REFERENCES

1. J.C. Yu. National Trends in Transportation Energy Conservation Practices. Technical Report UTEC 83-036. University of Utah, Salt Lake City, April 1983.
2. P.A. Brown and G. Gibson. A Quantified Model for Facility Site Selection--Application to a Multiplant Location Problem. AIIE Transactions, March 1972.
3. J.C. Yu and L.M.G. Pang. Identification and Ranking of Transportation Cost Reductions through Energy Conservation Strategies. Final Report. UMTA, U.S. Department of Transportation, Jan. 1983.
4. H.A. Linstone and M. Turoff. The Delphi Method--Techniques and Applications. Addison-Wesley Publishing Co., Reading, Mass., 1975.
5. Kimely-Horn Associates, Inc. Transportation Energy Efficiency Manual. Florida Governor's Energy Office, Florida Department of Transportation, West Palm Beach, March 1981.
6. Energy Conservation Through Transportation Systems Management Actions. Kentucky Department of Transportation; Kimely-Horn and Associates, Raleigh, and John Hamburg and Associates, Chapel Hill, N.C., Feb. 1981.
7. New York State Department of Transportation. Energy Impacts of Transportation Systems Management Actions. Final Report, UMTA, U.S. Department of Transportation, Oct. 1981.
8. Barton-Aschman Associates, Inc. Energy Saving Traffic Operations Project Guide. U.S. Department of Transportation, May 1981.
9. Barton-Aschman Associates, Inc. ESTOP Guide Traffic Operations Benefits. Illinois Department of Transportation, Evanston, May 1981.
10. J. Raus. A Method of Estimating Fuel Consumption and Vehicle Emissions on Urban Arterials and Networks. FHWA-TS-81-210. FHWA, U.S. Department of Transportation, April 1981.
11. F.A. Wagner. Energy Impacts of Urban Transportation Improvements. Institute of Transportation Engineers, Washington, D.C., Aug. 1980.
12. Wasatch Front Regional Council. Citizen's Goals and Policies. Land Use and Water Committee, Bountiful, Utah, Oct. 1973.
13. Wasatch Front Regional Council. Goals and Policies for Planning Orderly Growth. Bountiful, Utah, March 1977.
14. JHK and Associates. Salt Lake City Traffic Signal System Feasibility Study. San Francisco, Calif. 1977.

Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Rail Rapid Transit and Energy: A Reexamination of Current Conventional Wisdom

DANIEL K. BOYLE

ABSTRACT

Rail rapid transit is often advocated as a major part of solutions to the energy problems of urban transportation. In the wake of Lave's energy analysis of the BART system in San Francisco and Oakland and the Congressional Budget Office study, in conventional wisdom the view is reflected that new rail transit systems often expend more energy than they save. Lave's analysis is reexamined in this study. Energy costs are calculated for six energy categories (propulsive, construction, maintenance, vehicle manufacture, calorific, and miscellaneous) for BART and a freeway alternative. The results indicate that BART uses 3.6 percent more energy annually than the freeway alternative when all energy costs are annualized. This is not a significant difference. Differences in key assumptions account for the difference in results. An alternate analysis using the assumptions of Usowicz and Hawley is discussed to show the sensitivity of an analysis of this type to the assumptions used. The notion that new rail transit construction wastes energy is not supported by the available evidence.

It is generally believed that new rail transit systems are energy wasters. Studies and articles by Healy and Dick (1), Lave (2), and the Congressional Budget Office (3) have found that the energy used to construct a rail transit system outweighs the marginal energy savings resulting from its operation. Despite occasional dissenting opinions [see the discussions following Lave's article (4-7), and Pushkarev and Zupan (8)], these findings are generally considered current thinking on the subject.

Construction of the Bay Area Rapid Transit (BART) system was examined as a case study for an UMTA-funded project concerning the relative importance of indirect energy considerations. The energy costs (in terms of energy consumed) associated with the construction and operation of the BART system are compared to those of a freeway alternative. The approach used by Lave is followed generally in this paper, and special attention is paid to the assumptions necessary for this type of analysis. Many of Lave's energy factors, which were taken from a previous study by Fels (9), are also used in this paper. Results obtained here are compared to Lave's findings; there is a considerable difference, explained primarily by the assumptions chosen. As an example of the sensitivity of an analysis of this type to the assumptions employed, results of an alternate analysis based on Usowicz and Hawley (7) are also presented.

CATEGORY OF ENERGY COSTS

Following the format of the larger report from which this paper is taken (10), energy consumed (energy costs) is analyzed by category of energy use. Propulsive or direct energy is the energy used to propel BART vehicles or automobiles. Indirect energy categories include construction, maintenance, vehicle manufacture, and calorific. Construction energy is the energy needed to operate construction machinery and perform related activities at the construction site; it also includes energy needed to transport construction materials to the site and the energy required to convert raw materials into a usable form. Maintenance energy is that needed to maintain roadways, guideways, and vehicles. The energy used in the manufacture of automobiles, buses, and BART vehicles is vehicle manufacturing energy. Finally, calorific energy is the potential energy of a material (such as asphalt) that may be used as a fuel, and it measures the heat energy released when the material is completely burned.

BART also requires energy to operate the stations, and the freeway alternative requires energy for the construction of additional parking garages to accommodate increased automobile traffic in the central business district (CBD). These energy costs fall outside the categories defined earlier, so they are placed in an "other energy costs" category.

Lave's analysis is presented in metric units. For simplicity, metric units are also used for the calculations in this paper, and the results for each energy type are converted to billions of British thermal units (BBtu).

Propulsive Energy

Lave uses 65.5 megajoules (MJ) per vehicle kilometer for the marginal operating power factor for BART; this is based on studies from 1975 and 1976. Because it was presumed that BART's energy efficiency would improve over time, more recent articles and data were consulted. In a 1979 article, Chomitz reported the traction energy of BART as 14.8 MJ per car kilometer (11), or 71 percent of total energy. Assuming a 30 percent efficiency in generating and transmitting electricity, the energy actually required is 14.8/0.3 or 49.3 MJ per vehicle kilometer. The most recent Section 15 report indicates an annual energy use of 171,430,000 kilowatt hours (kwh) for BART's fiscal year 1981 and 28 million car miles (12). This energy use reflects only vehicle propulsive energy; energy costs for station operations are addressed later. Converted to metric units, the result is

BART propulsive energy factor
= (171,430,000 kwh x 3.6 MJ/kwh/0.3 efficiency)/
28 million vehicle miles x 1.6 km/mile
= 45.9 MJ/vehicle km.

This latter figure is comparable to Chomitz' factor, so the annual propulsive energy cost for BART is the numerator of the previous equation, which expressed in BBtu's is 171,430,000 kwh x 3,413 Btu/kwh/0.3 efficiency = 1,950 BBtu.

To calculate the freeway propulsive energy costs, Lave first divided the energy used to produce a liter (L) of gasoline by the energy efficiency of an automobile. This number is adjusted for automobile occupancy to produce an MJ-per-passenger-kilometer factor for the automobile mode. The same was done for buses. BART's passenger kilometers were then divided between automobile and bus in proportion to the former mode used by BART passengers. Input data were derived from the Section 15 report (12), Environmental Protection Agency (EPA) over-the-road mileage (13), the Caltrans energy study (14), and Lave (2). Because transit efficiency was derived for fiscal year 1981, automobile efficiency should be an average of the 1980 and 1981 mile-per-gallon (mpg) figures, in according with the principle of giving equal consideration to both modes. The following data were used in the calculations:

- Energy in gasoline was 37.3 MJ/L (2), which includes energy lost in the refining process.
- Automobile fuel efficiency was (15.78 + 16.34)/2 mpg/2.35 mpg/km/L, which equals 6.8 km/L (2,13).
- BART passenger kilometers for fiscal year 1981 were 624,749,000 passenger miles x 1.6 km/mile, which equals 1 billion passenger km (12); 46.5 percent of these were attributed to former automobile users and 53.5 percent to former bus users (2).
- Automobile occupancy was 1.3 passengers per vehicle (2).
- Bus fuel efficiency was 0.234 gallon per mile or 0.550 L/km (14) (1/0.55, which equals 1.82 km/L).
- Energy in diesel fuel was estimated to be 41.2 MJ/L (2), which includes energy lost in the refining process.

The marginal operating power used for automobiles and buses was

- Automobile propulsive factor = 37.3 MJ/L/6.8 km/L = 5.49 MJ/vehicle km/1.3 passengers/vehicle = 4.22 MJ/passenger km and
- Bus propulsive factor = 41.2 MJ/L/1.82 km/L = 22.6 MJ/vehicle km/11.5 passengers/vehicle = 1.97 MJ/passenger km.

Therefore, propulsive energy costs can be calculated as follows:

- Automobile propulsive energy = (1 billion x 0.465) passenger km x 4.22 MJ/passenger km x 948 Btu/MJ = 1,860 BBtu,
- Bus propulsive energy = (1 billion x 0.535) passenger km x 1.97 MJ/passenger km x 948 Btu/MJ = 999 BBtu, and
- Total propulsive energy costs for the freeway alternative = 1,860 + 999 = 2,859 BBtu.

Construction Energy

Lave estimated that BART cost $2.119 billion in 1974 dollars to construct (not including the cost of purchasing vehicles), and his analysis uses a factor of 81.9 MJ per dollar, which was taken from Healy and Dick's input-output analysis of BART (1,2). As Usowicz and Hawley point out in their discussion (7), however, this 81.9 MJ per dollar figure is based on 1963 dollars. Lave argues that energy per current dollar tends to rise, but it appears spurious to apply a factor based on 1963 dollars to 1974 costs. The implicit price deflator developed by the Bureau of Labor Statistics (BLS) was used to estimate BART costs in 1963 dollars (15):

BART costs in 1963 dollars
= $2.119 billion x (71.67/114.92)
= $1.322 billion.

The construction energy for BART is then $1.322 billion x 81.9 MJ/dollar x 948 Btu/MJ = 102,642 BBtu.

Healy and Dick assume a useful service life of 50 years for BART (1). This may be low in light of experience in other American cities but was used in this analysis as a conservative assumption. Annualized construction energy costs then would be 2,053 BBtu.

For the freeway alternative, Lave calculated the lane kilometers of highway needed if BART were not available by estimating the number of peak-hour automobile and bus trips diverted to BART and calculating the additional highway capacity needed in the peak hours to accommodate these vehicles. Factors for dollar cost per lane kilometer and energy cost per dollar are used to determine total construction costs.

For fiscal year 1981, BART's ridership was 50,294,000 unlinked passenger trips (12). Assuming that 10 percent of these unlinked trips were transfers, there were 45,264,600 linked trips per year. Lave estimates that 59 percent of BART's patronage rides in the peak hours (2). Assuming 300 travel days per year, the following calculations can be made:

- BART daily trips = 45,264,600 annual trips/300 days/yr = 150,000 trips.
- Trip length = 1 billion passenger km/45,264,600 trips = 22.1 km/trip (13.8 miles/trip).
- Daily peak-period automobile trips diverted to BART = (150,000 x 0.59) peak-period BART trips x 0.465 automobile share/1.3 passengers/automobile = 31,650 trips.
- Highway needed for automobiles
  = (31,650 peak-period automobile trips x 22.1 km/trip)/4 hr/peak period x 2,000 automobiles/lane hour
  = 87.4 lane km.

For former bus trips, Lave uses a peak-load factor of 25 persons per bus, a diversion factor of 0.535 (i.e., 53.5 percent of BART riders were former bus users), and a capacity factor of 1,200 buses per lane hour. List points out that this capacity factor is too high; he cites the Highway Capacity Manual figure of 690 and the highest achieved value of 490 buses per lane hour (6). In this analysis 600 buses per lane hour was used. The bus calculations are

- Daily peak-period bus trips diverted to BART = (150,000 x 0.59) peak BART trips x 0.535 = 47,350 trips,
- Highway needed for buses
  = (47,350 peak bus person trips x 22.1 km/trip)/25 persons/bus x 4 hr/peak x 600 buses/lane hour
  = 17.4 lane km, and
- Total highway needed = 87.4 + 17.4 = 104.8 lane km (65.5 lane miles).

This is approximately 40 percent greater than Lave's estimate.

Lave uses a 1974 dollar cost that must be converted to 1963 dollars to match the energy-per-1963-dollar factor. The BLS implicit price deflator factors (15) used again here are

- Freeway costs per lane km in 1963 dollars = $579,000 x (71.67/114.92) = $361,000, and
- Construction energy costs for freeways = 104.8 lane km x $361,000/lane km x 118 MJ/dollar x 948 Btu/MJ = 4,232 BBtu.

A 25-year service life is assumed for roadways. Although at first glance this may appear to violate the principle of equal treatment of modes in cross-modal comparisons, it is an accurate reflection of reality because rapid rail structures last longer than roadways. Thus annualized construction energy costs for roadways would be 169 BBtu.

The preceding calculations measure the energy costs for constructing 65.5 lane miles of roadway in lieu of BART. They do not address the need for a trans-Bay bridge or the need for widening an existing bridge nor do they consider the necessity of tunneling under Berkeley Hills. A freeway alternative providing equivalent trans-Bay capacity would need a bridge and tunnel, and their construction energy costs should be included in this analysis.

Usowicz and Hawley (7) and Lave (2) argue over the width of the necessary bridge and tunnel. An assumption was made here that a two-lane bridge and a two-lane tunnel would be built as part of the freeway alternative. This is essentially the minimum feasible construction. It is unlikely, however, that such a narrow bridge would be built; a wider facility capable of handling future travel increases could be expected. Nonetheless, a two-lane width is used as a conservative assumption for both bridge and tunnel.

Usowicz and Hawley estimate the cost of a trans-Bay bridge as $27.04 million per lane in 1963 dollars. Berkeley Hills tunnel costs were derived from actual BART costs, which were $24.01 million (1963 dollars) for a double tube. Using the highway energy conversion ratio of 118 MJ/dollar and a service life of 30 years, calculations for bridge construction were

Bridge construction energy costs
= $27.04 million/lane x 2 lanes x 118 MJ/dollar x 948 Btu/MJ
= 6,050 BBtu/30 years, or
= 201.7 BBtu annually.

Because tunneling for a highway is similar to the BART construction work, the BART energy conversion ratio of 81.9 MJ/dollar was used and a service life of 50 years was assumed:

Tunnel construction energy costs
= $24.01 million/double tube x 81.9 MJ/dollar x 948 Btu/MJ
= 1,864 BBtu/50 years, or
= 37.3 BBtu annually.

The total construction energy cost for the freeway alternative is the sum of the roadway, bridge, and tunnel construction energy costs (i.e., 169 + 202 + 37 or 408 BBtu).

Maintenance Energy

Lave does not address maintenance energy. Chomitz reports that 5 percent of total electricity consumed by BART is used for maintenance, whereas propulsive energy accounts for 71 percent of total electricity (11). It was assumed that this 5 percent of total electricity used for maintenance includes guideway and vehicle maintenance. Using the propulsive energy costs of 1,950 BBtu calculated earlier, the calculation for BART annual maintenance energy was (1,950 BBtu/0.71) x 0.05, which equals 137 BBtu.

For the freeway alternative, vehicle and roadway maintenance must be considered. Factors obtained from the Caltrans study and Erlbaum (14,16) are 2,713 Btu per vehicle mile for automobile maintenance and 0.134 BBtu per lane mile for roadway maintenance (assuming an asphalt road). In addition, the Caltrans study cites a factor of 13,142 Btu per vehicle mile for bus maintenance (14). These are annual factors. In calculating construction energy, the number of daily peak-period automobile trips diverted to BART was derived. Here the annual number of automobile trips diverted to BART was needed. Assuming, as before, that 46.5 percent of BART riders formerly used an automobile and using factors of 150,000 BART trips per day, 1.3 persons per automobile, 300 weekday equivalents per year, and 13.8 miles per trip (22.1 km/trip), the following calculations can be made:

- Annual automobile miles diverted = (150,000 x 0.465/1.3) automobile trips/day x 300 days/yr x 13.8 miles/trip = 222,126,920 miles, then
- Freeway automobile maintenance energy = 222,126,920 vehicle miles x 2,713 Btu/vehicle mile = 603 BBtu.

The number of bus trips diverted can be calculated considering that 53.5 percent of BART riders formerly took a bus and using an overall load factor of 11.5 persons per bus. Calculation of bus miles diverted by BART annually is then:

- Annual bus miles diverted = (150,000 x 0.534) person trips/day/11.5 persons/bus x 300 days/yr x 13.8 miles/trip = 28,890,000 miles; then
- Freeway bus maintenance energy = 28,890,000 x 13,142 Btu/vehicle mile = 380 BBtu, and
- Total freeway vehicle maintenance energy = 603 + 380 = 983 BBtu.

There are 65.5 lane miles of additional roadway required under the freeway alternative; therefore,

- Freeway road maintenance energy = 65.5 lane miles x 0.134 BBtu/lane mile = 9 BBtu, and
- Total freeway maintenance energy = 983 + 9 = 992 BBtu.

Vehicle Manufacture Energy

Lave calculated the vehicle construction energy for the automobile, BART, and diesel bus in megajoules per vehicle kilometer. Instead of Lave's present and future automobile categories, a single calculation is done for the automobile assuming an average weight of 3,000 lb (1361 kg) and using a Caltrans-derived energy factor of 91.3 MJ/kg (14).

Lave assumed service lives that are much too high. Instead of his 180 000-km life for an automobile, this paper uses 160 000 km (100,000 miles), a value obtained from Caltrans (14). Lave cites 1 600 000 km as the service life of a bus; this is three to four times too high. Caltrans gives a value of 480 000 km (300,000 miles) for a standard 53-seat bus (14), and experience in New York State supports that number. In this paper the service life of a transit bus is 300,000 miles. Lave's estimate of the service life of a BART vehicle (4 480 000 km or 3,000,000 miles) is also unreasonable. Experience in New York State indicates that an appropriate service life for a rapid transit vehicle is 1,250,000 miles or 2 000 000 km. Although New York's experience is not always transferable to the BART system, this service life appears more appropriate and was used in this paper. Lave's values for manufacture energy match Caltrans figures for a standard 53-seat bus and a commuter rail car (no figures are available for a rapid transit rail car, which may be less energy intensive to build).

The factors for vehicle manufacture energy were

- BART: 4 430 000 MJ/2 000 000-km service life = 2.215 MJ/vehicle km,
- Automobile: 1361 kg x 91.3 MJ/kg/160 000-km service life = 0.777 MJ/vehicle km, and
- Bus: 1 080 000 MJ/480 000-km service life = 2.250 MJ/vehicle km.

In fiscal year 1981 BART provided 28 million vehicle miles or 44 800 000 vehicle kilometers of service. As calculated previously, BART replaced 222,126,920 automobile miles and 28,890,000 bus miles. The calculations are straightforward:

- BART vehicle manufacture energy = 44 800 000 vehicle km x 2.215 MJ/vehicle km x 948 Btu/MJ = 94 BBtu,
- Freeway automobile manufacture energy = 222,126,920 vehicle miles x 1.6 km/mile x 0.777 MJ/vehicle km x 948 Btu/MJ = 262 BBtu,
- Freeway bus manufacture energy = 28,890,000 vehicle miles x 1.6 km/mile x 2.25 MJ/vehicle km x 948 Btu/MJ = 99 BBtu, and
- Freeway total manufacture energy = 262 + 99 = 361 BBtu.

Calorific Energy

The freeway alternative involves an additional 65.5 lane miles of asphalt pavement. The calorific energy contained in this asphalt must be calculated. Assume that the lanes are 12-ft wide and the pavement is 7-in. thick. At a compacted density of 145 lb/cu ft and a 5 percent asphalt content, the amount of asphalt needed for the freeway alternative is

Tons of asphalt = 5,280 ft/mile x 65.5 lane miles x 12 ft/lane x 7/12 ft depth x (145/2,000) tons per cu ft x 0.05 asphalt content = 8,776 tons.

Halstead provides a calorific energy factor of 37,100,000 Btu per ton of asphalt (17). Assuming a 25-year pavement life, freeway calorific energy per year would equal 8,776 tons x 37,100,000 Btu/ton/25 years, or 13 BBtu. No calorific energy is associated with the transit alternative.

Other Energy

The energy cost for BART's station operations is addressed here. A parallel energy cost for the freeway alternative is also addressed (i.e., the energy cost of parking garages). Both transit stations and parking garages are necessary in using a particular mode, but their associated energy costs have not yet been taken into account. Energy cost for station operations is treated similar to maintenance energy. Chomitz reports that 24 percent of the total electricity used is for station operations (11). Propulsive energy (1,950 BBtu) makes up 71 percent of total energy; therefore, BART station operating energy would equal (1,950 BBtu/0.71) x 0.24, or 659 BBtu.

Parking garage costs are addressed in several different ways by Lave and the various discussants (2,4,7). Usowicz and Hawley imply a cost per space of $2,265 in 1963 dollars and suggest a facility construction energy factor of 65,400 Btu/dollar. For the sake of argument, Lave accepts Tennyson's approach of providing a space for each commuter automobile trip and one space for every two off-peak automobile trips (2,4). Assume that two spaces are needed for every three automobile round trips, or one space for every three trips, and assume a 30-year life, which is typical for a major structure (14,18). Then calculations would be

- Automobile trips diverted = 150,000 x 0.465/1.3 = 53,654 trips,
- Spaces needed = 53,654/3 = 17,885 spaces, and
- Freeway garage construction energy = 17,885 spaces x $2,265/space x 65,400 Btu/dollar/30 years = 88 BBtu.

It is not clear whether station maintenance energy costs are included in any energy-per-dollar figure considered thus far, so garage maintenance will not be considered.

It might be argued that the energy costs for parking lots at BART stations should also be considered, because energy costs for parking are included under the freeway alternative. Lots at the stations do not involve a structure as a CBD parking garage does. Cohen provides a factor of 1.74 gal (217,500 Btu) per space (18). BART reports 20,200 spaces at 23 stations (19). Assuming a 25-year service life, BART lot construction energy = 217,500 Btu/space x 20,200 spaces/25 years, or 0.2 BBtu. This is insignificant. Because garage maintenance was not addressed, lot maintenance energy costs were not considered.

Use of the car left home by those switching modes might also be considered in this category. A study by Gross revealed that of the energy saved by shifting from the automobile to transit 40 percent is spent by household members using the car left home (20). However, in accordance with the first principle concerning equal treatment for all alternatives, consideration should also be given to operating and vehicle manufacturing energy saved by reduced automobile ownership levels brought about by transit service. Pushkarev and Zupan argue that this energy saving is significant (8) but methods to calculate it are not well developed. Thus, neither energy consumed by the car left home nor energy savings brought about by reduced automobile ownership are considered here.

TOTAL ENERGY COSTS

Component energy costs are given in Table 1. Total annual energy costs for BART are 4,893 BBtu and for the freeway alternative 4,721 BBtu. For BART there are significant propulsive, construction, and station operating (other) energy costs, whereas propulsive and maintenance energy costs account for the bulk of the freeway energy requirements. The difference in construction energy costs is the major factor in determining relative total energy costs for the alternatives. Overall BART energy costs are 3.6 percent higher than the freeway energy costs. Given the large number of assumptions employed, a difference of less than 10 percent between alternatives cannot be considered significant.

Lave expressed his results in number of years of operation that would be required for BART to pay back the initial energy investment. If these construction energy costs were converted to an annual basis (assuming a 50-year life for BART and a 25-year life for roadways) and petajoules were converted to BBtu's, then Lave's calculations would result in 5,385 BBtu for BART, 2,563 BBtu for the freeway alternative with a 14-mpg average for the fleet, and 1,710 BBtu for the freeway alternative with a 27.5-mpg average for the fleet. On the other hand, using Lave's approach, the analysis in this paper results in a payback period of 63 years as follows:

- BART total construction energy costs = 102,642 BBtu,
- Freeway total construction energy costs = 12,146 BBtu for construction + 2,649 BBtu for the garage, or 14,795 BBtu,
- Annual operating energy costs (including everything but construction and parking garage costs) for BART = 2,840 BBtu/yr and for the freeway option = 4,225 BBtu/yr.

The years required to recover the initial expenditure, then, are (102,642 - 14,795) BBtu initial expenditure/(4,225 - 2,840) BBtu/yr savings, or 63 yr.

Given the different service lives involved in the various components of the freeway alternative, nearly all of which are less than BART's assumed service life, this calculated figure for the energy payback period should be viewed with caution. Before the BART system reaches the end of its service life, the roadway, bridge, and parking garage will all face extensive reconstruction; the payback approach does not reflect this. A clearer picture of relative energy costs can be obtained by using annualized construction energy costs, as has been done here.

Usowicz and Hawley used several different assumptions in their analysis, described briefly in their discussion of Lave's original article (7). A summary is given in Table 2 of the differences in results obtained by this analysis, by Lave, and by Usowicz and Hawley. Obviously conclusions regarding relative energy efficiencies can be affected significantly by changing basic assumptions. For those interested in pursuing the matter further, the differences in assumptions and energy factors among the three studies are summarized in Table 3.

TABLE 1 Energy Costs: BART Versus Freeway (annual BBtu's)

Energy Category	BART	Freeway
Direct		
Propulsive	1,950	2,859
Indirect		
Construction operating	2,053	408
Construction hauling	-[a]	-[a]
Maintenance	137	992
Vehicle manufacture	94	361
Processing	-[a]	-[a]
Calorific	-	13
Other	659	88
Subtotal indirect	2,943	1,862
Total	4,893	4,721

[a]Included in construction operating energy.

TABLE 2 Total Energy Costs: BART Versus Freeway, Using Three Different Methods (annual BBtu's)

	BART	Freeway
Boyle	4,893	4,721
Lave	5,385	2,563[a] 1,710[b]
Usowicz and Hawley	2,714	4,735

[a]Current automobile.
[b]Future automobile.

TABLE 3 Assumptions and Factors Used in the Three Analyses

	Boyle	Lave	Usowicz and Hawley
BART propulsive energy	(Actual kilowatt hours from Section 15 data		
MJ/passenger km	adjusted for power plant efficiency)	65.5	1.488
MJ/vehicle km		3.06	31.8
Btu/vehicle mile		99,350	48,234
Operating energy factor (includes energy lost in refining)			
Automobile			
MJ/passenger km	4.22	4.82[a] 2.45[b]	4.22
Btu/passenger mile	6,401	7,311[a] 3,716[b]	6,401
Bus			
MJ/passenger km	1.84	1.84	1.532
Btu/passenger mile	2,791	2,791	2,324
Bus efficiency			
km/liter	1.94	1.94	2.3
mpg diesel	4.5	4.5	5.4
Prior mode			
Automobile (%)	46.5	46.5	56.5
Bus (%)	53.5	54.5	43.5
BART cost ($1963, billions)	1.322	2.119[c]	0.902
BART construction energy factor			
MJ/dollar	81.9	81.9	45.5
Btu/dollar	77,641	77,641	43,134
BART trips			
Daily	150,000	130,000	150,000
Peak hour	88,500[d]	76,700[d]	29,250
Roadway needed in lieu of BART			
Lane km	104.8	74.7	198.4
Lane miles	65.5	46.7	124
Freeway cost ($1963)			
Per lane km	361,000	579,000	5441,130[e] 178,432[f]
Per lane mile	577,600	926,400	370,133 (231,333)[g]
Freeway construction energy factor			
MJ/dollar	118	118	118.4
Btu/dollar	111,864	111,864	112,243
Costs of bridge and tunnel considered?	Yes	No	Yes
Maintenance energy factor			
BART			
MJ/passenger km	(5% of total energy)[h]	–[i]	0.511
Btu/passenger mile			8,133
Automobile			
MJ/passenger km		–[i]	1.071
Btu/vehicle mile	2,713		2,112
Bus			
MJ/passenger km		–[i]	0.564
Btu/vehicle mile	13,142		9,838
Annual travel diverted			
Automobile			
Million passenger km		379	565
Million vehicle miles	222.1	182.2	271.6
Bus			
Million passenger km		436	435
Million vehicle miles	28.9	23.7	23.6
Passenger per vehicle			
Bus			
Peak period	25	25	11.5
Overall	11.5	11.5	
BART	22.3[j]	21.4	21.4
Automobile	1.3	1.3	1.3
Manufacture factor			
BART vehicle			
MJ/vehicle km	2.215	0.923	0.043
Btu/vehicle mile	3,360	1,400	1,400
Automobile			
MJ/vehicle km	0.777	0.772[a] 0.420[b]	0.654
Btu/vehicle mile	1,178	1,171[a] 637[b]	922[k]
Automobile weight			
kg	1361	1633[l]	1633[l]
lb	3,000	907[m]	907[m]
Bus			
MJ/vehicle km	2.250	0.675	0.058
Btu/vehicle mile	3,413	1,024	1,024
Service life			
BART vehicle			
km	2 000 000	4 800 000	4 800 000
miles	1,250,000	3,000,000	3,000,000
Automobile			
km	160 000	180 000	180 000
miles	100,0001	112,500	112,500
Bus			
km	480 000	1 600 000	1 600 000
miles	300,000	1,000,000	1,000,000

TABLE 3 continued

	Boyle	Lave	Usowicz and Hawley
Asphalt in freeway (tons)	8,776	–[i]	–[i]
Calorific energy of asphalt (million Btu/ton)	37.1	–[i]	–[i]
Station operating energy (% of total energy)	24[h]	(Included in operating energy)	(included in maintenance energy)
Parking spaces needed in CBD	17,885	–[i]	17,550
Cost per space ($1963)	2,265	–[i]	2,265
Parking garage energy factor ($1963)			
MJ/dollar		–[i]	69
Btu/dollar	65,400		65,400
Highway capacity (buses/lane hour)	600	1,200	1,250

[a]Current.
[b]Future.
[c]1974 dollars not corrected to 1963.
[d]In 4 peak hours.
[e]Cost for 28.7 urban lane km.
[f]Cost for 169.7 suburban lane km.
[g]Weighted cost.
[h]Propulsive energy is 71 percent of total.
[i]Not addressed.
[j]Derived from section 15.
[k]Based on 1361 kg weight.
[l]Per 3,600 lb—current.
[m]Per 2,000 lb—future.

ENERGY IMPLICATIONS OF RAIL TRANSIT CONSTRUCTION

The wide disparity in overall energy costs calculated by different methods needs to be emphasized. Lave indicates that a rail transit system such as BART is much more energy intensive than a comparable freeway alternative. The results of this paper indicate that both alternatives are roughly equal in terms of annual energy costs. Usowicz and Hawley show BART to be much more energy efficient than the freeway alternative. The differences in results may be found in the assumptions employed, as indicated in Table 3. In almost every case energy factors and assumptions used by Usowicz and Hawley are more favorable to BART than those used in this analysis. On the other hand, Lave's assumptions tend to be less favorable to BART. Although many differences between this paper and Lave's analysis are revealed in Table 3, the key differences can be summarized as follows:

- Lave incorrectly applies an energy factor based on 1963 dollars to a cost expressed in 1974 dollars; the analysis in this paper converts all costs to 1963 dollars. Lave's defense of this facet of his analysis is not convincing.
- Actual fiscal year 1981 BART ridership was taken from the UMTA Section 15 report and was somewhat higher than that used by Lave.
- Lave does not take into account vehicle maintenance energy, nor does he consider the energy costs of additional parking structures required in the CBD under the freeway alternative.
- Lave overestimates the service life of vehicles, which affects the calculations of vehicle manufacture energy.
- The highway capacity figure of 600 buses per lane hour is based on observed traffic flows; Lave's figure is twice as high.

In addition to these differences, there is a major difference in the format used to present the results. Lave calculates the payback period, which may not be appropriate in comparing alternatives with different service lives. This analysis uses annualized energy costs, which take service lives into account, and thus provides a clearer idea of relative energy costs.

The results of this analysis do not support the belief that construction of new rail transit systems wastes energy. Using reasonable assumptions and Lave's approach, it has been shown here that the annualized energy cost of BART is only 3.6 percent higher than that of a freeway alternative. Others may fault the assumptions used here or argue that further energy considerations are needed. Trips induced by BART have not been considered here; use of the car left at home and the effects of rail transit on automobile ownership also have been ignored.

Excluding induced trips from the analysis was also a simplifying assumption made by Lave, who pointed out the difficulty in separating trips induced by normal mobility of people (who did not formerly make "this trip," but did make a similar trip from their previous location) from trips induced by BART (2). In Pushkarev and Zupan's analysis, reduction in the level of automobile ownership related to the availability of rail transit strongly affects their findings concerning the energy efficiency of rail transit (8). It is difficult to gauge the extent to which automobile ownership has been reduced; Pushkarev and Zupan use data from New York City and Long Island, which may not be transferable to San Francisco or to other areas. To balance this omission, use of the car left at home is also not considered.

Pushkarev and Zupan also claim that generalizations concerning the energy efficiency of rail transit should not be based on BART, because BART's reliance on complex technology has resulted in unusually high energy costs (8). Although it is difficult at present to evaluate this claim, new rail transit construction in Washington, D.C., Atlanta, Baltimore, and other cities will broaden the existing data base and provide a stronger foundation for energy analysis of rail transit systems.

The reputation of rail rapid transit has been damaged by its adherents who have overstated its contribution to energy conservation. The findings here agree with those of the Congressional Budget Office report and a previous New York State Department of Transportation study of transit's role in an energy-saving effort (3,21). A rail transit system is not the answer to an energy crisis; however, this is not the same as saying that construction of a rail transit system wastes energy. In reaction to the failure of transit to meet the extravagant claims made for it, conventional wisdom has swung too far in the opposite direction. The Congressional Budget Office report stated that slight variations in assumptions could lead to a conclusion that the energy impact of rapid rail transit system does not have clear-cut advantages or disadvantages in terms of energy consumption. Further studies on other new systems are needed; meanwhile, the idea that new rail transit construction wastes energy should be discarded on the grounds of insufficient evidence.

ACKNOWLEDGMENT

The paper is part of a larger report funded by a grant from the Urban Mass Transportation Administration entitled Transportation Energy Planning: Procedural Guidance. The author thanks David T. Hartgen of NYSDOT and Richard Steinmann of UMTA for valuable suggestions offered after a review of an earlier draft. The author also thanks Charron Many, Tedi Toca, and Tammy Zitzmann for preparing this paper.

REFERENCES

1. T.J. Healy and D.J. Dick. Total Energy Requirements of the Bay Area Rapid Transit System. In Transportation Research Record 552, TRB, National Research Council, Washington, D.C., 1975, pp. 40-56.
2. C.A. Lave. Rail Rapid Transit and Energy: The Adverse Effects. In Transportation Research Record 648, TRB, National Research Council, Washington, D.C., 1977, pp. 14-36. See also Author's Closure.
3. D.J. Kulash, R.P. Mudge, D. Prywes. Urban Transportation and Energy: The Potential Savings of Different Modes. Congressional Budget Office, Washington, D.C., Dec. 1977.
4. E.L. Tennyson. Discussion Paper. In Transportation Research Record 648, TRB, National Research Council, Washington, D.C., 1977, pp. 18-20.
5. W.H.T. Holden. Discussion Paper. In Transportation Research Record 648, TRB, National Research Council, Washington, D.C., 1977, pp. 20-22.
6. G.F. List. Discussion Paper. In Transportation Research Record 648, TRB, National Research Council, Washington, D.C., 1977, pp. 22-23.
7. T.W. Usowicz and M.M. Hawley. Discussion paper. In Transportation Research Record 648, TRB, National Research Council, Washington, D.C., 1977, pp. 23-26.
8. B. Pushkarev and J. Zupan. Urban Rail in America: An Exploration of Criteria for Fixed-Guideway Transit. Regional Plan Association; UMTA, U.S. Department of Transportation, Nov. 1980.
9. M.F. Fels. Comparative Energy Costs of Urban Transportation Systems. Transportation Research, Vol. 9, No. 5, Oct. 1975.
10. D.K. Boyle. Indirect Energy Considerations in Transportation Projects. Planning Division, New York State Department of Transportation, Albany, 1983.
11. K. Chomitz. Survey and Analysis of Energy Intensity Estimates for Urban Transportation Modes. In Transportation Research Record 726, TRB, National Research Council, Washington, D.C., 1979, pp. 8-14.
12. M. Jacobs. National Urban Mass Transportation Statistics: 1981 Section 15 Report. UMTA, U.S. Department of Transportation, Nov. 1982.
13. Energy and Environmental Analysis. In The Highway Fuel Consumption Model: Ninth Quarterly Report. Energy and Environmental Analysis; U.S. Department of Energy, Feb. 1983.
14. J.A. Apostolos, W.R. Shoemaker, and E.C. Shirley. Energy and Transportation Systems. California Department of Transportation, Sacramento, Dec. 1978.
15. Summary National Income and Product Series, Annually 1925-1980 and Quarterly, 1947-1981. Bureau of Economic Analysis, U.S. Department of Commerce, June 1981, Table B.
16. N.S. Erlbaum. Procedures for Estimating Energy Consumption in Transportation Projects. Preliminary Research Report 174. Planning Research Unit, New York State Department of Transportation, Albany, June 1980.
17. W.R. Halstead. Energy Involved in Construction Materials and Procedures. NCHRP Synthesis of Highway Practice 85, TRB, National Research Council, Washington, D.C., 1981.
18. G.S. Cohen. Transportation System Management Actions: A Study of the Energy Costs. In Transportation Research Record 764, TRB, National Research Council, Washington, D.C., 1980, pp. 103-108.
19. Metropolitan Transportation Commission. BART in the San Francisco Bay Area--The Final Report of the BART Impact Program. U.S. Department of Transportation and U.S. Department of Housing and Urban Development, June 1979.
20. J.M. Gross. The Car Left Home. In Preliminary Research Report 168, Planning Research Unit, New York State Department of Transportation, Albany, Aug. 1979.
21. D.K. Boyle. Transit Use and Energy Crises: Experience and Possibilities. In Transportation Research Record 870, TRB, National Research Council, Washington, D.C., 1982, pp. 16-21.

Sole responsibility for any errors or omissions rests with the author, and the views expressed in this paper do not necessarily reflect those of USDOT, UMTA, or NYSDOT.

Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.