Potential of the Dual-Mode Transit System to Conserve Energy

John G. Lieb, Mitre Corporation

The energy efficiency of the dual-mode transit system is compared with that of the following urban passenger transportation vehicles: motorcycle, light truck, passenger automobile, school bus, commercial bus, trolley bus, streetcar, and rail rapid transit vehicle. These modes account for 33 percent of the total energy consumed by the transportation sector in the United States in 1971 and 8 percent of the total energy consumed by the entire country. The automobile consumes 95 percent of urban transportation energy. The transit bus and rail rapid transit vehicles are from 2.4 to 2.6 times as efficient as the standard-sized passenger automobile, but, because these modes consume only 1.5 percent of the total energy, they have little effect on the energy situation. The estimate of dual-mode transit efficiency is based on simplified dynamic equations and an assumed vehicle duty cycle. Dual-mode transit is expected to be from 10 to 20 percent less efficient than the transit bus and rail rapid transit vehicle and, by providing a high level of service, has the potential of attracting significant numbers of people who are currently using the energy-intensive automobile. To achieve this promise, a dual-mode system must be designed with careful attention to energy-related design details (particularly vehicle weight) and must provide the type of service necessary to produce high average vehicle load factors.

The role of transportation in future national energy conservation strategies is critical. Transportation consumes 25 percent of the total raw energy used in the United States (Figure 1). Of the energy used for transportation, 96 percent is dependent on petroleum; transportation consumes 50 percent of all U.S. petroleum each year (1). This paper focuses on one part of this critical energy sector, urban ground passenger transportation, and establishes the potential for the dual-mode transit system (DMTS) to conserve energy.

As shown in Figure 1, urban ground passenger transportation consumes 33 percent of the total transportation energy and 8 percent of the total U.S. energy. This energy is distributed among the various urban ground passenger transportation modes (Figure 2). The automobile dominates the vehicle mileage and energy consumption statistics. Only the rail rapid, trolley bus, and streetcar modes are electrified. Since the other modes use petroleum-based fuels almost exclusively, 99.5 percent of the energy is derived from petroleum as the primary energy source.

Therefore, further efforts to conserve urban ground passenger transportation energy must concentrate on the automobile. Efforts to improve the efficiency of the other modes (e.g., mass transit, which is already 2 to 3 times more efficient than the automobile) will have little overall effect on the total energy situation unless many automobile users are attracted to them. It is this potential for attracting many automobile users that is fundamental to the future role of DMTS in energy conservation.

EXISTING MODES

The base-line year of this study is 1971. Of all available urban ground transportation modes, only the powered and ground-based modes, whose fundamental purpose is to transport people, are considered. These include

1. Passenger automobiles, including taxis and rental, fleet, and private automobiles;
2. Light trucks, including pickups and vans;
3. Motorcycles;
4. Commercial buses, including transit buses, special tour buses, and intercity buses traveling in urban areas;
5. Rail rapid transit vehicles;
6. School buses, excluding transit buses used for school purposes;
7. Trolley buses; and
8. Streetcars.

Bicycles, airplanes, and boats are not included. Commuter rail is not considered because source data on the energy consumption of the equipment are not readily available.

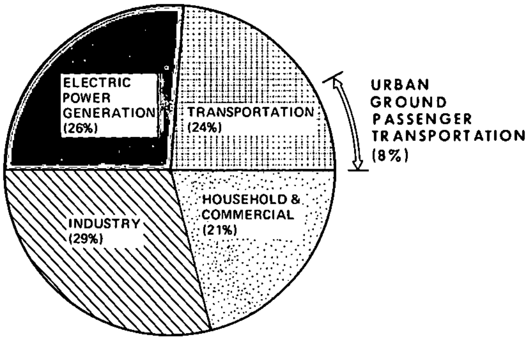
The energy consumed by these urban ground passenger transportation modes is generally characterized in Figures 1 and 2. The detailed data used to generate these figures are given in Table 1.

DUAL-MODE TRANSIT SYSTEM

DMTS can be viewed as a transit bus system with partially automated operations. The DMTS vehicle is a 20-passenger transit bus that operates under automatic control on the guideway and manual control off the guideway. The guideway, or exclusive automated busway, is located in major corridors and in the central business district, where movement of vehicles on the existing street network is normally hindered by peak-period congestion. The busway network is expected to be sparse, similar in density to the Bay Area Rapid Transit system.

The off-guideway collection and distribution operations are performed under manual control on the existing street network. This characteristic, combined with the potential for use of the demand-responsive mode of operation (afforded by the use of small buses), gives DMTS a unique capability to provide areawide, no-transfer, door-to-door service on a transit system that has automated operations.

Figure 1. U.S. energy consumption in 1971.



Several propulsion concepts are being considered for DMTS. In the electric concept, electric energy from a battery is used during the off-guideway trip and electric power from a wayside rail is used on the guideway. The internal combustion engine (ICE) concept uses the ICE for propulsion power both on and off the guideway, and the hybrid concept will most likely use electric power on the guideway and ICE power off the guideway.

The data presented here are based on the electric concept. The consumption rate for a diesel-powered DMTS is not expected to differ significantly from the electric.

ENERGY MEASURES

Only the energy directly consumed by the vehicles of each transportation mode is considered. Direct energy is required by the propulsion system and accessories, such as air conditioning and lighting. This energy is

Figure 2. Mileage, energy sources, and consumption of urban passenger transportation vehicles in 1971.

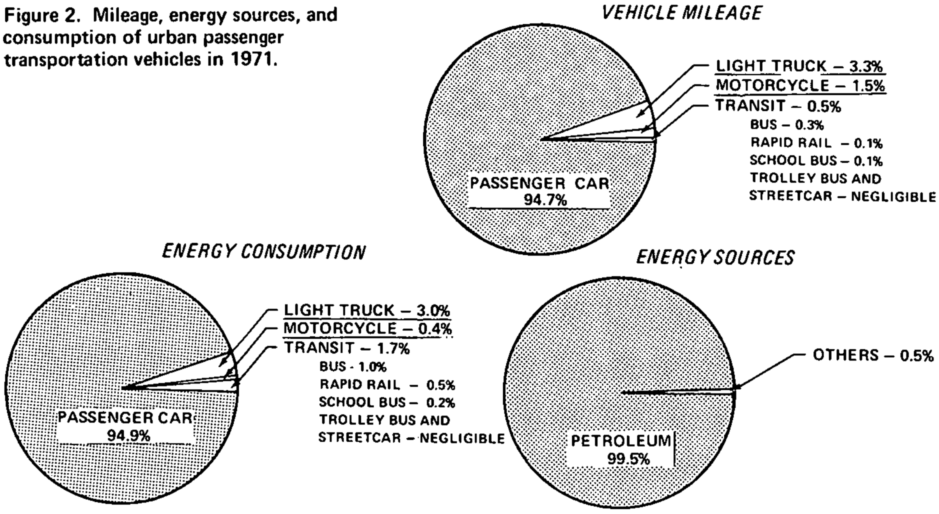


Table 1. Energy consumption of urban passenger transportation vehicles in 1971.

Vehicle	Vehicle-Miles (millions) Amount	Vehicle-Miles (millions) Percent	Energy Source	Fuel Consumption (millions of gal) Amount	Fuel Consumption (millions of gal) Percent	Electricity Consumption (millions of kw·h) Amount	Electricity Consumption (millions of kw·h) Percent	Total Energy Consumption (trillions of Btu) Amount	Total Energy Consumption (trillions of Btu) Percent	Petroleum-Based Energy Consumption (trillions of Btu) Amount	Petroleum-Based Energy Consumption (trillions of Btu) Percent
Passenger automobile	516 506.0[a]	94.66	Gasoline	42 686.0[b]	95.45	–		4972.9[c]	94.94	4972.9	96.37
Light truck	18 179.0[a]	3.33	Gasoline	1 377.0[d]	3.08	–		155.8[c]	2.97	155.8	2.99
Motorcycle	8 279.0[e]	1.52	Gasoline	186.0[f]	0.42	–		21.7[c]	0.41	21.7	0.42
Commercial bus	1 767.0[a]	0.32	Diesel oil	401.6[g]	0.90	–		52.1[h]	0.10	52.1	1.00
Rail rapid vehicle	407.4[i]	0.08	Electricity	–	–	2262[a]	88.50	24.5[j]	0.47	3.4[j]	0.07
Streetcar	32.7[i]	0.01	Electricity	–	–	153	5.99	1.7[j]	0.03	0.2[k]	0.004
Trolley bus	30.8[i]	0.01	Electricity	–	–	141	5.52	1.5[j]	0.03	0.2[k]	0.004
School bus	429.0	0.08	Gasoline	69.2[l]	0.16	–		8.1[c]	0.15	8.1[k]	0.16
Total	545 630.9	100.00	–	44 719.8	100.00	2556	100.00	5238.2	100.00	5241.4	100.00

Note:\1 Btu = 1055 J; 1 kW·h = 3600 kJ; 1 gal = 3.8 dm^3; 1 lb = 0.45 kg; and 1 mile = 1.6 km.

[a] From reference 7.

[b] Data in reference 9 indicate that the average automobile in the U.S. weighs 4000 lb. Reference 10 provides the distribution by age of automobiles in use in 1971, reference 3 presents EPA fuel consumption data for the 4000-lb weight class for each year. Average fuel rate is 12.1 mpg.

[c] From data in reference 12, the energy content of gasoline is calculated to be 116 500 Btu/gal.

[d] Data in references 9 and 11 indicate that the average light truck weighs 3500 lb. It was assumed that these light trucks exhibit the same fuel consumption rate as a 3500-lb automobile and the same age characteristics. EPA data from reference 3 were used to estimate the fuel rate of 13.6 mpg.

[e] Derived from reference 7 assuming the split between urban and rural mileage is the same as that of the passenger automobile.

[f] Reference 7 states that the motorcycle averages 50 mpg. The passenger automobile urban rate is 11 percent lower than the total average given in reference 7. The motorcycle urban rate was also assumed to be 11 percent less or 44.5 mpg.

[g] Data in references 7 and 8 show that 78 percent of the urban commercial bus mileage is generated by transit buses. The fuel rate of transit buses was used for the total commercial bus population. The transit bus fuel rate is 4.4 mpg as determined from data in reference 2.

[h] From data in reference 12, the energy content of No. 1 diesel oil was calculated to be 129 800 Btu/gal.

[i] From reference 8.

[j] Assumed an electric power plant efficiency of 35 percent and electricity transmission and transformation efficiency of 90 percent.

[k] Reference 13 shows that 14 percent of fuel used to generate electricity is petroleum based.

[l] From reference 7, with 11 percent reduction as described in footnote f. Fuel rate is 6.2 mpg.

only part of the total energy requirement. For instance, Hirst estimates that gasoline consumption by the power plant accounts for 61 percent of the total automobile energy consumption, which includes items such as the energy of automobile manufacturing and fuel refining (2). According to the New York City Transit Authority, 19 percent of the electrical energy purchased for its rail rapid system in fiscal year 1971 was used for purposes other than vehicle propulsion and accessories (3).

To compare the energy consumption rate and efficiency of various transportation modes requires that quantitative measures be defined and evaluated. Five measures appear to be useful. Energy is presented in British thermal units (Btu) in each measure as follows: Btu per vehicle-mile (Btu/VM), Btu per seat-mile (Btu/SM), Btu per full load-mile (Btu/FLM), Btu per crush load-mile (Btu/CLM), and Btu per passenger-mile (Btu/PM). Btu per vehicle-mile is the average fuel consumption rate required to propel the vehicle through its daily duty cycle and power its accessories. The other four measures are indications of the efficiency of the modes while performing the desired function—transport of people. Btu per passenger-mile is a measure of the efficiency of the transportation mode with an average passenger occupancy that represents either actual experience or, in the case of DMTS, the expected average occupancy. Average occupancy is defined as the total annual passenger-miles divided by the total annual vehicle-miles. This measure is the best indication of the efficiency of existing transportation modes as they are currently performing and is termed "actual efficiency."

Many of the proposed energy conservation options (e.g., car pooling) are directed toward increasing the average occupancy. Hence, the other measures that reflect potential efficiency are useful. The three measures of the potential efficiency of the modes may be calculated by assuming that the occupancy of the vehicle is the maximum possible within three comfort categories: all passengers are seated, all seats are occupied and there is a comfortable number of standees, and all seats occupied and there is a crush load of standees.

The effect of variations in total vehicle weight due to the different passenger loadings used for the potential efficiency measures is not determined. A crush load of people will increase the total weight of rail rapid vehicles by 50 percent and of a transit bus by 70 percent. As an indication of the potential effect of ignoring this weight shift, data of the U.S. Environmental Protection Agency on automobile fuel consumption indicate that a 50 percent increase in the weight of an automobile will increase fuel consumption by 33 percent when the vehicle is operated in the urban driving cycle (3). This could have a significant impact on the measures of fuel consumption rates that assume high-occupancy rates. Nevertheless, the consumption rate data for high-occupancy rates are still useful in judging the relative efficiency of the modes. Furthermore, the actual efficiency of the modes is the most significant measure of efficiency relative to the findings presented here, and this measure is not affected by this assumption.

VEHICLE CONFIGURATION

Potential efficiency is a function of the passenger accommodations, which, in turn, are a function of the vehicle configuration. Difficulty arises when the efficiency of different modes is compared because, within each of the transportation modes, vehicles of varying configurations are operated. For instance, transit bus sizes range from 53 passengers to 19 passengers. Passenger automobiles range in size from 2 passengers to as many as 8 passengers in a large station wagon. The potential capacity of the rail rapid vehicle is particularly sensitive to seating arrangement. Subway cars operated in New York City are configured to accommodate the maximum number of standees, and those in San Francisco and Washington, D.C., are designed to allow for the maximum number of seated passengers. A representative configuration for the vehicles of each mode is selected, and the major characteristics of the vehicles are given in Table 2.

The basic weight per passenger (including standees) of the DMTS bus is optimistically assumed to be the same as that of the average of the subcompact automobile (500 lb, 228.6 kg) and a transit bus (285 lb, 129.3 kg), or about 400 lb (181.4 kg) per full load passenger position. An additional 20 percent is added to the base weight for command and control equipment. Also, a 1000-lb (453.6-kg) lead-acid battery, which provides an off-guideway range of 10 miles (16.1 km), was included. The total weight of the vehicle without passengers is 14 400 lb (6531.8 kg).

LEVEL OF SERVICE

When comparing the efficiencies of the various urban ground passenger transportation modes, one must recognize that each mode provides a different level of service to the passenger. For instance, during the peak-capacity period, the rail rapid system provides an uncongested and high-capacity corridor service with a low level of personal privacy, while the automobile is very much affected by peak-hour congestion but provides a door-to-door, private service to the passenger. Rail rapid is used in only a few U.S. cities and, except for New York, only a small percentage of the total populations of these cities have ready walking access to the system. The initial capital cost of a rail system is high and can be afforded by only large, high-density cities. The transit bus is more pervasive and less expensive for most cities, but access is still limited to those living near established routes, and the vehicles, for the most part, have to compete with the automobile on congested roadways.

One must also recognize that different types of vehicles provide different types of physical space for passengers. The light truck, passenger automobile, and motorcycle are designed to allow seated passengers only, but the rail rapid vehicle and streetcar provide space for a significant number of standees. The DMTS vehicle, the commercial bus, and the trolley bus provide limited space for standees.

Thus, level of service and feasibility of implementation must be considered when the energy efficiency of various transportation modes is evaluated. As an extreme case, a large-vehicle commuter rail system (providing infrequent service so that occupancy rates are high) is probably an efficient mode but, because the resultant level of service is poor and because only a few people have ready access to the system, it will not attract the ridership necessary to affect the energy situation. The ability of DMTS to provide a reasonably high level of service to a large percentage of people and its inherent good efficiency provide the potential to conserve energy.

OCCUPANCY RATE

The actual efficiency (measured in terms of Btu per passenger-mile) is the best indication of operating efficiency of existing transportation modes. The variance in recent estimates of passenger transportation efficiency is partially due to the variance in the estimated average

Table 2. Characteristics of urban passenger transportation vehicles.

Vehicle	Energy Source	Seats	Full Load[a]	Crush Load	Avg Load	Empty Weight (lb)	Length (ft)	Width (ft)
Passenger automobile	Petroleum	6	6	6	1.5	4 000	18	6.5
Light truck	Petroleum	3	3	3	1.3	3 500	20	6.5
Motorcycle	Petroleum	2	2	2	1.1	300	6.5	2.5
Commercial bus	Petroleum	50	70	80	11	20 000	40	8
Rail rapid vehicle	Electricity	60	120	160	24	84 000	60	10
Streetcar	Electricity	37	74	89	13	36 000	46	8
Trolley bus	Electricity	50	70	80	9	20 000	40	8
School bus	Petroleum	60[b]	60	60	23	11 000	27[c]	8
DMTS vehicle	Electricity	20	28	32	8.4	14 400	20	8

Note: 1 lb = 0.45 kg; and 1 ft = 0.3 m.

[a] With standees, who are comfortable. [b] Children. [c] Passenger compartment only.

Figure 3. Load factors.

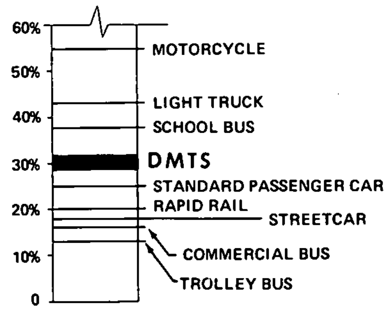


Table 3. Load factors of urban passenger transportation vehicles.

System	Vehicle	Vehicle Full Load Capacity[a]	Average Occupancy	Load Factor[b] (%)
Existing personal	Passenger automobile	6	1.5[c]	25
	Light truck	3	1.3[d]	43
	Motorcycle	2	1.1[e]	55
Existing transit	Commercial bus	70	11[f]	16
	Rail rapid vehicle	120	24[g]	20
	Streetcar	74	13[h]	18
	Trolley bus	70	9[h]	13
	School bus	60	23[i]	38
New	DMTS	28	8.4[j]	30

[a] All seats filled and maximum number of comfortable standees if applicable.

[b] Average occupancy divided by full load capacity.

[c] For urban areas only and from reference 14.

[d] Conservatively assumed to be 1.3, which is lower than automobile since seating capacity is 3 people.

[e] Conservatively assumed to be 1.1, which would be equivalent to saying that 1 out of every 10 motorcycles is carrying 2 people.

[f] Average occupancy is assumed to be equal to total annual passenger-miles divided by total annual vehicle-miles. Number of passengers and vehicle-miles is given in reference 8; 20 was used for city average. Average trip length of passengers determined from data in five cities given in reference 14 and from information from the Metropolitan Washington Council of Governments.

[g] Some technique as in footnote f except rail data were used and the average trip length was determined from data given for three cities in reference 14.

[h] From reference 15.

[i] Data from Virginia indicate that 92 children ride on each school bus each day (16). Average occupancy is based on following assumptions: each child makes two one-way trips per day, each bus makes four round trips per day, and the children's homes are evenly distributed over the route.

[j] Optimistic assumption taking into account the level of service provided by DMTS and the high load factors experienced by intercity buses and airplanes and by school buses and passenger automobiles.

occupancy (4). The average occupancy rates (or load factor) of the modes studied here are shown in Figure 3. Load factor is defined as the average occupancy divided by the full load capability of the vehicle expressed as a percentage.

Clearly, the DMTS benefits from a high estimated load factor relative to other existing transit modes. But these load factors are not unrealistic relative to the existing personal modes (passenger automobile, light truck). Furthermore, intercity buses and airplanes travel at average load factors close to 50 percent, and the school bus operates at a load factor close to 40 percent—indicating that high load factors are possible if the service provided meets the demand. DMTS has the additional advantage of being capable of providing demand-responsive service during periods of low demand. In this way, a portion of the off-peak, nearly empty vehicle movement normally required by transit to maintain schedules is eliminated. The use of relatively small vehicles and the potential for attracting a significant level of off-period patronage increase the likelihood that DMTS will achieve the predicted load factor.

Load factors vary significantly from city to city, from hour to hour, and from season to season. The load factors used here are selected to characterize the experience of the United States as a whole. The data and sources used to calculate the load factors for the existing urban ground passenger transportation modes are given in Table 3.

DMTS ENERGY MODEL

Energy consumption rates based on actual operating experience are not available for DMTS. Instead, these data are estimated through the use of an energy model based on simplified kinematic equations, assumed vehicle physical characteristics, and an assumed vehicle duty cycle. The resultant estimate, by necessity, heavily depends on the assumptions made. Whether the technique is reasonable was determined by the same general approach used to estimate the fuel rate of a standard-sized automobile traveling over a simplified version of the Federal Urban Driving Cycle (FUDC). The result was 20 percent less than the results of the EPA dynamometer tests using the same FUDC.

Simplified Energy Equation

The energy requirements for the propulsion of a wheeled vehicle may, for convenience, be divided in elements as follows:

$$E_t = E_{acc} + E_{rr} + E_{ad} + E_g + E_a \qquad (1)$$

where

E_t = total energy required,
E_{acc} = energy required to accelerate,
E_{rr} = energy required to overcome rolling resistance,
E_{ad} = energy required to overcome aerodynamic drag,
E_g = energy required to climb grades, and
E_a = energy required to power accessories.

For convenience, accessory energy is considered to be a simple percentage of the other energy elements:

$$E_a = k\,(E_{acc} + E_{rr} + E_{ad} + E_g) \qquad (2)$$

where k = 0.3. Accessories include air conditioning (heating, cooling, and ventilation), lighting, power steering, and other equipment needed for command, communications, and control. The factor, k, for all new systems is estimated to be 0.3 and is based on automobile test experience that indicates that accessories such as air conditioning, alternator, fan, and power steering increase by 23 percent the fuel consumption of an intermediate class automobile exposed to an urban driving cycle (5). Although the DMTS is expected to experience a higher average speed than that of the automobile (implying less energy demand per mile for some accessories), DMTS will require even more energy to power interior lights, doors, brakes, electronic equipment, and probably an active vehicle steering and switching system.

The energy required to overcome grades was calculated by arbitrarily assuming that the average grade throughout the system is 1 percent. The energy required to overcome aerodynamic drag is proportional to the frontal area of the vehicle, the drag coefficient, and the square of the average speed. The rolling resistance energy is directly proportional to vehicle weight and the coefficient of rolling resistance of the tires (the effect of speed was judged insignificant). The energy required to accelerate the vehicle is directly proportional to the mass of the vehicle and the difference of the squares of the final and initial speeds. It is assumed that the DMTS vehicle does not regenerate energy during braking and that the rotational inertia is negligible. The primary energy required at the electricity generating plant was determined by making assumptions as to the efficiencies of the various elements of the DMTS energy conversion process. These efficiencies and key vehicle characteristics used to calculate energy consumption are as follows:

Item	Value
Coefficient of rolling resistance	0.012
Aerodynamic drag coefficient	0.5
Frontal area, ft^2	65
Average grade, percent	1
Accessories load, percent	30
Energy conversion efficiency, percent	
Electric generation	35
Transmission and transformation	90
Local distribution, motor, and controller	75
Battery charge and discharge	65
Net weighted average	22

Vehicle Duty Cycle

A typical DMTS vehicle duty cycle is used to estimate the energy required for vehicle acceleration and aerodynamic drag. This duty cycle is shown in Figure 4 and defined below.

The vehicle duty cycle is divided into three segments: residential collection (1 mile, 1.6 km), line-haul (5 miles, 8 km), and CBD distribution (1 mile, 1.6 km). The line-haul and major CBD distribution functions are assumed to occur on the guideway as the vehicle draws electrical power from the wayside, and the neighborhood collection is performed with battery power. The maximum vehicle speed is 30 mph (48 km/h) in the residential and CBD areas and 50 mph (80 km/h) in the line-haul portion of the trip. The average numbers of stops per mile on the residential, line-haul, and CBD portions are 4, 0.2, and 2 respectively. The energy consumed by the accessories during station dwell was ignored.

OBSERVATIONS

1. The vehicle energy consumption rate is closely dependent on vehicle weight. The larger the vehicle is, the greater the rate will be. The energy consumption rates of vehicles (Btu per vehicle-mile) of the various urban ground transportation modes are shown in Figure 5. However, fuel consumption is not directly proportional to vehicle weight alone—the rail rapid vehicle weighs 20 times more than a standard automobile, but consumes only 6 times more energy. Also, the weight ratio of a bus and automobile is 5 to 1, but the fuel consumption ratio is 3 to 1. Fuel consumption is also a function of design characteristics, such as wheel type (rubber versus steel) and aerodynamic drag qualities.

Fuel consumption is affected also by vehicle duty cycle. A rail rapid vehicle averages one stop per mile, but a transit bus averages more than four stops per mile. An automobile stops 2.4 times per mile during the FUDC. The difference in duty cycles is probably responsible for the difference in energy consumption of the transit bus and trolley bus, which are of equal weight.

2. The estimated fuel consumption data for the DMTS vehicle are in line with the data for existing transit modes for which actual operating data are available; therefore, more credence is given to the theoretical technique used to determine DMTS energy consumption. The numerical values for the energy consumption rates of the modes studied are given in Table 4.

The energy efficiency of the various modes (Btu per passenger-mile) is shown in Figure 6. The data points may be grouped into (a) existing transit systems and (b) existing personal systems. The dual-mode transit system falls in between. The school bus appears to be an anomaly: The transport of small "captive" riders provides for high load factors, and the vehicle is relatively light.

3. The transit bus and rail rapid vehicle are from 2.4 to 2.6 times more efficient than the standard-sized passenger automobile. Clearly, the large-vehicle transit systems carry passengers more efficiently than the existing personal modes, as represented by the standard automobile. However, partially because of their large sizes, these vehicles provide a lower level of service, as may be measured in terms of wait time, privacy, independent routing, and door-to-door convenience. The motorcycle and subcompact automobile provide efficiency equal to the large transit vehicles, but not without a significant sacrifice of personal comfort and safety.

4. The efficiency of DMTS is estimated to be from 10 to 20 percent lower than that of the transit bus and rail rapid vehicle. This estimate is based on an energy model that includes a simplified dynamic equation and an assumed vehicle duty cycle. More important than the inherent efficiency of DMTS is its potential for attracting the people who are currently using the energy-intensive automobile. As shown in Figure 7, DMTS fills an energy gap by providing an efficiency comparable to that of the existing transit modes but at a level of service approaching that of the private automobile.

5. DMTS offers the potential for use of non-petroleum-based fuels since it is capable of operating on electrical power. This characteristic is particularly important to the long-term future, when nuclear power may provide a large portion of the total national electrical energy budget (6).

6. The energy efficiency of a particular mode depends heavily on assumed occupancy rates. Figure 8 shows the relation between energy rate and passenger load. Lines of constant energy rate per vehicle-mile and of constant passenger load are superimposed on lines of energy required per passenger load. The energy rates of the various modes are shown on bars

along lines of constant energy rate per vehicle-mile. The bars for each mode extend from the energy rate with an average occupancy to the energy rate with a crush load. The dominant mass transit vehicles, with high crush load occupancy rates, are 4 times more efficient than the passenger automobile. On a crush load basis, DMTS is expected to be from 2 to 3.5 times more efficient than the personal modes.

7. To achieve its promise, DMTS must exhibit a high average load factor. The estimated DMTS load factor is from 1.5 to 1.8 times higher than those of the dominant existing transit modes and is 20 percent higher than that of the passenger automobile. The school bus, light truck, intercity bus, and airplane possess higher average load factors than that of DMTS.

To attain this high occupancy rate, DMTS must be managed in such a way as to minimize empty vehicle movement and to attract the off-peak-period riders necessary to level the peak-period demand characteristics experienced by existing transit systems. DMTS vehicles must move only when the demand exists much in the way that school buses, intercity buses, and airplanes operate. Fare incentives and special services may be necessary. Demand-responsive services on routes of low demand

Figure 4. DMTS vehicle duty cycle.

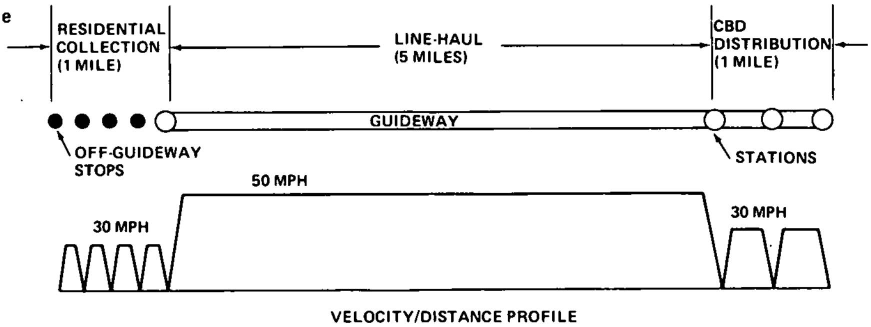


Figure 5. Energy consumption by vehicle weight and miles.

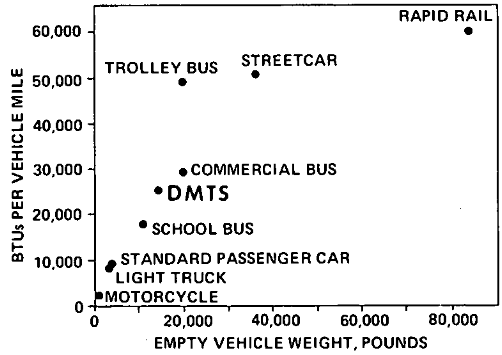


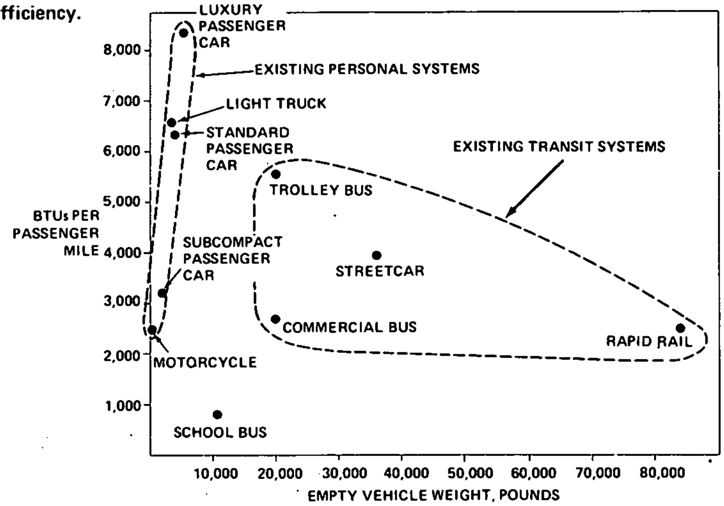
Table 4. Energy consumption rates of urban passenger transportation vehicles.

Vehicle	Btu/ Vehicle-Mile	Btu/ Seat-Mile	Btu/ Full-Load-Mile	Btu/ Crush-Load-Mile	Btu/ Passenger-Mile
Passenger automobile	9 600[a]	1600	1600	1600	6400
Light truck	8 600[a]	2900	2900	2900	6600
Motorcycle	2 600[a]	1300	1300	1300	2400
Commercial bus	29 400[a]	600	400	400	2700
Rail rapid vehicle	60 200[b]	100	500	400	2500
Streetcar	50 800[b]	1400	700	600	3900
Trolley bus	49 700[b]	100	700	600	5520
School bus	18 800[a]	300	300	300	800
DMTS vehicle	25 100[c]	1300	900	800	3000

Note: 1 mile = 1.6 km.

[a] Fuel consumption rates in miles per gallon are passenger automobile, 12.1; light truck, 13.6; motorcycle, 44.5; commercial bus, 4.4; and school bus, 6.2. These rates are converted to Btu per vehicle-mile based on the assumption that gasoline contains 116 500 Btu/gal and No. 1 diesel contains 129 800 Btu/gal.
[b] The total energy consumption in kilowatt-hours and total vehicle-miles are given in reference 8.
[c] Based on simplied dynamic equations and an assumed vehicle duty cycle.

Figure 6. Energy efficiency.

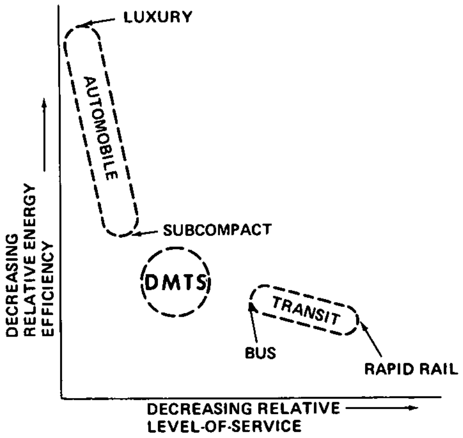


and during the off-peak periods may also aid in achieving the load factor goal.

8. Minimization of vehicle weight is of overriding importance to the design of an energy-efficient DMTS vehicle. The allocation of the total DMTS energy budget to major consuming elements is shown in Figure 9. (These allocations are based on the DMTS energy model described previously.) Energy is lost in the energy conversion process in which the primary energy is transformed into useful work. These losses account for 78 percent of the total. The remainder of the energy budget, the useful energy, is expended on the elements of transportation activity and is fairly evenly distributed among grades, aerodynamic drag, rolling resistance, acceleration, and accessories. The energy expended producing the useful work and the energy lost during conversion are naturally interdependent. A reduction in the task will decrease the energy conversion losses in the same proportion that the useful energy requirement may have been lowered.

The grade, rolling resistance, and acceleration energy elements, which account for 13 percent of the total energy and 54 percent of the useful energy elements, are directly proportional to the weight of the vehicle. To illustrate the effect of weight reduction on energy consumption, an arbitrary 2000-lb (907.2-kg) reduction (14 percent) in the DMTS vehicle weight will result in an estimated 8 percent reduction (14 percent x 59 percent) in total energy consumption. The effects of weight reduction on aerodynamic and accessory energy, which are to some extent proportional to weight, are not considered.

Figure 7. Bridge for energy gap.



The potential benefits of other important energy conservation techniques are given in Table 5. The amount of change associated with each technique is, to some extent arbitrary, but was selected as the reasonable and practical high amount. Most important, these changes illustrate the significant benefits that can be attained through careful attention to many energy-related design details.

9. The cost benefits derived from DMTS energy conservation techniques appear to be significant. The cost benefits that result from the somewhat arbitrary energy savings techniques are also given in Table 4. These cost savings are related to the lowest practical subsystem—for instance, rolling resistance energy savings are related to tires.

a. Weight reduction through the use of lightweight material is economically feasible if the new part costs no more than $2.46/lb ($5.42/kg) more than the original part.

b. The switch to radial-ply tires is cost effective if the rolling resistance energy requirement is reduced by 40 percent and each tire costs no more than $19 more than a bias-ply tire.

c. Aerodynamic streamlining is cost effective if the vehicle cost does not increase more than $4390 with the necessary design changes.

d. A 25 percent reduction in accessory requirements through selection of high-efficiency environmental conditioning equipment makes economic sense if the vehicle cost does not increase more than $3420.

e. An estimated $272 000/guideway-mile ($163 256/guideway-km) is available from energy cost savings if

Figure 8. Composite energy consumption rates.

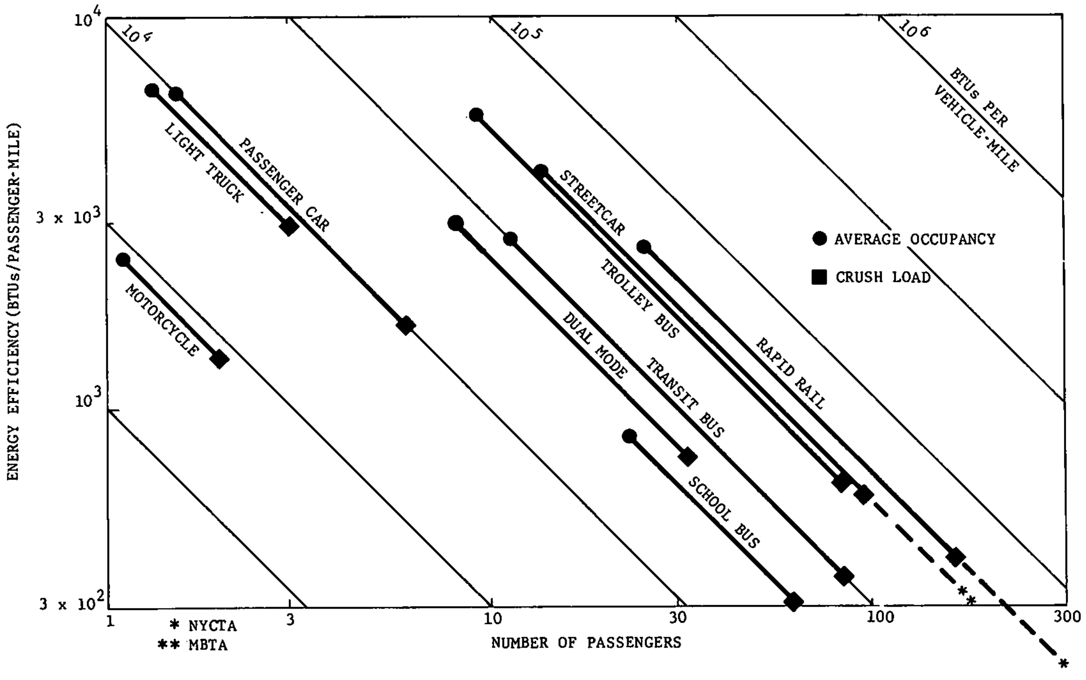
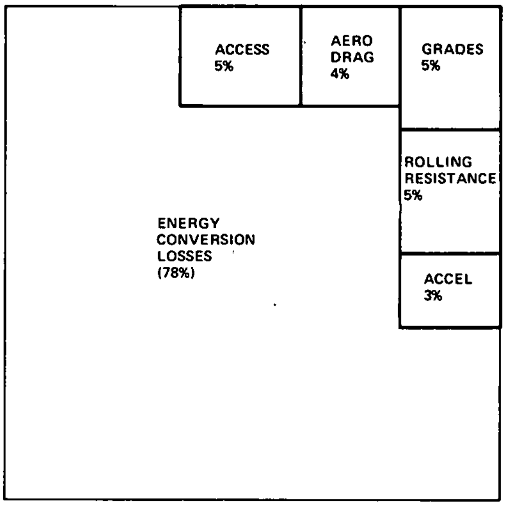


Table 5. Potential benefits of DMTS energy conservation techniques.

	Conservation Technique		Benefit	
Item	Change	Possible Methods of Implementation	Annual Energy Savings (%)	Energy-Related Cost Savings
Vehicle	Reduce weight 2000 lb or 14 percent	Use lightweight materials; give careful attention in design and manufacture details	8.2	$2.46/lb reduced/vehicle life
	Reduce rolling resistance 25 percent	Give attetion to tire design or selection (e.g., radial versus bias ply); maintain tire air pressure	5.7	$19/tire/tire life
	Reduce aerodynamic drag 40 percent	Streamline; reduce speed	7.3	$4390/vehicle/vehicle life
	Reduce accessory requirements 25 percent	Increase efficiency of and decrease need for environmental conditioning	5.7	$3420/vehicle/vehicle life
Guideway	Reduce average grade 25 percent	Select other routes; reduce non-geographic-related altitude changes	5.7	$274 000/guideway mile/guideway life
Propulsion system	Reduce energy conversion losses 5 percent	Improve efficiency of motor and controller	3.9	$2340/vehicle/vehicle life

Notes: The assumptions are that there are 100 miles of guideway and 2000 vehicles; each bus travels 100 000 miles/year; 80 percent of the bus-miles is generated on the guideway; 8964 Btu/vehicle-mile is purchased from the power company at 1.5 cents/kW·h; guideway life is 75 years; vehicle life is 15 years; and tire life is 50 000 miles.
1 Btu = 1055 J; 1 kW·h = 360 kJ; and 1 mile = 1.6 km.

Figure 9. Elements of DMTS energy budget.



the average on-guideway grade is reduced 25 percent through careful route selection and reduction of non-geographic-related grades (such as grades caused by constructing the guideway on ground level and providing frequent elevated sections for grade crossing of existing roadways).

f. A 5 percent increase in the efficiency of the power plant of the DMTS vehicle can be afforded if the necessary change costs less than $2340 per vehicle.

CONCLUSION

The energy efficiency of DMTS is expected to be 10 to 20 percent lower than that of the transit bus and rail rapid vehicle. The future energy conservation role of DMTS is related more to the level of service provided than to the inherent efficiency of the DMTS vehicle. By providing high-speed, no-transfer, point-to-point service throughout the urban area, DMTS has the potential of attracting significant numbers of people who are currently using the energy-intensive passenger automobile. To achieve this promise, DMTS must be designed with careful attention to energy-related design details and must provide the type of transit service necessary to produce average load factors significantly higher (1.5 to 1.8 times) than the existing transit bus and rail rapid vehicle.

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