Energy Cost Considerations in Light Rail Vehicle Size Specification

Steven E. Polzin
Dallas Area Rapid Transit
Dallas, Texas

The purpose of this paper is to encourage the consideration of vehicle energy consumption in the specification of light rail vehicle size. Although the prospect of uneconomic operation of large light rail vehicles has been acknowledged in previous writings, this paper documents the situation in Cleveland and postulates a scenario that could provide some advantages (1,2). In a more general sense it is hoped that this discussion and the empirical evidence it draws on will create a better understanding of the energy use levels and cost associated with light rail operation. Admittedly, several other considerations including labor costs, fleet compatibility, procurement costs, right-of-way geometrics, and aesthetics are the major determinants in vehicle choice decisions. Nevertheless, energy use and energy operating cost should play a role in this important decision. The ability to economize on power bills is premised on the ability to provide more energy efficient vehicle design or to provide adequate service capacities with a smaller, more efficient vehicle. The prospects of a smaller vehicle size providing operating economies will be reviewed.

MOTIVATION

The concern about light rail vehicle energy use is motivated by the empirical data collected in Cleveland, Ohio, that shows substantial deterioration in vehicle miles per kilowatt hour of energy use since light rail vehicles (LRVs) replaced Presidents' Conference Committee (PCC) vehicles. This evidence gives rise to a number of concerns. The rail mode, particularly light rail, has claimed as a virtue its energy efficiency relative to automobiles and buses. This claim has contributed to some strong political and public support for rail system construction and renovation. Failure to accomplish this objective not only results in lost benefits but undermines the credibility of the industry.

It is increasingly difficult to make claims about rail energy efficiency because of changes in both light rail performance and in automobile energy use performance. Energy efficiency of the light rail mode has been dropping as a result of vehicle changes. These changes, such as vehicle weight increases, have provided benefits in terms of ride quality and safety and increased performance capabilities. Likewise, passenger amenities (heating, lighting, and air conditioning) have been improved to attract or hold passengers. One of the trade-offs of this has been the tendency for energy use per vehicle-mile and per seat-mile to increase. These trends are a reversal of the historic changes in light rail vehicles during the 1920s when weight, riding comfort, and performance were sacrificed for economy.

The automobile, on the other hand, has shown a relatively dramatic energy use performance improvement during the past 10 years. Automobile vehicle weight per passenger seat has come down dramatically, and technological changes have provided significant fuel efficiency gains. These contrary trends have resulted in a situation in which energy use performance of rail vehicles is now subject to far less favorable comparisons with the competing highway and automobile mode. This is particularly true if the attained operating performance of the light rail mode, not its theoretical performance capabilities, is considered.

Of even greater concern is the prospect that light rail vehicles being procured now will be in competition with automobiles purchased in the next century. The much larger automobile market provides a greater opportunity to develop and implement technologies that improve vehicle operating efficiencies. Furthermore, the shorter vehicle life (compared to rail vehicles) means improvements can be implemented faster.

The Cleveland situation exemplifies the potential problem. The fleet of light rail vehicles put in service in 1982 operates 1,075,000 vehicle-miles per year under the current schedules. With a projected vehicle life of 1.5 million mi and a 48-car fleet, these vehicles could be expected to be operational until the year 2050. The operating performance of automobiles in service at that time is a matter of speculation.

EMPIRICAL PERFORMANCE DATA

This discussion relies on data from the Greater Cleveland Regional Transit Authority's Blue and Green (Shaker) light rail lines. The data contrast the performance of PCC vehicles operated until the early 1980s with that of the articulated light rail vehicles (LRVs) put in service in 1982. It is important to acknowledge several characteristics of the Cleveland operation that may make it inappropriate to broadly generalize these results. However, the general findings indicate that other agencies may

need to consider ways to optimize rail vehicle energy performance.

Service Profile of Shaker Light Rail System

The Greater Cleveland Regional Transit Authority's (GCRTA's) Blue and Green light rail lines (Shaker Rapid) provide transit service from Cleveland Union Terminal in downtown Cleveland to areas of eastern Cleveland and its eastern suburbs, primarily Shaker Heights. Service is provided 7 days a week with weekday service from 4:30 a.m. to 1:00 a.m. The current weekday schedule provides 150 train trips in the peak direction. Some two-car rush-hour trains being the peak direction vehicle trips to 188. Ninety-nine Saturday and 45 Sundays trips are provided. The Green and Blue lines share right-of-way with the GCRTA high-platform Red line for 2.6 mi after leaving downtown Cleveland (see Figure 1, which is not to scale but is time related). After the Red line branches off, the two light rail lines continue on shared right-of-way to Shaker Square, where they branch into two largely parallel lines serving residential and some commercial areas. The Van Aken branch serves a higher density area and more commercial space. It carries approximately 60 percent of light rail passenger volume. There are numerous at-grade crossings of the 3.2-mi Van Aken Blue line leg and the 3.7-mi Shaker Boulevard Green line leg. The 6.1 mi of shared right-of-way are grade separated, with the exception of two grade crossings at Shaker Square.

Other factors relevant to the operating performance of the system include an elevation change in excess of 500 ft from the central business district (CBD) station to the ends of the line. Most of this grade is in a 3.2-mi grade-separated portion between where the Red line branches off and Shaker Square. The lines have 29 passenger stations more densely spaced at the outer ends of the line. The Cleveland climate provides significant seasonal variation. Winters average approximately 50 in. of snow and 5 days with temperatures below zero. Summers typically include a few days with temperatures in excess of 90 degrees. High humidity levels are not uncommon in the summer months. Both heating and air-conditioning systems are subject to regular sustained operation.

Ridership levels on the lines have been relatively stable for the past 2 years. Average weekday ridership is approximately 17,000. The Cleveland Union Terminal is the system's dominant station and the only downtown station. In excess of 60 percent of the total trips either begin or end there. The farthest outlying stations also generate significant passenger volumes. The maximum load point occurs between Shaker Square and Cleveland Union Terminal.

More than half of average daily riders travel during the rush hours (7-9 a.m. and 4-6 p.m.). During the evening rush hour there are also significant peaks for outbound trips originating at the Cleveland Union Terminal station. Rush-hour headways are 8 min for both the Blue and Green lines, resulting in a 4 min headway in the shared right-of-way section.

Energy Use Performance Data

Energy use for the light rail system was derived from high-voltage alternating current meter readings at GCRTA substations and assignments to modes (light or heavy rail in cases where a single substation serves both lines) (3). Thus the data represent net energy consumption for vehicle operation and all other uses powered by the high-voltage current fed to the substations. The nonvehicle uses for direct current are almost exclusively rail switch heaters. These heaters use from 8 to 14 kilowatts per hour and operate during the winter months. They are on almost continuously during the worst of the winter. Line and substation losses also are included in the energy use measurement. Other on-vehicle but nonpropulsion uses of energy include vehicle amenities, principally heating in the older PCC vehicles and both heating and air conditioning in the newer light rail vehicles. Night storage heating also has a significant impact on energy use.

It is important to realize that the net power consumption differs significantly from propulsion power consumption as measured with test equipment on the vehicles. It includes auxiliary power used during operation and in storage, line and substation losses, and switch heating in Cleveland's case. The relevant vehicle characteristics are given in Table 1.

The Cleveland statistics are also slightly biased in two respects. The larger articulated vehicles result in fewer vehicle-miles of operation because they have greater passenger-carrying capacity and require fewer trips to move the same number of persons. The second factor, ridership declines and budget cuts resulting in reduced operations on light rail by the greater Cleveland Regional Transit Authority, has further reduced the vehicle-miles of light rail service. These reductions in vehicle-miles of operation have the effect of causing the nonvariable power uses such as overnight storage to be spread over fewer miles of operations. Thus a higher portion of the kwh/vm number is now for nonvariable

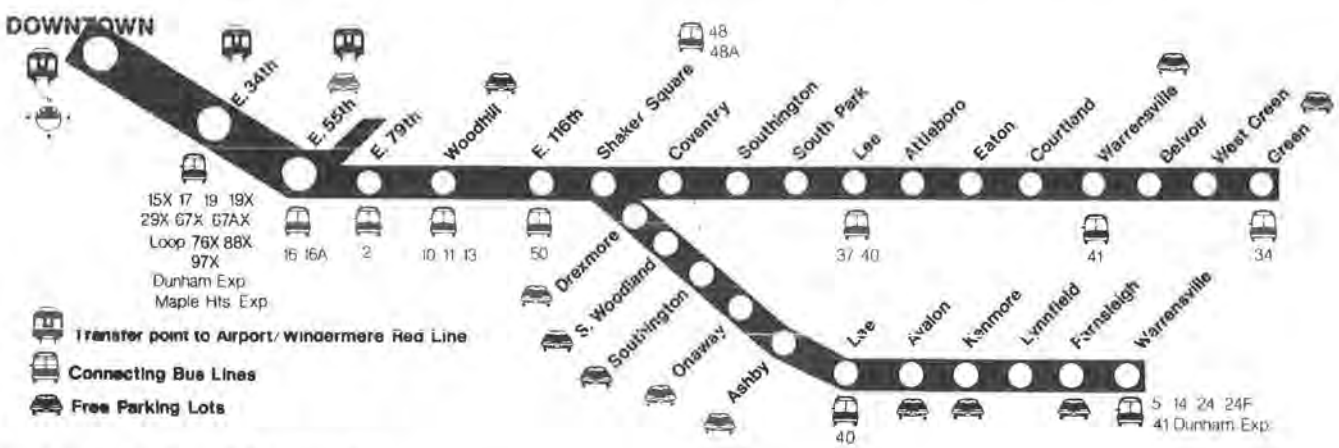

FIGURE 1 Shaker and Van Aken lines.

TABLE 1 Vehicle Characteristics

	Vehicle	
	LRV	PCC
Length (m)	23.5	14.1
Width (m)	2.82	2.74
Weight (kg)	40,370	18,370
Weight/seat (kg)	481	306
Motors	2 BBC FLO 2050, 328 HP each	4 GE 1220E1 approximately 55 HP each
Seats	84	60
Heating (kw)	51.3	16.5
Air-conditioning	Dual, 7.5-ton units	None
kwh/vehicle mile[a]	12.38	5.80
kwh/seat-mile	0.149	0.097
Configuration	6-axle articulated double-end	4-axle single-end
Other	Regenerative braking, chopper control	Cam control

[a]Gross propulsion energy use per vehicle-mile for 1979-1981 for PCC and for 1983 for LRV.

costs. Unfortunately, power use data that would allow the separation of these nonvariable power uses from total use are not available.

On the basis of the energy consumption rates for two vehicle types given in Table 1, the energy cost of vehicle operation can be calculated. Electricity rates in Cleveland resulted in an average cost of 7.9¢ per kwh for rail system propulsion power in 1983. This cost was calculated by dividing gross electric bill dollars by gross kwh; thus it assigns all costs, including demand charges, to kilowatt hours. This cost can be multiplied by line length and vehicle energy consumption rates to determine the energy operating cost of the LRVs and PCCs in Cleveland. Average round-trip electricity costs per vehicle in 1983 are given in the following table (3):

	PCC ($)	LRV ($)
Blue line	8.55	18.25
Green line	9.01	19.23

True marginal operating costs are not known, though it is known that winter operating costs can be as much as 60 percent greater than summer operating costs.

The GCRTA schedule requires approximately 1.2 hr per round trip including layover. Thus, for labor operating costs (just the operator) to exceed energy operating costs, the gross hourly compensation (total compensation divided by net hours worked) has to exceed $15.50 per hour.

To put these numbers in perspective, let us contrast intermodal performance at GCRTA and interpret energy costs (for 1983) on a per passenger basis:

	LRV (¢)	Heavy Rail (¢)	Bus (¢)
Energy cost per passenger trip	22.6	23.0	6.9

These and other numbers shown exclude support energy costs. Station and parking area lighting, station heating costs, and utilities for maintenance and administration facilities are excluded. In Cleveland's case these costs would add 20 to 25 percent to the cost per use levels shown for the 1983 LRV data.

The numbers for energy cost per passenger trip are affected by vehicle utilization, a function of trip length, trip attraction rates, and energy performance of the mode. In the GCRTA case, rail passenger trips average 6.5 mi, bus trips average 4.0 mi, trip attraction rates average 4.32 trips per vehicle-mile for light rail operation, 3.18 trips per vehicle-mile for heavy rail operation, and 3.5 trips per vehicle-mile of bus operation. The light rail vehicles average 12.38 kwh per vehicle-mile, the heavy rail vehicles average 9.23 kwh per vehicle-mile, and buses average 3.5 mpg of diesel fuel.

Given a 6.5-mi average light rail trip, the energy cost per passenger-mile is approximately 3.5¢. To put this in perspective, an automobile with 1.5 occupants getting 22 mpg and paying $1.15 per gallon for fuel also has a fuel cost of 3.5¢ per passenger-mile.

Systemwide in 1983 GCRTA collected 45¢ per unlinked trip. This nets out the impact of free transfers, discount fares, and other conditions in which less than a full fare is paid. Thus approximately one-half of each fare collected on light rail goes just to cover the propulsion power costs. This suggests that the fares generated by light rail during low ridership time periods may not even cover the average operating propulsion power cost. For example, a late night trip probably fails to generate the average $18 in fare revenue required to cover the propulsion power costs of the trip.

VEHICLE SIZE SPECIFICATION

These numbers, the original motivation for taking a closer look at vehicle size specification, clearly include factors other than vehicle size alone. The local electricity rates, the overnight heating requirements, and the elevation changes in Cleveland that require a powerful vehicle may make both the absolute and the relative energy use performance of the Cleveland vehicles differ significantly from the situation in other locations. Nonetheless, the magnitude of the energy operating cost differences requires consideration of ways to avoid the negative financial consequences and preserve the energy efficiency of the mode relative to both automobile and bus performance.

This concern can be focused in either of two directions: (a) identify technological and operational changes that might be able to provide greater economies and (b) evaluate the possibility that a smaller, more efficient vehicle might provide energy cost savings (4,p.7; 5,p.3; 6,pp.61-79). Obviously, in the Cleveland case with a new fleet in place, operational actions are the most feasible. These include things like operating policies for air-conditioning and heating and vehicle operation, such as acceleration rates and peak speed. The subsequent discussion will not review these options but instead will focus on actions of the second type--addressing the question "Would smaller vehicles or a fleet consisting of vehicles of two sizes provide an opportunity to realize energy savings without offsetting service or cost consequences?"

Capacity Utilization

This analysis involves developing an understanding of the empirical data associated with ridership patterns. This will result in knowledge about the vehicle utilization levels and hence capacity needs as a function of time of day. Overall light rail service attracts 4.32 passengers per vehicle-mile of travel. Using an average light rail passenger trip length of 6.5 mi means that, on average, the GCRTA light rail operation provides 28 mi of passenger travel per mile of vehicle travel or that the vehicles have on average 28 of 84 seats filled. (The Cleveland car with wide aisles, six doors, and the articulation area has generous floor space and claims

a standing load capacity of approximately 200 persons.) Inevitably, rush hours are characterized by numerous loads with standees, whereas base-period and late evening services may have only a handful of passengers per trip. Low volumes are also characteristic of much weekend and holiday service.

An essential constraint in evaluating vehicle size considerations is to assure that the combination of vehicle size, train length, and frequency provides adequate capacity. The ability to increase train length and decrease headways between trains results in potential capacities, even with smaller vehicles, that are adequate for virtually all volume levels typical of light rail operation. The platform length, which constrains train capacity combined with the minimum safe headway constraint in the shared trackage still allow capacities of more than two times current levels in Cleveland.

This capacity constraint concern is only relevant during a limited percentage of the hours of operation. In Cleveland, the two 2-hr rush periods result in volumes that require scheduling that responds to the objective of providing adequate capacity. With the exception of special events, the remainder of the scheduling responds to the desire to provide an attractive frequency--vehicles are running with loads significantly below a policy load factor level. Thus, of the 140 hr of service provided weekly, only about 20 hr have their schedule frequency and train length determined by capacity needs.

Thus one aspect of the vehicle size determination problem, particularly when choosing a full replacement fleet or a fleet for a new system, is identifying which vehicle size allows the most efficient match of vehicle capacity to the range of service needs.

This problem could be analyzed quite readily through either an optimization or a simulation modeling approach, presuming adequate information about passenger demand and operating costs is available. In the Cleveland example, empirical ridership data are used to identify the extent to which capacity is needed by time of day. To do this, load count data for the maximum load point on the light rail line were reviewed to evaluate the feasibility of different size vehicles satisfying capacity needs.

Figure 2 shows a presentation of passenger loads by time of day. This graphic shows that, at vehicle

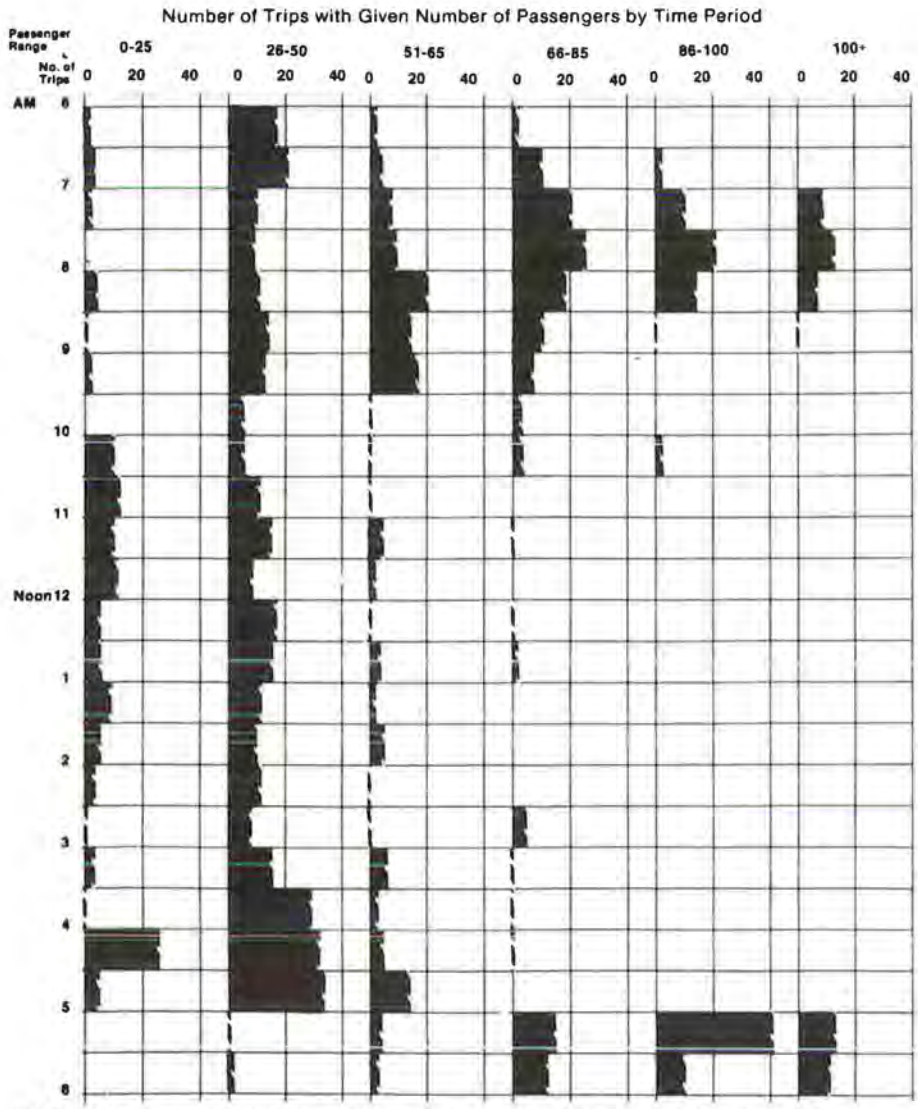

FIGURE 2 Capacity utilization. Note: Data are for vehicle trips; total trips are for 5 sample weekdays in 1984; peak-direction trips are from 6 a.m. to 10 a.m. and from 2 p.m. to 6 p.m.; and trips in both directions are counted from 10 a.m. to 2 p.m.

maximum load point, volumes only begin to utilize the vehicles' capacity during the rush hours: approximately 7:00 a.m. to 8:30 a.m. and 5:00 p.m. to 6:00 p.m. at the count location. Eighty-two percent of the counted trips show volumes of 85 or fewer, meaning adequate seated capacity for all passengers is provided. Two-thirds of the trips shown have passenger loads of 65 or fewer. The data in Figure 2 are from 5 weekdays for peak-direction trips from 6:00 a.m. to 10:00 a.m. and from 2:00 p.m. to 6:00 p.m. The 10:00 a.m. to 2:00 p.m. data include both direction trips. Because of this, and because early morning, evening, and weekend data are not plotted, the data only describe the constraining conditions. Thus far more than two-thirds of the total weekly trips have loads of fewer than 65 passengers.

Smaller Vehicle Scenario

These data along with a review of ridership data for early mornings, evenings, and weekends confirm the hypothesis that a smaller vehicle, even with the present frequencies, would normally provide adequate capacity for service during all but the peak weekday rush periods. The issue reduces to one of determining whether the additional frequency or train length for smaller vehicles to meet rush-hour loads would more than offset the operating economies of having smaller vehicles. To perform a simple analysis of this, the following calculations were performed: Given that

- Each vehicle requires an operator (with single-operator trains, the economies of smaller vehicles would become even more convincing);
- The 2-hr rush period has 42 vehicle movements or 3,528 seat movements in the peak direction;
- The peak 2-hr maximum load point, peak direction volume, is 3,000 passengers;
- The ratio of (peak direction, maximum load point) rush-hour seats to passengers is 117 to 100; and
- Operator labor cost is $17.14 per hour worked including fringes;

an evaluation can be made of the prospects of the energy savings from operating a smaller vehicle, which would provide fewer seat-miles of service in the nonpeak times against the additional operating cost of labor to operate the additional vehicles needed to provide the same number of seat-miles of service in the rush hours. In the following scenario, it was assumed that 64-seat nonarticulated vehicles would be used. Given the substantial weight penalty associated with the additional truck and the articulation it was assumed that the weight savings and the energy savings of the smaller vehicle would be more than the proportional reduction from 84 to 64 seats. Thus, for the sake of comparison, assume that the cars have 76 percent of the seated capacity but only require 65 percent of the energy use for operation. The simplified cost analysis is shown in Figure 3.

This scenario points out the reasonable prospects of providing modest economies with the operation of smaller, more efficient vehicles. Changes in any of the variables could affect the magnitude of the savings.

CONSIDERATIONS

The purpose of the preceding simplified analysis has been only to provide evidence of the potential of the efficiencies of smaller vehicles under certain

1. Current Direct Operating Cost where

   84 rush-hour trips per day,
   106 non-rush-hour trips per day,
   99 Saturday trips,
   45 Sunday trips,
   Energy cost for a trip is approximately $18.50, and
   Labor cost for a trip is the labor rate per hour times 1.2 hr per trip = $20.57.

Weekly Operating Cost can then be expressed as (Rush hour trips + Non-rush-hour trips) x (Energy operating cost + Labor operating cost). Thus, Operating Cost for one week is

$$420 + 674 \times (\$18.50 + \$20.57) = \$42,742.58$$

2. Operating Cost with Smaller Vehicles where

   Energy cost per vehicle round trip is

$$0.65 \times \$18.50 = \$12.03, \text{ and}$$

   3,528 rush-period seats require 55 trips or a weekly rush-hour volume of 550 vehicle trips.

Thus Operating Cost for one week is

$$550 + 674 \times (\$12.03 + \$20.57) = \$39,902.40$$

3. Net weekly savings with smaller vehicles = $2,840.18

FIGURE 3 Direct operating cost comparison.

service and ridership levels. Several other relevant concerns will either be acknowledged or discussed. The most important of these are ridership and service levels.

Service Consideration

Rail systems tend to have such a substantial capital commitment that there is heavy pressure to provide high service levels both to encourage use and to justify and utilize the investment. Limiting the hours of rail operation and restricting weekend service could increase the operating cost-effectiveness of service by eliminating the least productive service. Balanced directional flows associated with multiple nucleated urban activity patterns and less rush-hour peaking associated with staggered work hours could also provide opportunities for more efficient vehicle utilization, yet these conditions are not necessarily characteristic of urban light rail corridors.

Other operating considerations may also play a part in this decision. These include the relative share of operating costs attributable to labor and to propulsion energy. If electric rates increase faster than labor costs, which is quite probable in Cleveland as new nuclear plants are included in the rate base, then the more efficient vehicle argument gets stronger. Likewise, faster vehicle turnarounds (reducing round-trip time to less than 1.2 hr) or lower labor costs could increase the relative advantages of more efficient vehicles.

The physical capability of stations for handling longer train lengths or the traffic conditions that might interfere with greater frequencies might also preclude energy operating costs from playing an important part in the vehicle choice decision.

Other operating conditions that relate to vehicle size might also be relevant (1). For example, an articulated vehicle with on-board fare collection may result in longer station dwell time and enhanced opportunity for fare cheating. An articulated vehicle makes it difficult to monitor behavior (vandalism) in the car section beyond the articulation or to be

sure the doors are clear of passengers when closing. On the other hand, the extra capacity of a large vehicle may provide advantages in unanticipated situations such as early business closings for severe weather or unanticipated crowds from special events (sports events, parades). The larger vehicle is also more likely to provide the comfort of a full double seat per passenger.

Other Considerations

The provision of service is typically driven by policy decisions that dictate a high frequency, whereas vehicle choice decisions are more inclined to be driven by a desire to minimize labor operating costs during rush hours.

Numerous other variables affect the vehicle choice decision. These include the need to be compatible with existing equipment; the physical constraints on design including width, height, turning radius, floor and step height, power supply, door location requirements, performance requirements, and related concerns. Issues like vehicle cost and availability within a given time frame may also affect the vehicle choice decision as might maintenance costs by vehicle type and size.

A quantitative research effort directed at defining conditions of service, ridership, operating policies, and vehicle sizes that result in efficient operations could be useful to the industry. The need for a better understanding of off-peak ridership for making vehicle size decisions is also indicated by the results presented.

Mixed Vehicle Sizes

The preceding text urges more attention to optimizing vehicle size for a given situation. This concept can be expanded to include the prospect of having vehicles of two sizes serve a given property. This possibility might be particularly attractive for large operations with multiple lines. Small single vehicles could be used for low-volume off-peak services; then trains of these vehicles could be used with larger articulated or double-articulated vehicles to meet rush-hour demands. If such a fleet were planned concurrently there could be nearly complete component compatibility. A detailed, site-specific analysis could be helpful in evaluating the feasibility and benefits of such an arrangement.

SUMMARY

The objective of this paper has been to communicate the concern that energy operating costs are not given adequate consideration in the vehicle size decision. Energy operating costs have increased to the point where they may be as great as or greater than the labor cost for vehicle operation. This trend, coupled with the expansion of light rail into additional markets, highlights the need to pay more attention to energy costs if the rail mode is to maintain its competitive advantage in the energy efficient transportation of people. The high frequencies necessary to attract riders, the lower trip densities of many corridors under consideration for new systems, and the competitive environment for transit where gasoline is cheap and fares are expected to cover an increasing share of costs can result in a transit system providing many more seat-miles of service than are demanded. Unless these trends are watched closely, with corrective actions taken where necessary, the light rail mode may fail to capture the economies of a "mass" mode of transportation and be increasingly reliant on accessibility and mobility benefits to justify their construction and operation.

REFERENCES

1. R.J. Landgraf. Decisions on Physical Configuration for Light Rail Vehicles. In TRB Special Report 195: Light Rail Transit: Planning, Design and Implementation, TRB, National Research Council, Washington, D.C., 1982, pp. 97-103.
2. E.S. Diamant et al. Light Rail Transit: State of the Art Review. DeLeuw, Cather, and Company; U.S. Department of Transportation, Spring 1976, Chapter five, pp. 117-127 and 156.
3. The Greater Cleveland Regional Transit Authority Energy Report for 1983. Service and Grant Development Department, Greater Cleveland Regional Transit Authority, Cleveland, Ohio, March 1984, pp. 11 and 18-42.
4. S. Polzin. Initiating an Energy Management Program for The Greater Cleveland Regional Transit Authority. Presented at American Public Transit Association 1982 Rapid Transit Conference, Cleveland, Ohio, June 1982.
5. R.A. Uher, N. Sathi, and A. Sathi. Energy Cost Reduction Study of the Washington Metropolitan Area Transit Authority Metro Rail System, Executive Summary. Mellon Institute, Carnegie-Mellon University, Pittsburgh, Pa., May 1982.
6. R.A. Uher and N. Sathi. Reduction of Peak-Power Demand for Electric Rail Transit Systems. NCTRP Report 3. TRB, National Research Council, Washington, D.C., Dec. 1983, pp. 61-79.