reductions, decreased running time, or automobile disincentives.

Of course, improvements to transit systems offer benefits in addition to the relatively small energy savings obtained. The potential for reducing vehicle kilometers of automobile travel in today's urban areas is twice as great as the total energy-saving potential; it ranges from 1 or 2 percent up to a maximum of 6 or possibly 8 percent for the highest impact group of mode-shift strategies examined.

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Rail Rapid Transit and Energy: The Adverse Effects

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Because it is generally believed that transportation energy can be saved by diverting people from automobiles to rail transit, the United States is now building or planning a number of multi-billion-dollar rail systems. These new-generation rail systems were examined and found to be a net user of energy. The two main points prompting this conclusion are that (a) the energy invested in building a rail system is enormous and thus difficult to repay and (b) the possible savings in operating energy are small, or even negative, because most rail passengers are diverted from buses and buses are more energy efficient than modern rail systems. The analysis was done for San Francisco's Bay Area Rapid Transit (BART) system, but evidence is cited to show that the results are typical for other modern rail systems as well. To the extent that BART is atypical, it appears to be atypically efficient. The analysis takes into account the reduced demand for automobiles and buses because their passengers are diverted to rail and then calculates the energy saved because these conventional vehicles are not built or driven and the roads on which they would travel are not constructed. It is concluded that even radical improvements in automobile diversion, rail patronage, and load factors would not significantly alter the results.

This paper examines the overall energy impact of modern rail transit systems and concludes that they are energy users. Although the analysis is done for a single example, the San Francisco Bay Area Rapid Transit (BART) system, it is shown that the conclusions are probably general. These conclusions are the result of two main points: (a) that the energy required to build a rail system is enormous and thus hard to repay and (b) that the possible savings in operating energy are small, or even negative, because most rail passengers are diverted from buses rather than from automobiles and buses are much more energy efficient than modern rail systems.

First, calculating the energy required to build BART and the amount of energy saved by building fewer kilometers of freeway as a result of the diversion of automobile and bus users to rail transit yields the net energy investment. This net figure would be essentially the same even if a doubling of the diversion figures were assumed. Next, energy figures are developed for automobile, bus, and rail operation that take into account the energy required to build the vehicle as well as to operate it. Finally, the length of time it would take to repay the net energy invested in constructing the system is calculated by using various assumptions about BART patronage. Under most of these assumptions the BART system can never repay the energy investment.

Had this analysis been done several years ago, it would have assessed the BART system in terms of the dollars of social cost rather than the units of energy expended. However, since the oil crisis focused attention on energy, many people have begun to discount financial analyses of alternative transportation systems by claiming that dollars do not matter—only energy matters.

Many economists may find the analysis that follows strange because it uses energy as the measure of all things. But, because a dispute over ways of measuring social cost would only compound the transportation issues, the joule—an energy measure—is used as a basis for assessing the effectiveness of BART.

The literature on energy use in transportation has

Table 1. Former travel mode of current rail passengers for three systems.

System	Formerly Used Bus (%)	Formerly Used Automobile (%)	Formerly Used Other Modes (%)	Formerly Did Not Make Trip (%)	Calculated Fraction of Former Automobile Users (%)	Calculated Fraction of Former Automobile Drivers (%)
BART	44.6	38.7	1.6	15.2	46.5	33.7
Lindenwold Line (Philadelphia)	49	38	0	13	43.7	28
South Shore MBTA extension (Boston)	52	29	3	16	35.8	N.A.

been preoccupied with the question of operating energy. In the case of modern rail transit systems, however, careful attention must be given to the energy investment required to build the system in the first place. This energy requirement is so large compared with the number of people the system transports that it is one of the most important factors in determining the overall energy efficiency of rail transit.

The construction of a rail transit system has both negative and positive effects on energy use in transportation. The negative effect is the enormous amount of energy needed to build the system. The positive effect is that, as the system diverts people from automobiles and buses, there is less need for highways.

ENERGY USED TO BUILD A RAIL TRANSIT SYSTEM

In constant 1974 dollars, BART cost \$2.28 billion (3, p. 163), of which \$161 million was for transit vehicles. Healy and Dick (6, p. 25) analyzed the energy expenditure on BART when it was about half completed (classifying expenditures by input-output table categories and then using the known energy weights for each category) and concluded that the average conversion ratio was 81.9 MJ/dollar (22.7 kW•h/dollar). Hirst (7, p. 23), using a different method and other data, estimated essentially the same conversion ratio. The total energy invested in BART can be calculated as follows (1 MJ = 0.28 kW•h):

$$(\$2.28\text{ billion} - \$0.161\text{ billion}) \times 81.9\text{ MJ/dollar} = 174\text{ PJ} \tag{1}$$

The cost of BART, in constant 1974 dollars, amounts to \$20.0 million/km (\$32.1 million/mile) of system. The average projected cost, in constant 1974 dollars, of three other systems now under construction—Boston's Massachusetts Bay Transportation Authority (MBTA), Atlanta's Metropolitan Atlanta Rapid Transit Authority (MARTA), and Metro in Washington, D.C.—is \$21.4 million/km (\$34.4 million/mile) of system (3, p. 163). Because the BART figure represents an actual measurement and the other figure is based on projections (and such projections have been underestimated in the past), it can safely be concluded that BART is not an unusually capital-intensive system and thus that the amount of energy invested in building it is not atypical of modern rail transit systems.

ENERGY SAVED BY OPERATING A RAIL TRANSIT SYSTEM

Because a rail transit system attracts passengers from automobiles and buses that now use highways, the need for highway lane kilometers is reduced and the energy saved by not building these lane kilometers should be credited to the rail system. Table 1 gives the former modes of travel used by BART passengers and passengers of two other modern rail transit systems (3, pp. 108, 110, 136, 137; 8, p. 17). The large fraction of commuters now using the system who had made no trip before creates a problem for the analysis. Some of these people represent a trip-generation effect of the rail system: Because long-distance commuting is now easier and more luxurious, people are encouraged to move farther from the city to find better housing. These additional kilometers of travel should be treated as net energy loss; they are the waste encouraged by the rail system. (The average observed BART trip length is 40 percent longer than was forecast, and there is evidence that this trip-generation, energy-wasting effect is substantial.) However, some of the people who had not formerly made the trip simply represent the normal effects of changing jobs and housing in this mobile society. Because it is not known how people who formerly made no trip should be divided between the normal-mobility and the trip-generation hypotheses, the assumption most favorable to rail transit is made: These people are treated as representing normal mobility and are simply divided proportionately between bus and automobile. The small number of people who formerly used other modes are apportioned in the same way.

The calculated fraction of current rail passengers who formerly used the automobile ranges from a high of 46.5 percent for BART to a low of 35.8 percent for MBTA. (Because BART has been unusually successful in this dimension, the results of the calculations are biased in favor of the energy effectiveness of rail systems.) Not all of the people who formerly commuted by automobile were drivers, however; some were passengers. That is, the rail system is diverting some of its passengers from car pools, which represents a net energy loss. As passengers, these people used no extra energy and created no extra demand for automobiles or highways, and now, on the rail system at rush hour, they create a demand for more transit cars and more operating energy. The calculated fraction of former automobile drivers adjusts the calculated fraction of former automobile users to reflect this; for example, only 33.7 percent of the people who currently ride BART were formerly automobile drivers.

BART ridership in 1975 was 127 000/d, and it was not growing (3, p. 71). If this is rounded off to 130 000 trips/d, it can then be calculated that BART removed 43 800 automobile trips or 21 900 automobiles/d (or 33.7 percent of 130 000) from the highways. Not all of these 43 800 trips represent reduced demand for highways, however. It is only at rush hour that highways operate at capacity; at any other time, the presence or absence of an additional automobile does not affect congestion. Because highways are constructed to meet peak-hour loads, they have excess capacity in off-peak periods and it is only the reduction in peak-hour traffic that reduces the need to invest energy in highways. Fifty-nine percent of BART daily traffic occurs each day during the four peak hours (3, p. 86). If the average BART trip is 20.9 km (12.9 miles) and highway capacity is 2000 automobiles/lane•h (4, p. 304), putting these figures together results in the following (1 km = 0.62 mile):

$$\begin{aligned}&(0.59 \times 43\,800\text{ peak·h automobile trips/d} \times 20.9\text{ km/trip})\\ &\div (4\text{ h/peak} \times 2000\text{ automobiles/lane·h}) = 67.5\text{ lane·km of highway}\end{aligned} \tag{2}$$

where 0.59 is the peak factor. That is, BART diverts enough people from automobiles to reduce highway capacity needs by 67.5 lane•km (42 lane miles).

BART also attracts passengers from buses, and buses too are highway users. The bus capacity of a highway is 1200 buses/lane•h (4, p. 304). The average number of passengers per bus on the San Bernardino express bus service is 44 (10, p. A-26), but, because San Francisco service may not be this efficient, the estimate used here is 25. Thus,

$$(0.59 \times 0.535 \times 130\,000 \text{ trips/d} \times 20.9 \text{ km/trip}) \div (25 \text{ people/bus} \times 1200 \text{ buses/lane·h} \times 4 \text{ h/peak}) = 7.15 \text{ lane·km} \tag{3}$$

where 0.535 is the BART bus fraction. Thus, by reducing the number of automobiles and buses on the highway during peak hours, BART saves a total of 74.7 lane•km (46.5 lane miles) of highway.

Keeler (9, p. 28) estimates the average cost of building a lane kilometer of freeway in California as \$0.789 million for an urban central-city site and \$0.258 million for an urban-suburban site. BART is about evenly divided between these two kinds of sites. Calculating an average of these two figures, converted into constant 1974 dollars, results in \$0.579 million/lane•km (\$0.932 million/lane mile) for construction costs. Using an energy conversion ratio of 118 MJ/dollar (32.8 kW•h/dollar) (1, p. 670) gives

$$74.7 \text{ lane·km} \times \$0.579 \text{ million} \times 118 \text{ MJ/dollar} = 5.1 \text{ PJ} \tag{4}$$

That is, BART diverts enough buses and automobiles from the highways to reduce the necessary highway energy investment by 5.1 PJ (1.4 billion kW•h). Subtracting this from the total construction energy of 174 PJ (48.1 billion kW•h) gives a net energy investment in BART of 169 PJ (46.7 billion kW•h).

This figure for net energy investment is quite robust with respect to changes in the underlying assumptions. If BART daily patronage were to double and thus divert more automobiles and buses from the highways and reduce the number of lane kilometers of highway needed, the net energy investment would decrease by only 3.5 percent. Similarly, if BART were somehow to become so attractive that 100 percent of its passengers came from automobiles, the decrease in lane kilometers of highway needed would only be enough to reduce the net energy investment by 5.9 percent. That is, the net energy investment in building the system is so large that no conceivable change in patronage is going to affect it significantly.

VEHICLE OPERATING ENERGY

To simplify some of the calculations, a nonstandard definition of operating energy is used: The energy required to build the vehicle is added to the energy required to operate it, and thus the invested energy is treated as a variable cost. This is justified by the fact that the decision to purchase or replace a vehicle is a relatively flexible one and the decision to use a vehicle once it is purchased is even more flexible. The vehicle is treated here as though it had a given, innate number of kilometers of service, and the vehicle user is treated as making a decision about the time rate of use of these kilometers of service. Thus, a stock of invested construction energy becomes a flow of vehicle services, and

$$\text{Vehicle operating energy per kilometer} = \text{vehicle consumption energy per kilometer} + (\text{vehicle construction energy} \div \text{vehicle lifetime kilometers}) \tag{5}$$

Because energy consumption estimates in the literature vary widely and generally give little information as to their derivation, the assumptions, the figures, and the derivation used here are made as explicit as possible in Table 2. The main focus of the table is operating power per passenger kilometer, and it is worth commenting on the sensitivity of these figures to the intermediate assumptions. Automobile kilometers per liter and service lifetime are both taken, as national averages, from census data and are presumably reliable (they are certainly of plausible size); average occupancy is also taken from census data and is supported by recent observation of automobile occupancy on the San Francisco-Oakland Bay Bridge (12) and in the Caldecott Tunnel (13). Power consumption and average occupancy data for BART are actual measurements. They are similar to data for the Lindenwold Line, for which marginal power consumption is 66 MJ (18.3 kW•h) and average occupancy is 22 passengers/vehicle (2, p. 1). Service lifetime for BART is a guess, from a single source, but either doubling or halving it would change the final figures by only 1 percent. Bus fuel efficiency and occupancy are national averages; the lifetime figures are taken from a single source, but doubling or halving them would change the final figures by only 3 percent. Some idea of the sensitivity of automobile energy to vehicle size can be gained by comparing the two different automobile categories in Table 2. Because automobile manufacturers are under congressional mandate to produce automobiles that average 11.7 km/L (27.5 miles/gal) (sales-weighted average) by 1985 (8, p. 15), data for the 907-kg (2000-lb) automobile will probably be more accurate than data for the av-

Table 2. Vehicle operating energy.

Vehicle	Energy Used to Construct Passenger-Carrying Vehicle[a] (MJ)	Service Life of Vehicle[b] (km)	Marginal Operating Power per Vehicle Kilometer[c] (MJ)	Total Operating Power per Vehicle Kilometer (MJ)	Average Number of Passengers per Vehicle[d]	Operating Power per Passenger Kilometer[e] (MJ)
Average automobile[f]	139 000	180 000	6.26	7.09	1.3	5.44
Future automobile[g]	75 600	180 000	3.19	3.64	1.3	2.79
BART	4 430 000	4 800 000	65.5	66.6	21.4	3.11
Bus (diesel)[h]	1 080 000	1 600 000	21.2	21.8	11.5	1.90

Notes: 1 MJ = 0.28 kW·h; 1 km = 0.62 mile; 1 kg = 2.2 lb; 1 L = 0.26 gal; 1 km/L = 2.35 miles/gal.
For energy data, 37.3 MJ/L (10.36 kW·h/L) of gas and 41.2 MJ/L (11.44 kW·h/L) of diesel are used, which includes energy lost in the refining process (5, p. 14). Electrical energy is computed as power-plant-source energy.

[a] (4, p. 300; 5, p. 14).
[b] (4, pp. 303-304; 10, p. 8).
[c] (4, p. 302; 11).
[d] (10, 12, 13).
[e] Vehicle-construction energy plus marginal energy.
[f] 1633 kg (3600 lb) and 5.95 km/L (14 miles/gal).
[g] 907 kg (2000 lb) and 11.7 km/L (27.5 miles/gal).
[h] 1.94 km/L (4.5 miles/gal).

Table 3. Sensitivity analysis of results: time required to repay BART energy investment.

	Years to Repay	
Situation	5.95-km/L Automobile Efficiency	11.7-km/L Automobile Efficiency
Current BART (130 000 trips/d, 30 percent load factor, 46.5 percent of passengers from automobiles)	535	Never; more energy wasted each year
Current but with 75 percent of passengers from automobiles	163	Never; more energy wasted each year
Current but with 50 percent load factor	139	502
Current but with 260 000 trips/d	266	Never; more energy wasted each year
Ideal (260 000 trips/d, 50 percent load factor, 75 percent of passengers from automobiles)	44	168

Note: 1 km/L = 2.35 miles/gal.

erage automobile in projecting the lifetime energy characteristics of a system like BART.

IMPACT OF OVERALL SYSTEM

By using the estimates for net energy invested in BART and the energy required to operate the system, an overall evaluation of the system's energy characteristics can be formulated. First, current energy use per year is calculated as follows:

$$130\ 000\ \text{trips/d} \times 20.9\ \text{km/trip} \times 260\ \text{d/year} = 706\ \text{million passenger·km/year} \quad (6)$$

$$706\ \text{million passenger·km/year} \times 3.1\ \text{MJ} = 2.2\ \text{PJ/year} \quad (7)$$

for operation with the BART system. What it would have cost to produce the same number of yearly passenger kilometers if 46.5 percent of these people had used automobiles and 53.5 percent had used the bus (the pro-BART figures given in Table 1) can also be calculated, as follows:

$$0.465\ (706\ \text{million}) \times 5.4\ \text{MJ} + 0.535\ (706\ \text{million}) \times 1.9\ \text{MJ} = 2.5\ \text{PJ/year} \quad (8)$$

to operate without the BART system. That is, because of BART, 0.32 PJ/year (87 million kW·h/year) of operating energy are saved. If the energy investment in building the system, 169 PJ (46.7 billion kW·h), is divided by the energy saving per year, it will take 535 years of operation before the initial energy investment is repaid.

Thus, an overall evaluation of the effects of BART that takes into account the energy saved by building fewer lane kilometers of highway and the energy saved by building fewer automobiles and buses indicates that the energy invested in BART is so enormous and the yearly operating energy savings are so small that it will take 535 years even to repay the initial investment, much less to save any energy. Even this figure is based on the assumption that the efficiency of automobiles will continue at 5.95 km/L (14 miles/gal) for the next 535 years.

If it is assumed that the congressionally mandated 11.7-km/L (27.5-miles/gal) average is fulfilled (which is reasonable because such vehicles do exist), then BART actually wastes operating energy. A simple, weighted average of the energy efficiencies for automobile and bus shows that

$$46.5\ \text{percent}\ (2.8\ \text{MJ}) + 53.5\ \text{percent}\ (1.9\ \text{MJ}) = 2.3\ \text{MJ/passenger·km} \quad (9)$$

That is, the automobile-bus combination of modes requires 2.3 MJ/passenger·km (1 kW·h/passenger-mile), but BART requires 3.1 MJ/passenger·km (1.4 kW·h/passenger-mile). This means that shutting BART down altogether would save 0.6 PJ (160 million kW·h) of operating energy per year.

SENSITIVITY ANALYSIS

The results calculated above are clearly surprising in view of the conventional wisdom about rail transit. Are they believable? Perhaps the best way to examine their credibility is to compute their dependence on the assumptions made in the analysis. Table 3 gives the results of such a sensitivity test, which radically changes each of the five key assumptions and then recomputes the number of years it would take to repay the invested energy.

If the automobile-diversion percentage could somehow be increased to 75 percent, the payback period would still be 163 years given the current (unlikely) automobile efficiency and would become infinite given the probable future automobile efficiency. But BART already has the highest automobile-diversion percentage among the modern transit systems, and an increase to 75 percent seems essentially impossible.

The current load factor for BART is about average for the United States. No system has ever achieved a 50 percent load factor or is likely to do so, given the need to run trains both with and against traffic and during both peak and off-peak hours. But even were this possible, the payback periods would still be 139 and 502 years.

A doubling of current patronage is not likely to occur, given that patronage has been essentially constant since the opening of the trans-Bay tubes. In any case, this hypothetical change only lowers the payback period to 266 years.

Finally, in a situation referred to as the transit ideal, all of these essentially impossible changes have come to pass. Even so, and even with the 5.95-km/L (14-miles/gal) automobile, the payback period would still be 44 years. As an internal rate of return this would be equivalent to an investment that paid 1.5 percent per annum. But even this figure is far too optimistic, for any combination of circumstances that could double patronage, divert 75 percent of automobile trips, and persuade passengers to put up with the peak-load crowding implied by a 50 percent average load factor would have to produce a universal demand for an efficient, 11.7-km/L (27.5-miles/gal) automobile. Thus, even in the ideal situation, there would be a 168-year payback period.

SUMMARY AND CONCLUSIONS

Rail transit, examined from the perspective of energy use, was clearly found to be an inefficient mode of transportation. Although the analysis was done in terms of a single example—BART—cited evidence shows that the results are typical of modern rail transit systems; in fact, to the extent that BART is atypical of rail transit, it is probably atypically efficient.

These conclusions are the result of a relatively broad analysis of the BART system that takes into account the reduction in the number of automobiles and buses caused by passenger diversion to BART and the effects of energy saved by not building or driving those conventional vehicles and not constructing the roads on which they travel. Furthermore, the conclusions are robust in that even radical improvements in rail patronage, load factors, and automobile diversion do not significantly alter the results.

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Discussion

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Lave has assembled his data from a collection of references to which he applied ratios of energy consumption to dollar values of construction and kilometer rates for operation. He then calculated alternatives in the same way, using the ratio of automobiles and buses that made up the former modes of Bay Area Rapid Transit (BART) passengers. He then tested the results against variations in use to show that the conclusions were not sensitive to wide fluctuations and found that, based on the assumed data, (a) BART would save so little energy that it would take 535 years to recover the energy invested in it and (b) even if automobile efficiency could be increased as mandated by Congress, BART would be a waste of energy.

This is not a valid conclusion. Unlikely values were assigned for highway construction costs, transit load factors, and other elements of the study. More realistic values will produce far different and much more likely conclusions.

ENERGY INVESTMENT IN TRANSIT CONSTRUCTION

Two aspects of energy investment in transit construction must be considered. One is the cost of energy to construct BART, and the other is the cost of constructing alternative transportation capacity. Lave uses an estimated BART construction-energy cost of 81.9 MJ/dollar (77 600 Btu/dollar). This figure appears high. In 1974, the year calculated, the cost of 81.9 MJ of energy was \$0.215 on the dollar of total cost (1 MJ = 948 Btu):

$$81.9\ \text{MJ/dollar} \div 41\ \text{MJ/L} = 2\ \text{L/dollar of cost} \times \$0.107/\text{L} = \$0.215/\text{dollar} \qquad (10)$$

Labor input can be approximated at 70 percent of construction cost. Material and land, excluding energy, make up approximately 20 percent of construction cost (14):

$$2000\ \text{employees} \times 5\ \text{years} \times \$10.70/\text{h} \div \$307\,000\,000 = 70\ \text{percent} + 20\ \text{percent for material} + 10\ \text{percent for energy} \qquad (11)$$

$$10\ \text{percent} \div 21.5\ \text{percent} \times 81.9\ \text{MJ} = 38\ \text{MJ} \qquad (12)$$

Allowing for some variation in the estimate, it appears obvious that the energy used to construct rail rapid transit could not be much more than 36 to 40 MJ/dollar (34 120 to 37 912 Btu/dollar) of construction cost. BART construction-energy cost is more likely to be 84 PJ than the 174 PJ used by Lave:

$$(\$2.28 \times 10^9 - \$0.161 \times 10^9) \times 40\ \text{MJ/dollar} = 84\ \text{PJ} \qquad (13)$$

CONSTRUCTION ENERGY SAVED BY RAIL TRANSIT

To calculate the energy saved by rail transit, the energy cost of alternative highway capacity for the likely split between automobiles and buses must be calculated. Lave calculated this split in Table 1 based on data for BART, the Lindenwold Line, and the Massachusetts Bay Transportation Authority. Table 1 is in error. Table 4 duplicates the format of Table 1 but corrects Lave's figures. For example, Table 1 reports zero percentage of passengers on the Lindenwold Line who formerly used other modes. This is not the actual or reported fact. Only 36 percent of Lindenwold passengers formerly used the bus. Eleven percent used commuter trains stopping at Haddonfield or the shuttle subway to Camden and a feeder bus beyond. This changes the automobile-bus split to 52 to 48 percent and exceeds the rate of trip at-

Table 4. Former travel mode of current rail passengers.

System	Formerly Used Bus (%)	Formerly Used Automobile (%)	Formerly Used Other Modes (%)	Formerly Did Not Make Trip (%)	Calculated Fraction of Former Automobile Users (%)	Calculated Fraction of Former Automobile Drivers (%)
BART	43	39	3	15	48	36.5
Lindenwold Line (Philadelphia)	36	40	11	13	52	35
South Shore MBTA extension (Boston)	52	29	3	16	36	24
Riverside Line (Boston)	4	46	35	15	68	49

traction found in preliminary BART experience. Lave assumes BART has the highest trip attraction, but this too is in error. Lave uses only the trans-Bay automobile-diversion data (46.5 percent), whereas most BART riders are local to either side of the Bay (58.5 percent) where much higher diversion from automobiles occurs (42.6 percent versus 35 percent) (15, p. 13; 16, p. 195). Overall BART automobile diversions should be used.

A July 1967 route map of the Massachusetts Bay Transportation Authority (MBTA) shows that the 52 percent of passengers on the South Shore extension who formerly used buses were basically feeder-bus riders to Ashmont or Fields Corner rapid transit stations; thus, they were for the most part already rail riders. A few buses ran all the way through. On the west edge of Boston, when the Riverside trolley line was inaugurated through Newton, 18 000 passengers/d were attracted. About 1200 were formerly railroad commuter riders, and 2400 were Middlesex and Boston bus riders (17, p. 124). The balance of 80 percent came from automobiles and new trips, primarily from automobiles. Conversely, when the Chicago, Aurora and Elgin Railroad, a third-rail commuter line, was abandoned, it was carrying 12 500 passengers/d. The Leyden Motor Coach Line replaced it (18, pp. II-14 and II-38). Because only 1250 passengers used the buses, the service was soon abandoned. The ability of the bus to hold rail passengers was only 10 percent. In the BART case, however, where there is a toll bridge across a significant water barrier plus a long tradition of rail commuting, the bus alternative does unusually well. San Francisco has one of the highest transit ridership rates in the nation.

The nation's commuter rail lines have declined only 25 percent since the era of the 6-d workweek, and the older rail rapid transit lines have declined 40 percent in passengers carried. In contrast, city bus lines have lost 71 percent of their riders in spite of expansion, and suburban bus lines have lost 74 percent (19, p. 30; 20, p. 30). The basic point is that, at best, buses could not be expected to carry more than 52 percent of BART riders because the trans-Bay bus service is already one of the best in the nation (21, p. 6).

The transit peak is much sharper than are the calculated average 2-h morning and evening highway peak periods. BART carries 25 000 riders in a single peak hour (22, p. 9) of whom 48 percent have been found to be diverted from automobiles. My personal observation has resulted in the following calculation: (10 trains × 2 directions × 8 cars × 140 passengers) + (5 trains × 2 directions × 4 cars × 70 passengers). If 48 percent of these are diverted from automobiles, this would require the movement of 9000 automobiles/h at an observed occupancy rate for divertible peak-hour commuters of 1.3 passengers/automobile. At 2000 vehicles/lane•h on the freeway, the movement would require $4\frac{1}{2}$ more lanes, but additional local street capacity would also be needed to deliver the added traffic to parking areas. Assuming only 15 percent of the added movement on local streets, this would require $13\frac{1}{2}$ more lanes over 3.14 km (1.95 miles) (23, p. 316), as follows (1 km = 0.62 mile):

$$667 \text{ vehicles/lane}\cdot\text{h} = 9000 \text{ vehicles/h} = 13\tfrac{1}{2} \text{ lanes} \times (0.15 \times 21 \text{ km}) \quad (14)$$

The freeways would require 17.8 km (11.05 miles) [20.93 - 3.14 = 17.8 (13 - 1.95 = 11.05)] × $4\frac{1}{2}$ lanes or 80 lane•km (61.7 lane miles) of freeway.

Freeways in heavily developed urban centers cannot be built for \$0.579 million/lane•km (\$1 million/lane mile) as Lave assumes, particularly where bridges, subways, or elevated structures are required. If rights-of-way were available, BART could have used them instead of doing its own costly construction. Using the cost per lane kilometer of urban Interstate transfer highways typical of the rail transit alternative results in a construction cost of approximately \$6.2 million/km (\$10 million/mile). Local streets could probably be widened for \$0.579 million/km so that the total dollar and energy cost would be 80 lane•km × \$6.2 million = \$496 million; $13\frac{1}{2}$ lanes × 3.14 km × \$0.579 million = \$24.6 million; and highway and street capacity worth \$520.6 million × 118 MJ/dollar (111 840 Btu/dollar) = 61.4 PJ (58.2×10^{12} Btu).

To this must be added the cost of additional downtown parking. If one uses Lave's 23 725 automobile round trips, 59 percent of which are rush-hour commuter trips and the rest of which turn over twice daily, 18 861 parking spaces would be required at a dollar cost of \$94.3 million and an energy investment of 3.8 PJ (3.6×10^{12} Btu), at the energy-per-dollar rate for complex structures [40 MJ/dollar (37 912 Btu/dollar)].

Buses for the BART riders who do not drive automobiles will also require highway space, but buses cannot serve passengers at the assumed rate of 1200/lane•h. This is a theoretical figure for constant motion with no stops. To pick up or discharge passengers, only 120 buses/lane•h can be moved at even minimal speed. Terminal expansion would be needed for even this number of buses. To avoid terminal cost, I assume that curb stops for 120 buses/h will require 1.67 lanes in each direction, except at the 10-km (6.2-mile) Bay crossing where there are no stops and where one lane each way would be adequate. In all, 56 more lane kilometers (35.4 lane miles) will be needed for buses at \$0.579 million/lane•km (\$1 million/lane mile), for a total of \$32.4 million. Because of the Bay Bridge, there would be no low suburban costs. In fact, some freeway-level costs are likely.

If energy costs 118 MJ/dollar, the construction of highway capacity for buses to equal present BART operation would require 3.8 PJ (3.6×10^{12} Btu). However, BART is using only 60 percent of its cars and 75 percent of its routes because of initial electronic difficulties. When these problems are solved and all lines commence operation, BART may carry 33 percent more people for the same construction energy. This will require a 33 percent further increase in the relative energy cost of the highway alternative. Total highway construction energy would then approximate 69 PJ.

VEHICLE OPERATING ENERGY

Actual rail transit experience has revealed operating energy requirements of 15.6 MJ/car·km (14 785 Btu/car-mile) and 6.7 MJ (6350 Btu) for station lighting and other auxiliary uses. (For the highway alternative, no energy consumption was calculated for parking lots for automobile commuters, traffic controls, highway lighting, or bus-terminal operation.) BART expects its expensive choppers to recover and return 20 percent of its energy, but this can be ignored as experimental. The proven figures show that BART operating energy will be about 22.3 MJ/car·km (21 136 Btu/car-mile), not the 65.5 MJ/km (62 081 Btu/car-mile given in Table 2. This will reduce the comparable operating power per passenger kilometer to 2.2 MJ (3271 Btu/passenger-mile). Even this figure could be much improved if BART inaugurated service on the Richmond-San Francisco line to dilute the low efficiency of the Fremont-Richmond line, which shares its passengers between Oakland and Fremont with the heavier San Francisco line. Operating power for BART would thus be

$$\begin{aligned}&707 \text{ million passenger·km/year}\\&\times 1.05 \text{ MJ/passenger·km} = 740 \text{ million MJ}\end{aligned} \qquad (15)$$

Operating power without BART would be

$$\begin{aligned}&0.48\,(707 \text{ million}) \times 5.4 \text{ MJ/passenger·km}\\&+ 0.52\,(707 \text{ million}) \times 1.9 \text{ MJ/passenger·km} = 3.3 \text{ PJ/year}\end{aligned} \qquad (16)$$

Setting BART power-system losses against added lighting requirements for highway lanes, bus stations, and bus garages, BART would save 2.6 PJ/year (2.5 × 10^{12} Btu/year) in operating energy. If 15.76 PJ (14.9 × 10^{12} Btu) are added for BART construction, the energy invested in BART will be recovered in 6 years, well within the life expectancy of BART facilities:

$$15.76 \text{ PJ} \div 2.6 \text{ PJ} = 6 \text{ years} \qquad (17)$$

Because BART is not yet operating all of its routes and because its car fleet is not yet operating at conventional efficiency (22, p. 6), no effort will be made to compare BART with proposed future automobile efficiency, particularly because BART's energy-recovery system is not assumed to be working either.

SUMMARY

Not only can the energy invested in BART be recovered during its lifetime, but also the type of energy BART uses is far superior to present bus and automobile energy, which must come from foreign petroleum and must be burned in congested, heavily populated areas. BART energy can come from water, coal, nuclear power, or oil and can be burned at a controlled site where it will not impinge on the local population. In the future, BART energy should also be much less costly per joule than foreign petroleum.

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There is a growing concern today about energy efficiency in all aspects of our existence. Because some degree of mobility is essential to everybody, the energy consumed has become a matter of concern. At the same time, another nonrenewable resource should also be considered, one that is ignored by some authors of papers in this field: time. The necessity of considering a trade-off between the loss of time and increases in the consumption of energy to reduce time loss is especially apparent in the case of long-distance travel, in which air travel, in spite of its well-known high consumption of energy, has largely replaced the use of land transport.

The two modes considered today for providing urban mobility by means of public transit systems are bus and rail rapid transit. The bus system entails minimal capital costs but involves high operating costs because the productivity of platform labor is severely limited by the single-unit vehicle per operator. Rail systems involve higher capital costs but show lower total costs at sufficiently high volumes.

Many of the conclusions expressed in Lave's paper on rail transit and energy are erroneous. My analysis, which differs in its methods, is based on the following data (1 MJ = 948 Btu):

Fuel	Specific Gravity	Megajoules per Kilogram
Automobile gasoline	0.739	48.85
Diesel fuel	0.904	42.51

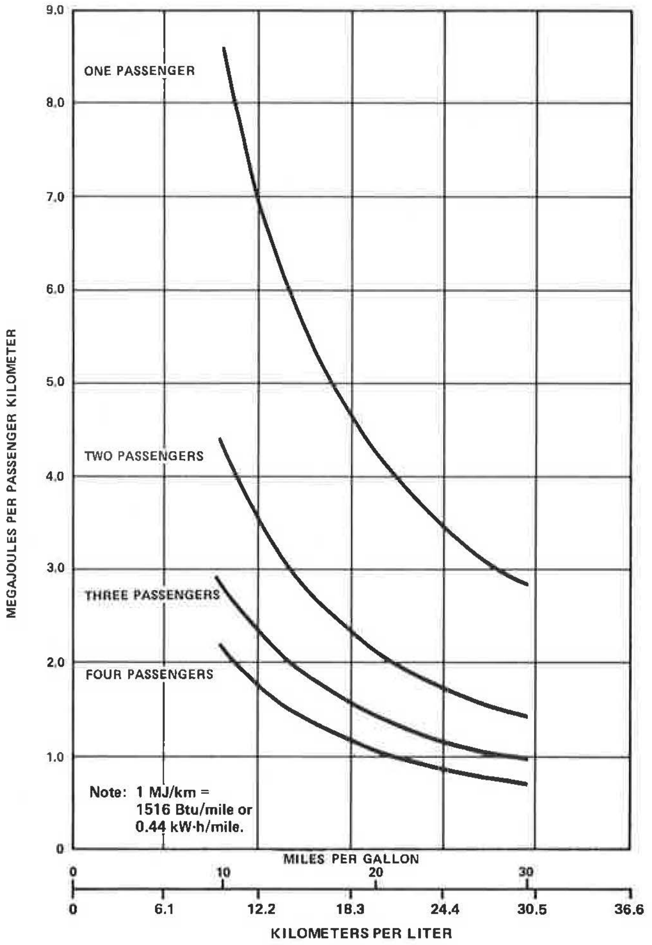
If 3.8 L (1 gal) of gasoline converts to 136.9 MJ (129 829 Btu) of energy, then for the automobile the following can be calculated (1 km/L = 2.35 miles/gal and 1 MJ/km = 1526 Btu/mile):

Kilometers per Liter	Megajoules per Passenger Kilometer			
	1 Passenger	2 Passengers	3 Passengers	4 Passengers
4.25	8.51	4.26	2.84	2.13
6.38	5.70	2.85	1.90	1.43
8.51	4.26	2.13	1.42	1.07
10.64	3.41	1.70	1.13	0.85
12.76	2.84	1.42	0.97	0.71

These figures are shown graphically in Figure 1.

The following April 1976 data were furnished by the New York City Transit Authority (NYCTA) (25) for the

Figure 1. Automobile energy consumption.



case of the standard diesel-engine transit bus (1 km = 0.62 mile, 1 L = 0.26 gal, and 1 L/km = 0.43 gal/mile):

Division	Bus Kilometers	Bus Hours	Fuel Consumed (L)	Liters per Kilometer
Brooklyn	4 892 559	414 968	3 344 739	0.68
Staten Island	1 625 638	82 339	812 159	0.50
Queens	1 977 609	136 018	1 194 175	0.60
Manhattan	489 661	52 783	326 819	0.68

Data of the Southern California Regional Transportation District show a figure of 0.50 L/km (0.213 gal/mile). Although there is some variation with operating speed (bus kilometers per bus hour), a conservative value of 0.5 L/km (0.21 gal/mile) will be used, equivalent to 2.22 bus·km/MJ (0.0014 bus-mile/Btu). Data for the average load, or passenger kilometers per bus kilometer, are available only for the Manhattan Division of NYCTA, for which a brochure issued by the Tri-State Regional Planning Commission gives an average trip length of 4.84 km (3 miles) (24). The number of passengers carried in that period of April 1976 was 2 599 000; an estimate of 12 579 000 passenger·km (7 797 000 passenger-miles) gives an average load of 25.68; thus, energy per passenger kilometer is 1.12 MJ (1065 Btu).

For rapid transit operation, nonpropulsion energy must be separated from that actually used by the traction motors. Unfortunately, this is not usually done in reports of operating results.

The energy for propulsion is a function of maximum speed and of station spacing. The kinetic energy stored in the moving train is a quadratic function of maximum speed and is divided by station interval to express it in terms of distance. Some part of this energy can be recovered by regenerative braking, by energy storage in on-board flywheels, or by the use of line profiles dipped between stations. A second component of propulsion energy is the amount needed to overcome train resistance. This is a cubic function of maximum speed. Like kinetic energy, it is proportional to train mass for the linear and constant terms of the train-resistance force; the quadratic function is proportional to area of cross section. No attempt is made here to evaluate these quantities, but they are pointed out to indicate that values for different types of functions may differ widely.

NYCTA has separated propulsion energy from other uses according to fiscal year (26) (1 TJ = 277 000 kW·h, 1 MJ = 0.28 kW·h, and 1 km = 0.62 mile):

Item	Fiscal Year 1975	1974
Total terajoules purchased	7390	7408
Terajoules lost in transmission and conversion to direct current	509	516
Terajoules of alternating current for lighting, signals, shops, and other uses	801	805
Terajoules of direct current used for operation of cars	6061	6068
Megajoules per car kilometer	12.3	11.7
Car kilometers	487 515 282	511 583 777

It should be noted that in 1975 the larger R-44 cars came into service. Car kilometers were thus reduced, but—because of the greater weight and speed of these cars—energy per car kilometer increased. The average operating speed of the New York City Rapid Transit System is rather low—29.5 km/h (18.3 mph)—corresponding to the short intervals between stations.

Haikalis of the Tri-State Regional Planning Commission has estimated average trip length on the New York system as 11.3 km (7 miles) so that the average load figure is 24.91. Megajoules per car kilometer are 12.31 (19 449 Btu/mile); energy per passenger kilometer is 0.493 MJ (754 Btu/passenger-mile). This, based on an overall efficiency of 34 percent, equals 2.3 MJ (2218 Btu) from fuel at a generating station. This appears to assume that all energy is provided by fossil-fuel generating stations. But some energy currently comes from nuclear-fission stations, and this fraction is expected to increase. Hydropower stations also carry some fraction of the total load. It is certain that in the more distant future other energy sources will be used, such as geothermal, solar, and fusion energy and other means not yet developed.

A more questionable item in the energy picture is the energy required for construction. In the paper by Lave, reference is made to the work of Healy (6) and Hirst (7) in which the dollar value of energy appears to be 1 MJ = \$0.012 (1 kW·h = \$0.044). There seems to be little relation between this and the actual cost of power. The dollars-to-energy conversion is erroneous. Furthermore, the life of many fixed works of a rapid transit system is indefinite. The London subway tunnels are more than 100 years old. The life of the iron elevated structures of 80 years ago is much less—about 50 years—but the life of a masonry or concrete structure may be very long. Some Roman aqueducts that are over 2000 years old could still carry a railroad track. In any case, inferring that the energy required to build can be determined by converting dollars to energy units is not a valid method of estimating construction energy. It must be recognized, however, that the funds invested in fixed works represent a fixed cost of the system. This can be evaluated on an annual percentage rate. Currently, 8 percent appears suitable. Equipment should be evaluated differently because it has a shorter life. There are also fixed costs of operation, which are independent of volume. But, in energy considerations, these costs seem irrelevant. The unit of output of the transportation system for passengers is taken to be the passenger kilometer.

Several analyses have been published recently in which the BART system is used as an example of modern rapid transit. In view of the many problems and the low availability of equipment experienced on this system, BART cannot be considered typical. Operation is still somewhat less than sufficiently reliable, and this appears to be a factor in the lower than expected patronage. Until its operational problems are overcome, the BART system is not a valid base for any general conclusions. For this reason, and because of the greater availability of detailed operations data, this discussion is based largely on New York data. At the same time, it must be noted that in many respects the New York operation does not take account of many advances in technology.

Finally, it should be noted that regenerative braking or energy storage can effect a 40 percent reduction in energy consumption with no sacrifice in performance. This lowers the energy at the generating station to 1.42 MJ/passenger·km (0.63 kW·h/passenger-mile). The automobile mode of travel can attain equally low values only at numbers of passengers per automobile that are difficult to achieve, and in New York the rather low schedule speed of rapid transit is still faster in Manhattan than automobile travel.

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Lave's paper expresses some rather categorical conclusions about the energy requirements of rapid transit compared with those of freeways. Before accepting these conclusions one must examine for reasonableness and validity the assumptions, the parameter relations, the methodology, and the general approach used. If any one or several of these are found to be suspect, the possible effect on the results must be determined.

METHODOLOGY

Lave compares two quite different alternatives—rapid transit versus bus and automobile on freeway—without considering such items as

1. Level of service (speed, comfort, and dependability;
2. Differences in land requirements;
3. Environmental impacts (noise, air pollution, and community disruption);
4. Potential for growth (reserve capacity);
5. Differences in the location of the facility that cause differences in accessibility and differences in the required investment of energy;
6. Differences in terminal facilities (stations, bus stops, and parking garages); and
7. Differences in the prerequisites for using the system (for most automobile users, access to an automobile and a license to drive).

Although there are major differences between the two alternatives in all of these areas, these differences have been largely or totally ignored.

Lave's study also seems to be based on combinations of averages for many parameters. In many cases the distribution functions on which these averages are based are not independent of one another; the combined averages can thus be misleading. It is also true in transportation that these averages are not only mode specific but also time and location specific. They must therefore be used very carefully in analyses.

Lave's methodology compares the full energy investment of the BART alternative with the marginal energy investment for freeways to handle BART's present ridership (the study ignores the possibility that the marginal energy investment per freeway lane could be higher than the average for the entire system).

In Table 5, Lave's approach is used, but the full energy investment in BART is compared with the full energy investment required to provide a freeway of the same capacity. If Lave's energy-investment ratios are correct, it seems impressive that equivalent transportation can be provided by BART in about 14 percent of the space, about 2 percent of the downtown terminal area, and at only about 58 percent greater energy investment. In addition, 21 000 persons/h is only approximately 67 percent of BART's potential maximum capacity.

BASIC ASSUMPTIONS AND PARAMETER RELATIONS

Lave's study uses three basic assumptions:

1. The energy investment in facilities, which is a continuous linear function of the number of lane kilometers, has no constant term, and depends only on the mode and the general location;
2. The lane kilometers saved through diversion of trips to BART, which can be computed by a relation that can be restated as follows:

$$LM = \alpha P_m L_{avg}/NT_pC_m \qquad (18)$$

where

LM = lane kilometers saved,
α = percentage of trips in peak hours,
P_m = total trips per day diverted from mode m,
L_{avg} = average trip length,
N = number of persons per vehicle,
T_p = total number of peak hours (four), and
C_m = highway capacity (vehicles per lane hour); and

3. Empirical estimates of energy consumption per vehicle kilometer.

Lave gives unique numbers for energy investment per lane kilometer for both rapid transit and freeways and throughout his paper allows no variation in these numbers. This procedure is correct only if the following conditions exist:

1. The numbers are extremely accurate and constant (very little variance),

Table 5. Comparison of energy investment for BART and freeway alternative.

Item	BART	Freeway
One-way capacity, persons/h	21 000[a]	22 400[b]
Total tracks or lanes, two ways	2[a]	14[b]
Minimum width,[c] m	7.3	51.2
Average speed, km/h	72[d]	48[e]
Maximum running speed, km/h	112[d]	48[e]
Typical location of facility	Through population centers	Between developed areas
Downtown terminal space required, hm^2	1.65[f]	78[g]
Energy required,[h] TJ	173 000	110 000

Note: 1 m = 3.3 ft; 1 km/h = 0.62 mph; $1\ hm^2 = 2.5$ acres; 1 TJ = 948 million Btu.

[a] 70 persons/automobile, 10-car trains, 2-min headways, one track each way.

[b] 2000 vehicles/lane·h over entire freeway length for long, sustained periods of time; 1.6 persons/automobile.

[c] 3.6 m/track or lane, no shoulders, medians, interchanges, or stations.

[d] Presently achieved values.

[e] Level of service E (27, p. 264).

[f] 6-m platform depth each side, 213-m length, four stations.

[g] $2.8\ m^2$/automobile, 1.6 passengers/automobile.

[h] Based on Lave's data.

2. The numbers resulting from the studies (6, 7) require few assumptions or else are insensitive to the assumptions made,
3. The energy investment is constant for every lane kilometer added (i.e., the high initial increment) and economies and diseconomies of scale do not exist (in the real world they can be highly significant),
4. Construction conditions are uniform throughout the region, and
5. The cost of building a bridge across the San Francisco Bay (six lanes in the peak direction at 1.6 persons/automobile and 2000 vehicles/h) is already included in the average of $0.579 million/lane·km ($0.932 million/lane mile) (Lave uses a number that is based on a 50 percent weighting each of urban and rural freeway construction in California).

In regard to lane kilometers saved through diversion of trips to BART, the equations Lave uses for determining the number of lane kilometers needed to satisfy a given highway demand (Equations 2 and 3) would never be used by a highway engineer for planning purposes because they are extremely restrictive. That is, they implicitly assume the following:

1. The time distribution of trips during the peak hours is uniform. The correct procedure for this analysis should use the methods explained in the Highway Capacity Manual (27).
2. The additional lane kilometers needed are reversible (taking total trips and dividing by 4 h necessarily implies the use in both peaks of any lane built). Reversible lanes, although economical, are difficult to design and operate and have therefore been used at only a few locations in the United States.
3. Lanes can be added in noninteger amounts. This is particularly unrealistic when the spatial distribution of flows is nonuniform.
4. The addition of more lane kilometers to the system includes the provision of expanded interchange capacity at all affected interchanges.
5. The highway capacity is fixed at 2000 vehicles/lane·h.
6. The bus flow rate will be 1200 buses/lane·h. This far exceeds any currently observable value. The Highway Capacity Manual (27) gives 690, and the highest achieved value at the present time is that for the Lincoln Tunnel approach—490 buses/lane·h (28).
7. The average bus occupancy is only 25 persons/bus during the peak.
8. Ample station capacity has been provided along the route for the buses (184 berths are required for the station that handles the 490 buses/h in New York).

Equations 2 and 3 will obviously yield extremely low estimates (probably the lower bound) of the number of lane kilometers required to just cover the present BART load. It would be easy to challenge Lave's conclusions by assuming different numerical values. His approach is unsound inasmuch as it requires implicit acceptance not only of his general approach and methodology but also of his parameter relations.

Lave's analysis of vehicle energy consumption appears to be generally correct in that he includes the energy required to construct the vehicle and takes account of the efficiency of the electric power plant. His use, however, of energy per passenger kilometer as a common unit can be very misleading because it masks many things including seating design, vehicle weight, and changes in load factor. Such a number, although interesting and necessary, is not a constant but rather a variable that is highly sensitive to many factors.

CONCLUSION

Because many aspects in the approach, methodology, assumptions, and parameter relations used by Lave are questionable, his conclusions may be misleading. His posture that the comparison of energy investment among alternatives should be done on an absolute basis without consideration of the nature and quality of the product (transportation system performance and its impacts) would lead to incorrect conclusions if applied to any investment decisions, as it did in Lave's comparison of rapid transit and freeways.

Estimating the errors in the numerical analyses presented by Lave can only be done by adopting a correct methodology. Studies by others (28, 29) as well as numerous estimates performed in planning actual transportation systems indicate that Lave's findings are not realistic.

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Lave's conclusions challenge not only the conventional wisdom that assumes that rail transit is an energy-efficient mode of transportation but also the conclusions reached by other knowledgeable analysts. Bezdek and Hannon (1) have concluded that energy savings would result from a diversion of funds from highways to rail transit, and Fels (4) has shown that rail rapid systems are lower in their consumption of energy than are automobiles. The analysis presented here produces a similar conclusion: BART is an energy-saving form of transportation.

Lave's analysis is faulty in several important aspects.

1. BART and highway capital costs are inflated to 1974 price levels although the factor used to convert dollars to joules is based on the energy intensity of the dollar in 1963.
2. An inappropriate conversion factor is used to equate BART construction costs with energy requirements.
3. A completely erroneous estimate of the costs of a highway alternative to BART is used.
4. Total BART requirements for operating energy are compared with an incomplete estimate of the operating costs of highway-based modes.
5. The comparison of highway and BART operating costs is further biased against BART by the use of an incorrect pre-BART modal-split factor for BART patronage.

Lave also asserts that the energy use of newly generated travel on the BART system should be charged only to BART rather than to the highway system. Obviously, the encouragement and service provided for such new trips are matters of transportation planning policy, and their costs should be properly allocated.

ENERGY COSTS OF CONSTRUCTING BART

Three estimates of the energy cost of BART construction are shown here and discussed below:

1. Lave's estimate: 174 PJ (48.1 billion kW•h or 16.4×10^{13} Btu),
2. The estimate used to illustrate the first case in this analysis: 74.1 PJ (7.03×10^{13} Btu), and
3. The estimate used to illustrate the second case in this analysis, which is considered to be the more appropriate measure: 41 PJ (3.89×10^{13} Btu).

The first estimate is based on BART construction costs inflated to 1974 dollars and on a factor for converting dollars to energy requirements derived by Healy (6, p. 32). Because Healy's conversion factor measures the energy intensity of 1963 dollars, its application to costs inflated to 1974 dollars provides, to a large degree, a measure of price inflation that bears little relation to the actual energy costs of building BART.

The second estimate also uses Healy's conversion factor but represents BART construction costs in constant 1963 dollars. Healy himself has recognized and cautioned that his conversion factor is somewhat erroneous and misleading even when applied to constant 1963 dollars of expenditure. The factor was derived on the basis of current dollar costs for each economic sector of expenditure for building the BART system. The overwhelming majority of BART costs were incurred after 1963, the reference year for measuring the energy intensity of the dollar, and thus the actual energy requirement shown is inflated.

The third estimate is based on a conversion factor of dollars to joules developed by Bezdek and Hannon (1, p. 670) and on BART construction costs of $902 million (1963 dollars). This estimate is realistic for the purposes of this comparison and is compatible with the conversion factor used to estimate the energy cost of highway construction, which was also developed by Bezdek and Hannon.

ENERGY COST OF CONSTRUCTING AN ALTERNATIVE HIGHWAY SYSTEM

Lave's analysis is negligent in its failure to consider that (a) highways must be built to support peak travel in two different directions during the day rather than in the single direction on which his costs are based, (b) any truly alternative highway system would parallel BART in extent and reach, (c) any highway built to support automobile and bus traffic would be built according to specifications for carrying trucks and would therefore incur the full costs derived by Keeler and others (9, p. 28), (d) high energy-cost premiums must be paid for constructing highway access through the East Bay hills and across the San Francisco Bay, and (e) parking facilities must be constructed in the San Francisco and Oakland central business districts (CBDs) to handle the additional influx of automobiles.

One analysis of the costs of a highway system parallel and equivalent to BART has allocated $1.28 billion in 1974 dollars of highway construction costs to the patronage now carried on BART (31). Converting these construction costs to 1963 dollars by using the Engineering News Record building construction cost index and using a figure of 118.4 MJ/dollar (112 200 Btu/dollar), we calculate a construction energy cost of 80.6 PJ (76.4×10^{12} Btu), which is greater than either of the acceptable estimated energy costs for constructing BART. Parking-structure costs would add another 3.4 PJ (3.2×10^{12} Btu).

We have also computed highway costs for two cases by using Lave's approach of measuring incremental highway requirements. The first case is the typical November 1976 BART demand pattern with a daily patronage level of 131 151 trips, which includes 20 997 trips in the single evening peak hour. (Average weekday patronage for 1976 was approximately 131 300/d for the current three-route service levels, and the annual growth rate of daytime patronage is statistically significant at 4.2 percent/year.) The second case is based on a realistic projection of BART patronage in 1981 of 185 000 trips/d with 36 000 trips in the peak hour. Service in 1981 will be provided on four routes and headways will be decreased from 12 to 8 min; additional peak-period service will be provided on the busy Concord-to-San Francisco route.

The incremental requirements for constructing urban highways in the Oakland and San Francisco CBDs and suburban highways in the remaining BART service area, according to BART origin-destination trip patterns, are given in Table 6. Construction costs were derived from total highway construction costs given by Keeler and others (9). Trans-Bay crossing requirements, derived from estimates of costs for the proposed Southern Crossing of the Bay (31, p. 3), are $27.04 million (1963 dollars) for a single lane to span the Bay. Berkeley Hills tunnel costs, derived from actual BART construction costs for drilling and boring 5.3 km (3.3 miles) of double tube, are $24.01 million (1963 dollars). Parking-structure costs are based on costs for downtown San Francisco's Firth and Mission Street garage (32, p. 125) and on an estimate of the 3-h peak-period requirement for automobile spaces.

Alternative automobile and bus patronage is allocated by using 1976 pre-BART modal-split factors for BART patronage, which have been developed from a May 1976 survey of BART patrons that showed that approximately 46.5 percent of pre-BART peak-period trips to the San Francisco CBD have been diverted from buses. Peak-hour modal-split figures generated from this source were used on a segment-to-segment basis to determine highway requirements. A highway lane capacity of 2000 automobiles/lane•h or 1250 buses/lane•h is used. Modal-split data for the entire day, for all patrons, show that 56.5 percent of the BART patrons who previously used either automobiles or buses had used automobiles. This factor was used to determine alternative highway operating costs (Table 7) even though a larger

Table 6. Incremental construction costs for highway alternative to BART.

Condition	Requirements for Both Directions	Total Construction Costs ($000 000s)[a]	Total Energy Costs (PJ)
Current BART demand (131 300 trips/d)			
Urban highways	20.5 lane·km	11.18[b]	1.32
Urban-suburban fringe highways	122.6 lane·km	21.88[b]	2.59
Berkeley Hills tunnel	2.3 lanes	27.56	2.26[c]
Trans-Bay crossing	3.5 lanes	95.45	11.30
CBD parking structures	12 672 spaces	28.70	1.98[d]
Total		184.77	19.45
Projected 1981 four-route service demand (185 000 trips/d)			
Urban highways	34.9 lane·km	19[b]	2.25
Urban-suburban fringe highways	208.5 lane·km	37.22[b]	4.41
Berkeley Hills tunnel	3.1 lanes	37.21	2.57[c]
Trans-Bay crossing	5 lanes	135.19	16
CBD parking structures	21 675 spaces	49.09	3.39[d]
Total		277.71	28.62

Notes: 1 PJ = 948 billion Btu; 1 km = 0.62 mile.
Unless otherwise noted, a conversion factor of 118.4 MJ (112 200 Btu) per constant 1963 dollar is used.

[a] Constant 1963 dollars.

[b] Costs (9, p. 28) converted to constant 1963 dollars of $544 130/lane·km ($875 694/lane mile) of urban highway and $178 432/lane·km ($287 159/lane mile) of urban-suburban highway.

[c] BART conversion factor of 81.9 MJ/dollar (77 605 Btu/dollar) (30).

[d] Facility construction factor of 69 MJ/dollar (65 400 Btu/dollar) (1, p. 670).

Table 7. Operating energy costs for BART and for highway alternative.

	Operating Energy (kJ/passenger·km)				
System Option	Construction of Vehicle[a]	Propulsion	Stations and Vehicle Maintenance	Total	Total Annual Operating Energy (PJ)
BART					
Current three routes with 723 495 000 passenger·km/year	43	1721	698	2462	1.78
Upper bound on four routes with 1 019 583 000 passenger·km/year	43	1488	511	2042	2.08
Lower bound on four routes with 1 019 583 000 passenger·km/year	43	1349	465	1857	1.89
Highway					
Average automobile and bus					
Automobile (6.1 km/L)	604	4685[b]	1071[c]	6360	
Bus (2.3 km/L)[d]	58	1532	564	2155	
Average[e]				4531	
723 495 000 passenger·km/year					3.28
1 019 583 000 passenger·km/year					4.62
Future automobile and bus					
Automobile (11.7 km/L)	335	2454	570[c]	3359	
Bus (2.3 km/L)	58	1532	564	2155	
Average[e]				2835	
723 495 000 passenger·km/year					2.05
1 019 583 000 passenger·km/year					2.89

Notes: 1 kJ/km = 1.53 Btu or 0.000 45 kW·h/mile; 1 PJ = 948 billion Btu or 277 million kW·h; 1 km = 0.62 mile; 1 km/L = 2.35 miles/gal.
Occupancies (passenger kilometers per vehicle kilometer) are 21.4 for BART, 1.3 for automobile, and 11.5 for bus.

[a] Data given by Fels (4, p. 300) converted by using 3.6 MJ/kw·h; conversion inefficiencies were already included.

[b] Including total refining costs in conversion of 37.3 MJ/L (133 800 Btu/gal) for gasoline and 41.2 MJ/L (147 800 Btu/gal) for diesel.

[c] Average conversion of 76.24 MJ/dollar (72 260 Btu/dollar) (7, p. 22) and $0.019/vehicle·km ($0.03/vehicle mile) (or 23 percent of propulsion cost) for automobile maintenance and tires and $0.087/vehicle·km ($0.014/vehicle mile) for bus.

[d] Diesel efficiency of Alameda-Contra Costa County Transit.

[e] 56.5 percent automobile, 43.5 percent bus.

Table 8. BART energy-payback periods versus automobile efficiencies.

		Payback Period (in years) Versus	
Condition	Construction Energy Factor Used	6.1-km/L Automobile	11.7-km/L Automobile
Current BART demand of 131 300 trips/d and operating energy of 2462 kJ/passenger·km (723 495 000 passenger·km/year)	Healy	36.5	—[a]
	Bezdek and Hannon	14.4	—[a]
Projected 1981 four-route BART service (185 000 trips/d and 1 019 583 000 passenger·km/year)			
2042-kJ/passenger·km operating energy	Healy	17.9	56.3
	Bezdek and Hannon	4.9	15.3
1857-kJ/passenger·km operating energy	Healy	16.7	45.6
	Bezdek and Hannon	4.6	12.4

Note: 1 kJ = 0.948 Btu; 1 km = 0.62 mile; 1 km/L = 2.35 miles/gal.

[a] Comparison with the 11.7-km/L (27.5-miles/gal) automobile is not appropriate because BART will be in four-route service with a minimum of 1 019 583 000 passenger·km/year (633 538 000 passenger-miles/year) by 1981. The on-the-road automobile is not likely to approach this average gasoline consumption until well after introduction of 11.7-km/L automobiles, in 1985 or later. Using the Healy factor gives 202.2 years and using the Bezdek and Hannon factor gives 79.7 years for these cases.

proportion of the longer trips would be associated with the automobile, which consumes more energy.

OPERATING ENERGY REQUIREMENTS OF BART AND ALTERNATIVE HIGHWAY-BASED MODES

The total operating energy requirement for BART and the portion of that requirement represented by traction energy are given in Table 7. This analysis uses a California Department of Transportation conversion ratio of 2.07 J of energy used per joule of electrical output (7095 Btu/kW·h) to reflect the efficiency of hydroelectric power sources in California. Lave's calculation compares the total energy use of BART, including maintenance and station energy use, with the traction energy requirements of other modes of transportation. Any comparison that ignores the energy required to operate and maintain highways, parking facilities, and garages and at the same time includes those energy costs for BART is biased against rail transit. This analysis makes some conservative assumptions—also given in Table 7—about the energy costs of these items.

Data in Table 8, which uses the construction energy factors of Healy (30) and Bezdek and Hannon (1), clearly show that BART energy construction costs will be paid back from operating energy savings within a period of a few years. Even the worst cases used for each assumption about automobile energy consumption show payback periods shorter than those estimated by Lave for the ideal transit situation.

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31. W. English. A Comparison of the Capital Costs of Building BART and Freeway and Bus Alternatives. Proc., 4th Annual Intersociety Conference on Transportation, Los Angeles, July 18 to 23, 1976.
32. Parking in the City Center. Wilbur Smith and Associates, New Haven, Conn., May 1965.

Author's Closure

First, my paper was explicitly an energy analysis, nothing more. There are many possible reasons why some given city might want to build a rail transit system, and saving energy is only one of them. If a properly done benefit/cost analysis of these other factors shows that a rail system is justified, then the slightly adverse energy consequences may, of course, be ignored.

In the following comments, I take up the points of each discussant in order.

REPLY TO TENNYSON

Energy Conversion

Based on input-output analysis, I use a figure of 81.9 MJ/dollar (77 600 Btu/dollar) to calculate the amount of energy represented by a dollar of construction. Tennyson converts this into a gasoline equivalent by using the retail price of gasoline and the known energy per liter and concludes that my energy-per-dollar conversion factor is equivalent to $0.215 worth of gasoline for every dollar of construction and, therefore, my conversion factor must be wrong because $0.215 is too high a ratio.

But this is not the way that input-output analysis works. Those 81.9 MJ were put in at the source, not at the point of final consumption. Tennyson's calculation based on gasoline price is not relevant because the energy did not come from gasoline but from considerably cheaper energy sources at the origin of manufacture.

Diversion From Automobile Mode

Contrary to Tennyson's statement, I did not take my diversion figures exclusively from the trans-Bay link and ignore East Bay travel. The official BART impact report (3, p. 108) gives a detailed breakdown of prior mode for all three parts of the BART line. When these figures are weighted by the latest total patronage data (3, p. 71), they yield exactly the data in the BART line entry in Table 1. Furthermore, Tennyson's data and mine are in this case essentially identical.

Tennyson says that my 49 percent bus figure for Lindenwold actually represents the total of both former bus and former train passengers. This is true, but my only point was that the majority of the passengers were drawn from other public transit, which is still correct.

Peak-Hour Duration

My 4-h-peak figure comes from the official BART impact report (3, p. 86). Tennyson's 2-h figure comes, as he says, from "personal observation," as does his 9000-automobiles/h figure. In any event, I show below that his resultant lane-kilometer figure does not affect the outcome of my analysis.

Freeway Costs

Tennyson says that urban freeways cost $6.2 million/lane·km ($10 million/lane mile) to build but cites no evidence for this. I used $0.787 million/lane·km ($1.2 million/lane mile), which comes from a careful University of California, Berkeley, study of actual construction experience in California (9, p. 28). National figures from official publications of the Urban Mass Transportation Administration (33, p. IV-19) reveal a cost (in 1973 dollars) of $0.707 million/lane·km ($1.1 million/lane mile) for CBD construction in cities of 500 000 to 1 000 000 population.

Parking Structures

Tennyson requires parking structures for all automobiles diverted by BART. Surely there must be some surplus capacity in existing structures, and surely not all the excess people should be put into parking structures. After all, they were not all going to the high-density San Francisco CBD. Many could have been served by ordinary parking lots. Calculating the cost of such parking structures, however, does not affect my results.

The 1970 cost of a three-level parking structure was $1550/space (33, p. IV-24), which is $2260 in 1974 dollars (Engineering News Record construction index). This amounts to $42.7 million for Tennyson's 18 861 spaces. After this is converted into energy by using the very conservative highway coefficient, the amount of energy required to build parking structures turns out to be only 3 percent as large as the amount of energy necessary to build BART. Clearly 3 percent should not be a source of great concern, and in any event even this figure requires extreme assumptions about necessary parking-structure spaces.

Bus Capacity

I use 1200 buses/lane•h, the appropriate figure (4, p. 304) for a freeway, which is the kind of highway BART replaces. Tennyson uses 120 buses/lane•h, which is appropriate for constantly picking up and discharging passengers on a city street. As an alternative way of examining Tennyson's figure, the resultant passenger capacity would be 120 × 11.5 passengers/bus = 1380 passengers/lane•h compared to that for an all-automobile highway, which is 2000 cars × 1.6 passengers/automobile = 3200 passengers/lane•h. (Both the bus and automobile load factors are national averages.) That is, using Tennyson's suggested figures for bus capacity results in automobiles carrying more than twice as many people as buses on a lane of highway, which is clearly wrong.

Station Operating Energy

The difference here is that I included the energy used to heat, light, and air condition the BART stations and Tennyson wants to use traction energy only. Tennyson argues that the energy used for street lighting and traffic controls is the automobile analog of BART station energy and that, because I do not add the cost of lighting and signals to the operation of automobiles, I should not add the cost of stations to BART. There are three problems with this argument.

First, even if there were no automobiles at all, street lighting would still be needed for reasons of public safety (all of the new automobile-restricted zones still use such lighting). Traffic signals too would still be needed for public transit vehicles, police cars, and fire engines.

Second, Tennyson's argument does not distinguish between marginal effects and average effects. Energy used for street lighting and traffic signals cannot be counted against automobiles at the average rate because the marginal cost of accommodating additional vehicles is essentially zero. In more direct terms, what street lights and traffic signals should we turn off because BART has attracted some former automobile drivers?

Third, before a project is undertaken, all of its costs are marginal costs. The decision to build BART was a decision to incur large yearly energy costs to operate stations. A decision to terminate BART operations (which I am not advocating) would be a decision to save these station operating expenses. These energy costs are directly caused by BART and must be charged against it.

Future Energy Efficiency of BART

The most optimistic figures I have seen for possible improvement of BART energy efficiency show a possible future 25 percent energy-consumption improvement (3, p. 50). Meanwhile, Congress has mandated that automobile efficiency be increased by 100 percent by 1985, and the automobile companies are complying. In other words, BART may possibly improve by 25 percent, if it can double its present ridership, while automobiles will definitely improve by 100 percent. Future changes thus work in the direction of greatly decreasing the relative energy efficiency of BART.

Significance of Changes in Overall Results

Although I have shown that Tennyson's figures for extra lane kilometers of highway and for extra parking structures are not justifiable, if I accepted them and recalculated my results, would it matter? I have already shown that Tennyson's parking structures amount to only 3 percent of the energy cost of BART. As to the differences in highway figures, I calculated a BART-caused savings of 74.8 freeway lane•km (46.5 lane miles) and Tennyson calculated 99.3 lane•km (61.6 lane miles). Using his figure would raise my energy estimates by only one percentage point. That is, my original calculation showed that the kilometers of freeway construction replaced because of building BART amounted to an energy saving that was only 3 percent as large as the energy cost of building BART. Even if I use Tennyson's figures, this estimate would be raised to only 7 percent; thus, my overall conclusion would not be affected.

REPLY TO HOLDEN

Value of Time

The value-of-time concept, on which I did some of the pioneer work with regard to behavioral measures (34), does not seem to be operating in favor of BART. The reason BART attracts so few people out of automobiles is that it is not faster than automobiles for most trips. It is not even faster than express buses for most trips: Their patronage has been growing while BART patronage on parallel routes has been relatively stable. In addition, Holden does not indicate how this value of time is to be incorporated in my energy analysis.

Transit Operating Energy

First, it is irrelevant to compare the energy efficiency of the New York subway system with that of BART. All the literature in the field points out that the older subways operate in denser areas with higher load factors and lower vehicle acceleration and that they use much less energy on station amenities. Second, the BART energy figures are based on actual measured energy consumption over a long period of operation (3, p. 50; 35), and they are nearly identical to figures for the Lindenwold Line (2).

Construction Energy

Holden's position is the reverse of Tennyson's. Holden takes the construction/energy ratio, 81.9 MJ/dollar (22.7 kW•h/dollar), too literally, dividing $1 by 81.9 MJ (22.7 kW•h) to compute that 1 MJ = $0.012 (1 kW•h = $0.04). He then concludes that the energy conversion concept must be erroneous. Because it is the concept that is the subject of disagreement, I will substitute a simpler example of the same concept, namely, the energy represented in a ton of steel. Holden's argument would then be as follows: Claimed energy necessary to make 1 Mg of steel × current home cost of delivered electrical power ≠ selling price of 1 Mg of steel. That is, because Holden observes that the two sides of the equation are not equal, the concept must be wrong. The problem with this analysis is that (a) energy is not the only input used to produce steel and the other inputs have prices too and (b) furthermore, the energy represented by the ton of steel was put in at low cost and high efficiency in the furnace where the steel originated.

REPLY TO LIST

Importance of Energy Considerations

List makes the point that my analysis assumes only energy considerations are important. First, my reply to Holden concerning the value of time is relevant here. Second, for the record, I agree that there are many things a transit system might be called on to do other than to save energy. My paper is explicitly an energy analysis.

BART Energy Investment Versus Marginal Freeway Energy Investment

The comparison I made between the full energy investment in BART and the marginal energy investment needed to handle BART passengers via freeway expansion is the correct one for an energy analysis. If you are trying to make a decision to build a new, heavy rail system, you should balance the cost of building the whole rail system against the cost of accommodating the same number of people on highways—that is, the marginal cost of adding a rail system versus the marginal cost of adding new highway capacity.

List's suggested method of doing the calculation does not give the appropriate numbers. He says (a) BART could carry 21 000 passengers/h, (b) it would take 14 highway lanes to carry this many people, (c) BART is 114 km (71 miles) long, and, therefore, (d) 14 × 114 = 1596 lane•km of freeway (994 lane miles) needed to replace BART. There are two serious problems with this calculation:

1. It assumes that 100 percent of BART passengers come from automobiles. We now know that more than half come from buses; therefore, the 14-lane requirement is far too large.
2. There is no need for 14 lanes of freeway over the entire 114-km BART length. Traffic builds up slowly and only reaches 21 000 passengers/h on one small stretch of BART.

Alternatively, the traffic on the 1596 km of freeway that List says are needed can be compared with the load carried by BART. According to Kabel of the California Department of Transportation, one freeway lane in an urban area can be expected to carry about 18 000 people/d. (This figure is much lower than its capacity—48 000 automobiles/d; it is an expected-use figure for a corridor with enough traffic to justify a rail system.) Using the average BART trip length of 21 km (13 miles) and List's figure of 1.6 passengers/automobile gives 2.2 million person trips/d as the expected use of List's BART-equivalent highway system. But, in fact, BART itself carries only 0.13 million person trips/d. Therefore, the supposedly minimum necessary amount of highway would be used for 17 times as many trips as BART carries.

As an alternative way of looking at this, List says that it would take a 14-lane freeway parallel to BART to serve the people that BART serves. But before BART was built, no place along the route had 14 lanes of freeway. How did those commuters manage to get to work before BART? Furthermore, once BART was opened and somehow diverted 14 lanes of traffic from the existing highway system, why did not someone notice and write about the newly empty freeway space?

List's calculations of required terminal space and freeway width are subject to the same problems mentioned above.

Use of Unique Parameters

It is true that I used the best single estimate I could find for each parameter. However, I performed a tough sensitivity analysis on the final results, which is an alternative procedure for accomplishing List's goal here.

Other Issues

List states that I ignore the cost of a bridge across the Bay. My reply to Usowicz and Hawley, which follows, is relevant here. List then makes a number of points that I do not have the space to deal with here. Even if I accept his points, however, it makes a difference of only three to six percentage points in the energy analysis.

List ends with the statement that other studies dispute my results, and he cites two of them, neither of which is an analysis of BART. These non-BART studies cannot be analyzed here. But, if the weighing of authorities is relevant, I must point out that the recently completed analyses by the Congressional Budget Office (36) make an even stronger case than I do in my paper against energy saving by modern rail transit systems.

REPLY TO USOWICZ AND HAWLEY

First, Usowicz and Hawley also cite two studies that are not analyses of BART to show that other analysts contradict my findings. I deal with this in my reply to List and in my comments elsewhere on this type of analysis (37).

Energy-Conversion Factor

Usowicz and Hawley point out that my energy conversion ratio (in joules per dollar) is based on 1963 data, but my construction costs are in 1974 dollars. They advocate deflating all costs back to 1963 dollars by using a construction-cost deflator. This procedure would only be valid if the energy intensity of construction processes had remained constant between 1963 and 1974; that is, they are assuming that the energy used per real unit of output was constant. In fact, this assumption is contradicted by most of what has happened since the industrial revolution. One of the main reasons that output per unit of manpower has risen is that capital and energy are always being substituted for labor and thus increasing the ratio of energy to output. That is, inflation is working one way, and the change in technology is working the other. But which is dominant?

In 1963, average highway construction consumed 117 MJ/dollar (32.4 kW•h/dollar) of construction cost, and by 1967 this had risen to 124 MJ/dollar (34.3 kW•h/dollar), in current dollars, according to a detailed input-output analysis done by the University of Illinois (38). In other words, despite inflation of 18.8 percent over those 4 years, the energy per current dollar had gone up, not down.

For this period, the only one that has been analyzed by input-output techniques, the Usowicz and Hawley procedure would have understated energy costs by 25.1 percent. Furthermore, not only is their suggested procedure contradicted by the evidence on the increased energy intensity of technology, but it is also inconsistently applied in their own paper. They use the largest deflator, 1.89 ($1705/$902), for BART costs and a much smaller deflator, 1.45 ($1296/$876), for urban freeway costs. [All of these figures are taken from English (32).] That is, by using an inconsistent deflator, they overstate the relative construction-cost ratio. Finally, even if their procedure is used, it still gives an energy payback time of about 240 years: Both transit and highway costs have to be deflated, and so the 30:1 cost ratio still dominates the outcome. As to the proper 1963 energy-per-dollar conversion to use, I used the estimate of Healy and Dick (6), the only one based on actual BART experience.

In summary, then, (a) the only available evidence indicates that the suggested deflator procedure is inappropriate; (b) when Usowicz and Hawley apply it in their own work, they do so inconsistently in a way that greatly favors BART; and (c) even if the procedure is used, it does not alter the conclusion of my analysis.

Highway Costs

Usowicz and Hawley cite English's estimate (32) for the cost of a BART-equivalent highway system. But the English estimate used average daily modal split for the United States rather than the peak-hour BART modal split and average bus load factors rather than peak-hour load factors. English ends up needing 914 lane·km (568 lane miles) of highway to replace the 114-km (71-mile) BART system. In fact the replacement highway system would carry about ten times as many people as does BART. (My calculations in reply to List on relative energy investment for BART and for highway apply here.)

In Table 6, Usowicz and Hawley calculate the incremental size of a highway system to replace BART. Their major costs are for a bridge crossing and a tunnel. Both figures are far too high. According to the official BART impact report (3, p. xv), BART has reduced the total daily traffic over the Bay Bridge by 6000 to 10 000 vehicles. We know that 59 percent of BART patronage occurs during the 4 peak h, which means that BART reduced peak-hour traffic by 885 to 1475 vehicles/h. BART's net effect, in other words, was to reduce bridge needs by less than one lane, but in Table 6 Usowicz and Hawley assume it will take a 3.5-lane bridge to replace BART. This is too much by a factor of about four. (I am, of course, assuming a reversible lane such as the one on the Golden Gate Bridge.) Nor is the cost of a bridge as large as Usowicz and Hawley say. The best source of alternative data here is the projected cost of the Southern Crossing of the San Francisco Bay: $144 million (January 1972 dollars) for an eight-lane bridge, which is only $18 million/lane.

Concerning the question of tunnel replacement, patronage through the entire tunnel line is only 29 percent as much as trans-Bay patronage, which indicates that (at most) BART replaced 250 to 430 vehicle trips/h through the tunnel during peak hours. This is, of course, much less than the capacity of a single highway lane, and yet Usowicz and Hawley base their calculations on using a 2.3-lane highway tunnel to replace BART.

They then take up the need for parking structures and considerably overstate the cost and need for these (I have dealt with this issue in my reply to Tennyson).

In summary, under the most extreme possible assumptions, if I change my analysis to accommodate Usowicz and Hawley, it would make a difference of only three to seven percentage points in my calculation.

BART Modal Split

Usowicz and Hawley based all of their calculations on the assumption that 56.5 percent of current BART passengers were derived from automobiles. They seem to have assumed that all nonbus people must have come from automobiles. The former mode of current BART passengers was 44.6 percent from buses, only 38.7 percent from automobiles, and 1.6 percent from other modes; 15.2 percent had never made the trip before (3, pp. 71, 108, 110, 136, 137). The consequence of their assumption is that Usowicz and Hawley considerably overstate the number of highway lane kilometers necessary to replace BART and considerably underestimate the fuel efficiency of alternative modes.

Energy Conversion Efficiency

In their section on operating energy requirements, Usowicz and Hawley use an energy conversion constant of 2.07 J/J (7095 Btu/kW·h). This is, in fact, the average conversion efficiency in California. About 29 percent of its electricity comes from hydroelectric sources. But there have been no new hydroelectric sources for some years. The marginal megajoules in California, the megajoules that BART consumes, come from fossil fuels with an overall efficiency of only 29.1 percent (site plus transmission loss), which yields a conversion of $3.5\ J^2$ (11 753 Btu/kW·h). That is, the appropriate constant is 65 percent higher than the one used by Usowicz and Hawley, and BART energy consumption is increased accordingly.

Nonpropulsion Energy

In footnote c of Table 7, Usowicz and Hawley cite Hirst's 23 percent figure (7, p. 22) and then go on to calculate the cost as $0.019/km ($0.03/mile) for automobiles. But, in fact, 23 percent of propulsion costs is only $0.0059/km {0.23 [$0.158/L ($0.042/gal) ÷ 6.11 km/L (14.35 miles/gal)] = $0.0059}. I think the use of these nonpropulsion energy costs for automobiles is questionable in the first place (see my reply to Tennyson regarding station operating energy). In addition, a mathematical mistake has caused the estimates to be three times too big.

Finally, if Usowicz and Hawley want to assess such a cost against automobiles and buses, then they must assess it against BART also. In a recent calculation of BART energy consumption done by the Stanford Research Institute (SRI) for the Energy Research and Development Administration (39), the energy content of current nonsystem operating costs is estimated as 4.01 MJ/passenger·km (6120 Btu/passenger-mile). This is four times larger than the corresponding consumption figure for automobiles given in Table 7 by Usowicz and Hawley; BART energy consumption is nine times greater than the corrected figure for automobiles in Table 7. Furthermore, the SRI calculation of system operating energy is 3.97 MJ/passenger·km (6060 Btu/passenger-mile), which is almost twice as large as the Usowicz and Hawley figure. An alternative estimate of this figure is provided by Sherret of the BART evaluation team (35). He shows that the actual, measured energy consumption of BART last year was 3.53 MJ/passenger·km (5387 Btu/passenger-mile), a figure that is almost as large as the SRI estimate and is considerably larger than the 2.46 MJ/passenger·km (3754 Btu/passenger-mile) that is the basis of the Usowicz and Hawley calculations.

TRIP-CREATION EFFECTS

In an effort to simplify the original analysis, I made a deliberate decision to work at a somewhat abstract level; for example, I did not do a specific analysis of exactly where the highways that would replace BART would have to be located or of the detailed costs of highway widening (which accounts for most of the criticism). To compensate for this deliberate lack of detail I did a conservative analysis that always used the assumptions most favorable to BART; for example, I assumed that no trip-creation effects were caused by BART. I also performed a tough sensitivity analysis at the end of the paper to demonstrate that my overall conclusions were valid no matter what was assumed about the future. A "perfect" analysis might well demonstrate that BART can repay its construction energy in, say, 205.7 years instead of 535, but the conclusion would still remain the same. Furthermore, a perfect analysis is much more likely to show an infinite payback period, which I demonstrate below.

One of my major conservative assumptions about

BART was that it had not created any new trips. Such an assumption defies logic. By making distant suburbs more easily and comfortably accessible, BART obviously encourages people to live farther from their jobs in the city. Such an assumption also defies the empirical evidence: The average BART trip is 40 percent longer than had been anticipated by its planners, and the largest growth of patronage has been at the most distant stations (20).

Assuming that BART has created no new trips also contradicts the results of on-board surveys done shortly after each BART route was opened, which show an overall trip-creation effect of 15.2 percent (Table 1). According to the on-board surveys, 15.2 percent of the passengers indicated that they had never made the trip before. In my paper I ignored these people. If they are to be counted in explicitly, the simplest way to do so is to make a 15.2 percent reduction in the BART load factor in Table 2, which increases energy intensity to 3.67 MJ/passenger•km (1.65 kW•h/passenger-mile). Making the conservative assumption that all of the 1.6 percent who formerly used other modes should be added to those who formerly used automobiles, I calculate that the diversion mode split would be 47.5 percent automobile/52.5 percent bus. Given the energy intensities in Table 2, it is easy to calculate that, on their former combination of modes, these people had an average energy use of 3.59 MJ/passenger•km (1.62 kW•h/passenger-mile). Thus, they use more energy now than they did before. It can be seen, therefore, that moving even this one assumption closer to reality would show that BART can never repay its invested energy. The same thing would happen if I were to use more realistic figures for gasoline consumption.

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Energy-Crisis Travel Behavior and the Transportation Planning Process

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This study investigated the adjustment strategies adopted by individual households in response to situations of real and potential fuel shortages and higher prices. It also determined the attitudes of individual households toward regional policies to deal with existing or prospective transportation facilities and costs. The study used a mail questionnaire distributed in November 1975 to a random sampling of households in southeastern Wisconsin. The results suggest that the transportation planning process needs substantial revision only under conditions of excessive fuel-price increases or restricted fuel availability. Moderate and gradual increases in fuel prices are unlikely to bring about significant modifications in the travel patterns of households.

During the post-World War II era, American cities physically expanded as the total population increased, and individual households, encouraged by the relatively inexpensive price of automobiles and fuel, began to locate in single-family homes in suburban areas. The availability of the automobile for the typical American family also enabled families to locate at greater distances from employment locations (5, 6). At the same time, federal, state, county, and local governments made massive financial commitments to the construction and maintenance of highway facilities. The post-World War II era has witnessed the near completion of a 68 383-km (42 500-mile) Interstate highway system as well as thousands of miles of urban expressways and suburban roads. The much improved highway network allowed trucking firms to become major transporters of manufactured goods and large factories to locate on the urban periphery to take advantage of lower land costs and larger available tracts of land (1, 2, 4).

The net result of these interacting factors is what is commonly referred to as urban sprawl. In many American cities, location is not dependent on distance from major activities but on total commuting time from place to place by the family automobile. This increasing reliance on the automobile has meant a commensurate increase in gasoline consumption for urban travel. Present estimates indicate that urban automobile travel consumes about 40 percent of the total energy used in the transportation sector or 10 percent of the nation's energy consumption.

The 1973 Arab embargo on shipments of crude oil to the United States was the first in a series of events that