Relative Costs of Bus and Rail Transit Systems

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There is a growing need for information on the relative costs of bus and rail systems for providing rapid transit service. Rapid transit is here defined as transit operating on its own exclusive right-of-way. The first step in comparing bus and rail costs is to analyze the various methods suggested for operating busway systems. This was done by comparing the relative service and costs associated with four separate operating patterns. The sensitivity of the conclusions was tested to determine the effect of line length, passenger traffic patterns, feeder bus route length, station spacing, and other variables. It appears that no particular operating method is inherently superior to any of the others. Any one method may be superior in a particular instance, depending on the operating environments and conditions that must be met. The bus and rail costs can then be compared with assurance that the analysis is not distorted by the method of bus operation selected or, at least, with insight into the direction and magnitude of the bias.

Hypothetical bus and rail systems were described so that each provided identical services. Relative costs for providing the service vary depending on line length, proportion of the line requiring subways, and passenger loadings. Sensitivity of costs to rising wage rates and variable interest rates was also examined.

Rail systems can demonstrate cost superiority where peak-hour passenger volumes exceed 12,000 and/or where more than 20 percent of the system requires subways. At volumes of 4,000 peak-hour passengers, and where no subways are required, buses show cost superiority.

•MANY CITIES in the United States are studying the desirability and feasibility of improving their public transit systems. Recognition of the importance of the transportation needs of those who cannot drive as well as a growing disillusionment with the concept of providing for all future travel demands with additional freeways has spurred interest in transit development. Several large cities have made commitments toward construction of high-capacity rail rapid transit systems. A number of others are in planning stages for rapid transit using either bus or rail vehicles.

Perhaps the single characteristic that distinguishes rapid from conventional transit is the use of an exclusive right-of-way, under the control of the transit system, that permits high-speed service unhampered by other traffic. The type of vehicle used may be rubber tired or steel wheeled, run in trains or as single vehicles, run on tracks or on pavement, and be guided by drivers or guideways. Each vehicle system has certain inherent characteristics as to speed, acceleration, construction costs, operating costs, noise, visual amenities, and contribution to air pollution that favor its use in particular circumstances.

For all but the largest cities, the cost of construction, when compared to the number of potential patrons, makes the decision to construct rapid transit difficult. Reviews of

Paper sponsored by Committee on Transportation System Evaluation and presented at the 48th Annual Meeting.

recent transit feasibility studies performed for several cities reveal potential peak-hour line volumes in the range of 3,000 to 15,000 per hour—from one-tenth to one-half the capacity of rail transit. A fundamental question in cases where full rail capacity is not required is whether some other vehicle type might have a cost advantage.

Buses on exclusive roadways have been suggested as a cost saver compared to rail, but there is disagreement as to whether and in what circumstances such savings might result. The present study was conducted in order to develop answers to these questions. Analytical work was done as part of studies conducted for the Atlanta Area Transportation Study (AATS). Alan M. Voorhees and Associates was commissioned in early 1968 to develop a preliminary transportation plan for highways and transit in the Atlanta area. AATS includes representation from the Georgia Highway Department, the Metropolitan Atlanta Rapid Transit Authority (MARTA), the Atlanta Regional Metropolitan Planning Council (ARMPC), and the Atlanta Transit System (ATS), as well as local jurisdictions. MARTA had proposed a regional network of rail rapid transit; the Atlanta Transit System, in late 1967, proposed a system of busways to be used as an interim solution to the transit problems. Some local officials felt buses operating on freeways instead of exclusive roadways would provide adequate transit. Much of the debate centered around relative cost, and it was essential that information be developed to provide insight into this problem.

BUS OPERATIONAL CONCEPTS

Rail rapid transit systems are in operation in a number of cities around the world, and a completely new system that takes advantage of the latest rail transit technology is under construction in the San Francisco Bay area. Operating procedures, performance, and costs of rail systems can therefore be reasonably approximated. Express transit utilizing buses, however, is an unknown in experience. There is no agreed-upon method of operating buses on exclusive roadways. Because buses are individually steered and can be driven on the street system, they can be operated in a variety of ways. Each method has its adherents, and consensus must be gained on the relative merits of various bus operational procedures before any acceptable comparisons to other modes can be made.

Type of Operation

Figure 1 illustrates four of the principal methods suggested for bus operations.

Type 1 uses buses in a fashion similar to most rail transit operations. Trunk-line buses run only on the exclusive busway and stop at all stations, including the station in the central business district (CBD), so that very frequent service is available. Passengers have access to busway stations either by the use of separate feeder buses (as illustrated by lines AB, CD, and EF) or by walking or driving to stations. Because buses need not operate on the streets, they can be specially designed with high platforms and extra-large doors; fare collection can take place outside the vehicle. This allows rapid boarding and alighting of passengers and reduces dwell times at stations to a minimum. Scheduled speeds are restricted because of the necessity to stop at all stations. Passengers going from, say, point E to the CBD are required to make a transfer from a feeder vehicle to the trunk-line vehicle at the station. On the other hand, crosstown movements, say from C to D, can be made without a transfer.

Type 2 service also utilizes the trunk-line vehicles on the exclusive right-of-way and separate feeder vehicles to serve the stations. Type 2 operation differs from Type 1, however, in that once a bus loads at a given station it moves to the CBD without stopping at intervening stations. This allows higher speed service but reduces the frequency of service at each station because fewer stops are made on any one trip. Another disadvantage of Type 2 service is the inability to move between outlying stations, say from point X to point Y or from C to F, without moving all the way into the CBD and back out again after transferring. Stations may require more right-of-way since turnarounds are needed at each station.

Type 3 operation has often been suggested for exclusive busways because it takes advantage of the capability of buses to move on local streets as well as over an exclusive

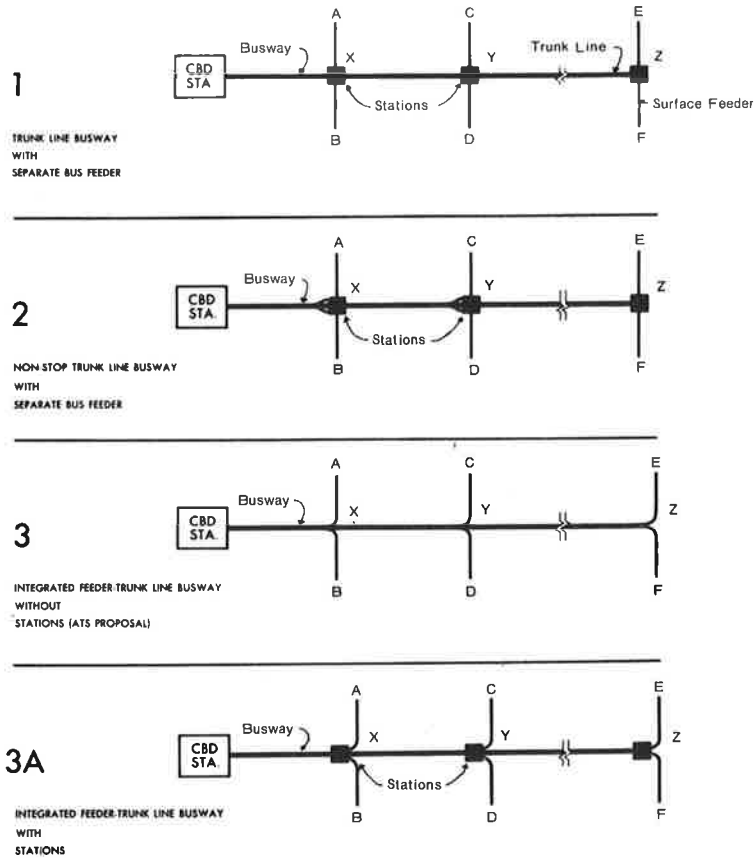

Figure 1. Alternative busway operating concepts.

busway. The same bus, therefore, feeds through local neighborhoods, enters the busway through the use of a ramp, and moves nonstop into the CBD. Such service eliminates transfers for CBD-bound patrons and also provides for nonstop service once the busway is reached. However, crosstown travelers, say moving from point E to point F, must transfer, and there are no points of high-frequency service such as that at Type 1 stations where all buses stop. Type 3 service has the same disadvantage as Type 2 in that movements between outlying points, such as from point X to point Y or from C to E, require a passenger to go all the way into the CBD station, transfer, and go back out again. Some capital cost savings are possible because stations are not required.

Type 3A service is a modification of Type 3 to add stations at the points where ramps feed into the busway. Such stations provide for interchange of passengers going crosstown as well as allow for movements between outlying stations, say from X to Y, without requiring a trip all the way into the CBD and back out again. Extra costs, of course, are incurred with Type 3A as a result of having to provide both ramps and stations, and the patrons are not provided with a nonstop ride into the CBD once gaining the busway because intervening stops must be made.

Doubtless other operating techniques could be developed, but these seem to be the principal ones advocated. There is nothing to prohibit an operation from using a combination of these procedures either simultaneously or at different times of the day in response to changes in volumes or travel patterns. However, there are limits to such changes, e. g., one cannot switch from Type 1 service to Type 3 without providing for ramps instead of stations. For purposes of relative costing and service comparisons, this study made estimates only for the four types described above.

Evaluation of Bus Operation

In order to determine whether one method of operation has a clear advantage, a series of hypothetical tests was made for each type. Evaluation was made of the relative service and cost of operation. Because all of the systems require right-of-way, grading, drainage, roadways, vehicles, communication systems, yards and shops, and stations (or ramps), they were assumed to have equal capital costs and these were not estimated. However, Type 3A requires both ramps and stations and, in fact, would have a somewhat higher capital cost than the others.

Service was measured in terms of total equivalent passenger time. Total equivalent time is defined as total movement time on the vehicle plus twice time spent waiting or transferring. Waiting time or transfer time is assumed to be one-half the headway of the line being waited for.

Costs were measured by estimating the number of vehicle hours required for one peak hour of operation. Vehicle hours were considered to be the best measure of costs because most bus operating costs are elastic and proportional to bus hours.

Assumptions

Line Lengths—Evaluations were made for two line lengths, 6 and 12 miles. The 6-mile line has 7 stations and/or ramps spaced 1 mile apart, including 6 outlying and 1 in the CBD. Additionally, there are 12 other loading points (shown as points A, B, C, D, E, and F in Fig. 1) that represent loading locations for feeder bus passengers. Similarly, the 12-mile line had a CBD station, 12 line stations (or ramp entrances), and feeder bus load points.

Traffic Patterns—In certain of the tests it was assumed that 67 percent of the passengers boarding at each point would have final destinations in the CBD. The remaining 33 percent would have final destinations divided evenly among the remaining origin points. In other words, 67 percent of all the persons boarding at point A in Figure 1 would have destinations at the CBD station, and the remaining 33 percent would be divided equally among B, C, D, E, F, X, Y, and Z. In other tests the traffic pattern was changed so that 80 percent of the patrons went to the CBD and 20 percent were divided equally among the remaining origin points.

Volumes—In most of the tests, volumes were assumed to be the same from each station and access point. That is, each point A through F and X, Y, and Z in Figure 1 had equal loadings. In one test, passenger volumes were varied in that the number of passengers boarding at each point became progressively less as the distance from the CBD station increased. This was done to see if non-uniform loading volumes would influence the relative cost-service factor of the different operational types. The four stations nearest the CBD were assumed to board 50 percent more passengers than the four middle stations, and the four outermost stations were assumed to board 50 percent less than the middle ones.

Acceleration and Deceleration Rates—All tests assumed identical acceleration and deceleration rates; however, speeds will vary for different operating types depending on the amount of nonstop operation and lengths of dwell times at stations. Acceleration and deceleration were set at 2 miles per hour per second (mphps).

Maximum Speed—Maximum speed of the busways was set at 50 mph; average speed on the feeder links, including acceleration, deceleration, and layover, was set at 10 mph.

Dwell Time and Layover—Layover was set at a minimum of 10 percent of round-trip running time; dwell times were dependent on passenger loading at particular stations. Dwell times were considered only at the stations and/or access points denoted by points X, Y, and Z in Figure 1. These dwell times vary with the number of passengers getting on and off each vehicle at each point. Dwell times were set at 2 seconds per boarding passenger plus 10 seconds for door open/close and clear time. Therefore, because one bus could board as many as 50 passengers at a point (as in Type 2), the dwell time could be as much as 110 seconds. A minimum dwell time of 20 seconds could occur in some cases where a large number of buses are servicing a particular point.

Headways—In all cases, buses were assumed to have 50 seats and to carry a maximum of one passenger per seat. Headways were set for each line by the number of

buses required to service the passengers at the maximum load points. If 1,000 passengers boarded the busway system at each point and each bus carried 50 passengers, feeder bus headways for Types 1 and 2 (in these types, feeder buses never enter the busway) would be 3 minutes (20 buses per hour). In Types 3 and 3A feeder buses enter the busway and have headways somewhat less (more frequent) because each feeder is required to take care of the total volume of its own feeder area plus half the volume of the station (e.g., points X, Y, or Z in Fig. 1) Therefore, the basic feeder headway in such circumstances is 2 minutes on each leg. Headways on the busway portions of each of the alternative concepts would be as follows:

On Type 1 the headway on the trunk line at the terminal station, Z in Figure 1, would have to be sufficient to carry the number of passengers originating at E, F, and Z; that is, 3,000 passengers (assuming that 1,000 loaded at each point) minus a small number bound from E to Z and F, from F to E and Z, and from Z to E and F. This small number is disregarded, and the headway to be scheduled from Z to Y would be 1 minute (60 buses per hour). Accordingly, that from Y to X would be approximately one-half minute and that from X to the CBD, approximately one-third minute. These headways would hold if turnbacks are considered at each station. However, if turnbacks are not considered, then the headway from X to the CBD (or one-third minute) would be controlling throughout the length of the busway portion of the system.

The headway is set individually at each station in the Type 2 system because the concept is that of a loop wherein each station has its own nonstop service to and from the CBD. In this case there would be approximately 3,000 persons at each station, and a 1-minute headway from each station would be necessary. Type 3 has 1-minute headways for boarding passengers at each ramp access point because this is controlled entirely by the feeders. (There would be additional buses coming from upstream stations, but these would not stop at intermediate stations.) However, in Type 3A buses entering at each previous access point stop at all successive points to the CBD, and they would have headways of 1 minute at point Z, one-half minute at point Y, and one-third minute at point X, a situation similar to that in Type 1 using turnbacks.

Feeder Bus Route Length—Feeder buses were assumed to run on routes perpendicular to the busway for a distance of one mile either side of the busway. In one test feeder routes were lengthened to two miles.

Results

Tests were made for the four-system operating types with variable line lengths, traffic patterns, feeder lengths, station spacing, and loading distribution. Conditions could be found that favor the use of any of the four types of operation, depending on the combination of variables chosen.

For purposes of illustrating the sensitivity of the variables, a system was selected that could be used for comparisons to other combinations. The basic system selected was 12 miles in length, had stations (or ramps) spaced a mile apart, had feeder bus routes of a mile, had uniform passenger loading with 67 percent of all passengers bound for the CBD, and allowed no bus turnback points for the Type 1 operation (i.e., all buses in the Type 1 system ran from terminal to CBD and back, even though most were relatively empty as they traveled the outer portions of the line).

A single cost-service measure was computed as:

$$I_n = BH_n \times EPT_n$$

where

I_n = Cost-service measure for Type N operation,
BH_n = Bus hours required to serve the trunk line and feeders for one hour using Type N operation, and
EPT_n = Equivalent passenger time in minutes $\times 10^{-3}$.

A system is better as I_n decreases because the objective of a good system is to reduce costs and passenger time to a minimum.

A comparison of the basic system to several variations is shown in Figure 2. For each test the type operation that gave the lowest cost-service measure was set at 100, and a cost-service index was computed for the other types relative to 100. For example, Figure 2 shows that Type 3A had a cost-service measure of 100 in Test A, and Type 3 had a measure 1.06 times this. One may say that Type 3 was 6 percent poorer than Type 3A from a composite cost-service standpoint.

Figure 2 shows that Types 2, 3, and 3A perform similarly under varying conditions. Type 1 appears to show an inferior cost-service performance. This may result partially from the no-turnback restriction. Types 2, 3, and 3A are designed to be inherently sensitive to passenger travel demands. Service on the outer ends of the busway is reduced, whereas Type 1 buses all run the full length of the busway. When two intermediate turnbacks are introduced, as in Test D, Type 1 narrows the differentials with the other types significantly.

The length of feeder route is also an important variable because Types 3 and 3A use the same vehicles for feeder and trunk service. If these feeder routes are longer, they affect a higher proportion of the total buses. Test E shows that the use of 2-mile feeder routes works to the relative advantage of Types 1 and 2. Though no test was run that combined longer feeder routes with cutback service for Type 1, it is possible that Type 1 could be superior to Types 3 and 3A under such conditions.

TEST	DESCRIPTION	Passenger Service Cost Index for Types 1	2	3	3A
A	BASIC SYSTEM Line Length: 12 miles % Passengers to CBD: 67% Type 1 Turnbacks: None Feeder Bus Route Lengths: 1 mile Station Spacing: 1 mile Passenger Loading: Uniform	124	104	106	100
B	CHANGE LINE LENGTH Line Length: 6 miles All other parameters same as basic system	110	108	114	100
C	CHANGE PASSENGER DISTRIBUTION % Passengers to CBD: 80% All other parameters same as basic system	127	104	101	100
D	USE TURNBACKS IN TYPE 1 OPERATION No. of Turnback Points: 2 All other parameters same as basic system	114	104	101	100
E	USE LONGER FEEDER ROUTES Feeder Bus Route Length: 2 miles All other parameters same as basic system	118	100	121	115
F	USE LONGER STATION SPACING Station Spacing: 2 miles All other parameters same as basic system	123	101	109	100
G	VARY LOADINGS WITH DISTANCE FROM CBD Passenger Loadings: First four stations from CBD load 50% more passengers than the second four stations. The third four stations from CBD load 50% less passengers than second four stations.	166	100	100	100

Figure 2. Summary comparison of types of bus operation.

Test G illustrates again the cost effectiveness of tailoring service to passenger demands. Type 1 service, without cutback, is clearly inferior when passenger demand diminishes with distance from the CBD. Types 2, 3, and 3A automatically tailor service, and they are not so adversely affected. Under such loading conditions, one would use cutbacks frequently if Type 1 service were in use.

Type 3A appears to have some advantages for the range of variables tested here. However, its operation is more complex, and its ramps and stations require somewhat more capital cost and would be more difficult to superimpose on an urban environment.

Figure 2 seems to suggest that Type 1 operation is inherently inferior to the others. However, this conclusion is not warranted because different results could be obtained by running the tests with multiple turnbacks on Type 1 operation and increasing the length of feeder routes. A more appropriate conclusion is that any particular operating type could be superior in a given instance, depending on the environment for which service is required. Additional study to specify boundary conditions where each operating type is superior could be helpful.

In the following section, Type 1 bus operation (with turnbacks) is used for comparison to rail systems. We can now proceed with this analysis with some assurance that the selection of Type 1 operation will result in an unbiased comparison or, at least, with some insight into the direction and magnitude of the bias.

BUS-RAIL COMPARISONS

Cost comparisons of bus and rail are often clouded by difficulties in ensuring that equal service is provided by each mode. Buses typically have on-board fare collection, confined seating, narrow doors, entrance steps, and low acceleration rates. These characteristics are generally not found in the newer rail systems. Special attention was given in these analyses to the task of ensuring that the service level was equal for each mode so that any differentials found in cost would be meaningful.

Because one bus operating method is reasonably equivalent to another from a cost-service standpoint and because it was essential to ensure equal service for bus and rail systems being compared, bus and rail vehicles were assumed to operate in identical patterns equivalent to those in the Type 1 system. All express transit vehicles would operate only on exclusive roadways, pick up or discharge passengers only at stations, and require either a walk or a feeder conveyance to gain access to the system. Station spacing was assumed to be 1.5 miles, and line lengths of 6 and 12 miles were tested.

Bus Performance and Comfort

Ordinary buses operating in such a system could not compete with modern rail vehicles because of longer passenger loading and discharge time and slower acceleration. To ensure that dwell times of bus and rail would be equal, it was assumed that the buses were provided with extra-wide doors so that the linear feet of door openings per square foot of passenger space would be approximately the same on both rail and bus. This meant that a 40-ft bus required one 30-in. door and one 50-in. door in order to be equivalent to the two 54-in. doors found on the 70-ft rail car proposed by MARTA. The MARTA rail car proposed for Atlanta was used as the standard for all comparisons. Seventy ft long, and 10.5 ft wide, it has 72 seats and two 54-in. doors. The seats are 41 in. wide, and there is a 34-in. longitudinal distance between seats (seat back to seat back). For the buses to operate in and out of high-platform stations without delay, it was assumed that a device would be installed at each door sill that would extend outward to bridge the gap between bus and platform.

Fare collection was assumed to take place in stations (off the vehicle) for all systems. Bus seats were widened and foot room increased by providing two seats on one side and one on the other. This was required in order to provide the same seating comfort (number of seats per square foot of floor space) as that provided on the MARTA rail vehicle. Air conditioning was assumed on both systems.

Equipped with the latest V-8 diesel engines, high-torque transmissions, and separate engines to power air conditioning equipment, a bus could be made to accelerate at 2

mphps up to 30 mph, at which point tapering begins. In contrast, the MARTA rail vehicle is designed to accelerate at 3 mphps up to 30 mph. There appeared to be no way to overcome this discrepancy in service. On the 12-mile line this differential in acceleration caused the bus to take 4 minutes longer than rail from terminal to terminal. The difference for most passengers, of course, would be much less than this. On the other hand, at most volumes buses must operate at closer headways to carry the same load, and this is a plus service factor for buses. For this analysis it was assumed that these factors traded off equally. Slower speeds, however, did reflect adversely on bus operating costs because relatively more vehicles were needed to provide the same service. All modifications to buses described above were included in vehicle cost estimates. Vehicle manufacturers were contacted to confirm the feasibility of some of the modifications.

Articulated Buses

One of the disadvantages of buses, particularly as passenger volumes increase, is that added passengers mean more drivers and higher cost, whereas longer trains can be operated on rail with the same number of personnel. Clearly, bigger buses that would increase the passenger/driver ratio could potentially reduce bus costs. Large articulated buses have been used in Europe for urban service for years. The Alameda-Contra Costa Transit District in the San Francisco Bay area has been experimenting with a similar vehicle. Such a bus, 60 ft long, could carry over 40 percent more passengers than a 40-ft bus using the same space standards. Although the larger bus would require somewhat large platforms at stations, its potential advantages were sufficient to justify separate analyses. The articulated bus is hereinafter referred to as the 60-ft bus.

Underground Systems

Ventilation and driving clearance requirements usually work to the disadvantage of buses used in tunnels. Thus, separate analyses were made for lines requiring no subway and those requiring 20 percent subway. Several lines in Atlanta could be built with virtually no subway construction because of the availability of surface right-of-way along railroad lines that continue through the center of the central business district.

Lower ventilation costs would be incurred if electric trolley buses were used instead of diesel coaches. However, there would be added costs for a larger tunnel to accommodate overhead wires and collection devices. The cost of the power distribution system that would be required over the entire private right-of-way line would tend to offset ventilation savings. Thus, diesel buses were assumed for all tests.

Wage Rates

All comparisons were made using 1967 unit costs and wage rates. Buses are more labor intensive than rail, and future increases in operator wages could work to the relative disadvantage of bus systems. An analysis was prepared of trends in transit personnel wage rates (after correcting for inflation) in recent years, and from this a 15-year projection was made. The future rates are expected to be 67 percent above today's rates, or the equivalent of a 3.5 percent annual increase. One could well project wage levels 20 or 30 years into the future, or use a different rate of increase, but the values used here are believed reasonable and were selected to show the relative effect of increased wages.

Cost of Capital

Rail systems cost more to construct than bus systems, and thus are more capital intensive. Two different costs of capital were assumed: (a) 4 percent, which was selected to represent a minimum borrowing cost for public agencies, and (b) 7 percent, which was selected to represent the opportunity cost of using capital that could otherwise be used in the commercial or private market. Presumably commercial risk capital would be worth 7 percent or more, and one may reasonably consider a denial of

its use in the private market as a cost that should be attributed to the transit system. Some economists might suggest a still higher opportunity cost, but these analyses will indicate the relative sensitivity of rail and bus cost to this variable.

Physical Standards

Physical standards were prepared for each system so that equivalent levels of service would be provided. Figures 3A and 3B illustrate the various standards used.

Roadway widths for bus and rail are quite similar (12.5 ft for rail and 12.0 ft for bus) but the right-of-way widths on grade, cut, and fill sections are somewhat wider for rail because a 2.5-ft safety walk is provided away from the third rail. The difference in subway widths (2.5 ft more for bus) is to provide buses with additional maneuvering room. Buses, which are 8.5 ft wide, are provided with standard 12-ft freeway lanes, plus 2-ft curbs on either side for safety. This gives actual wall-to-wall clearance of 16 ft. In aerial configuration, there is no difference between systems because both use identical structures. The safety walk for the rail system is in the center of the structure away from the third rail. (There is a 3-ft clearance between cars of opposite-direction trains, and the safety walk is elevated above the third-rail level.)

Rail stations are long enough to handle the peak number of cars per train indicated for each volume—140 ft (two 70-ft cars) for the 4,000-passenger tests and 420 ft (six 70-ft cars) for the 12,000-passenger tests. Two escalators were assumed at each station platform (4 per station); six escalators were assumed at the CBD station for the 12,000 volume test. Busway stations are shown in Figures 4A and 4B. The tests with 4,000 passengers maximum volume for the 40-ft bus assumed the type A1 station with two

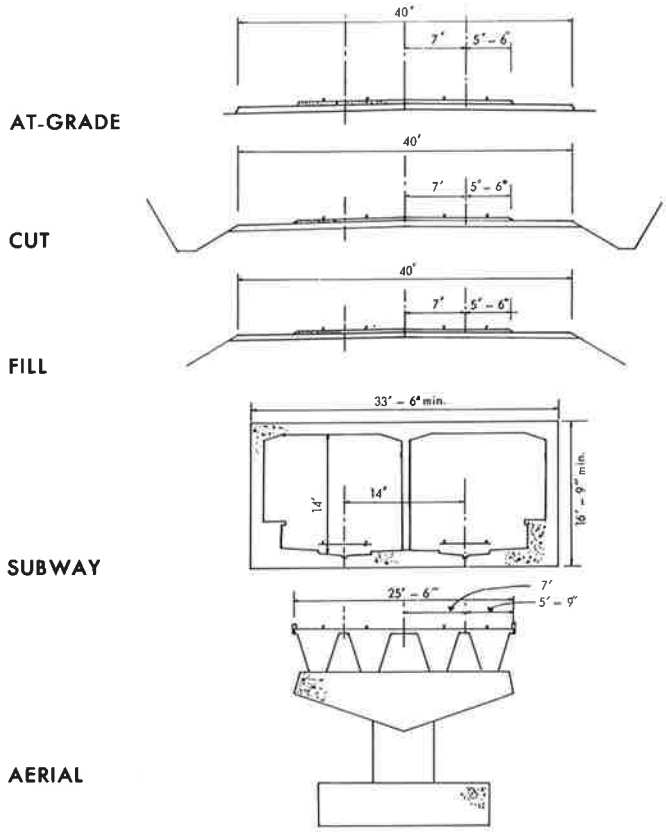

Figure 3A. Typical rail rapid transit configurations.

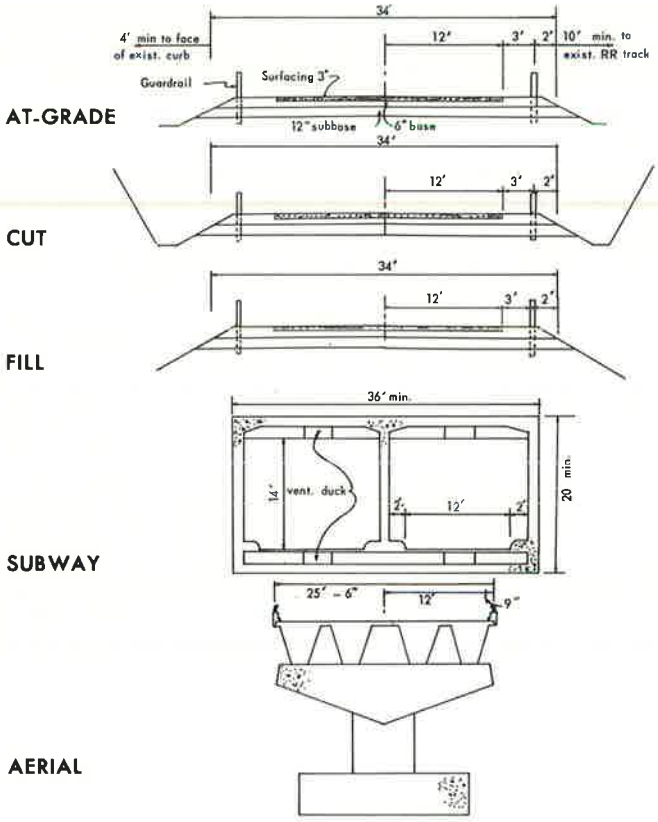

Figure 3B. Typical busway configurations.

escalators per platform (4 per station). The 60-ft bus tests, at the same volume, used the A2 station with the same number of escalators. At the 12,000-passenger level, the 40-ft bus system assumed type B2 stations up to and including the turnback point. Beyond the turnback point (3 stations), the A1 type station was assumed. The 60-ft bus used the B3 type station for the initial 6 stations, and the A2 station for points beyond the turnback to the end of the line. The reason, of course, for the increased number of platforms for the busway stations as volume increased is that the headways decreased as follows:

Passenger Volumes	40-ft Bus	60-ft Bus
4,000 (max. load)	35 sec	51 sec
12,000 (max. load)	12 sec	17 sec
12,000 (beyond turnback)	24 sec	34 sec

Construction costs were estimated using unit costs for labor and materials in the Atlanta area. These costs were estimated by Daniel, Mann, Johnson and Mendenhall, consulting engineers.

Operating Costs

Operating costs for each system were developed by using standard operating accounts and by staffing both systems at Atlanta wage rates for comparable positions. The rail accounts were comparable to MARTA estimates, and the bus costs reflect current ATS

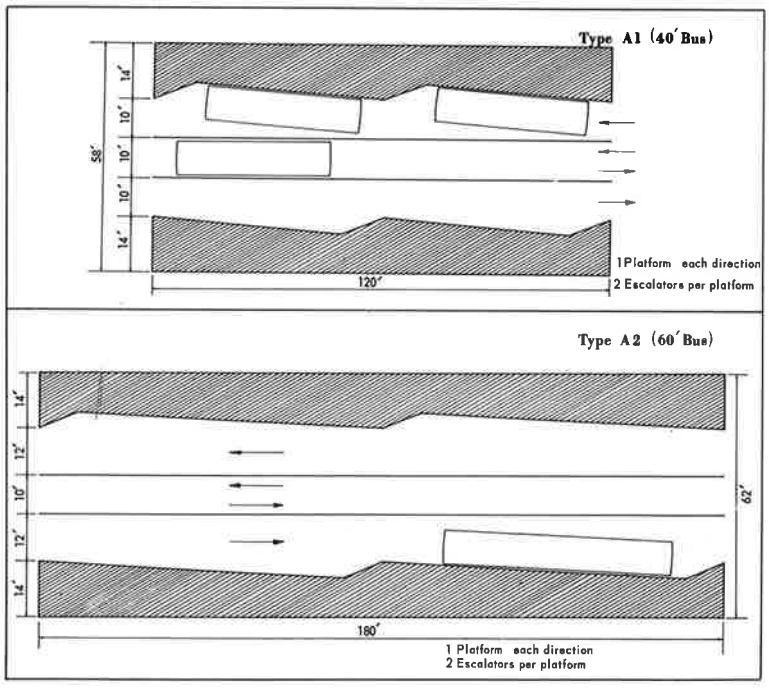

Figure 4A. Typical busway station layouts.

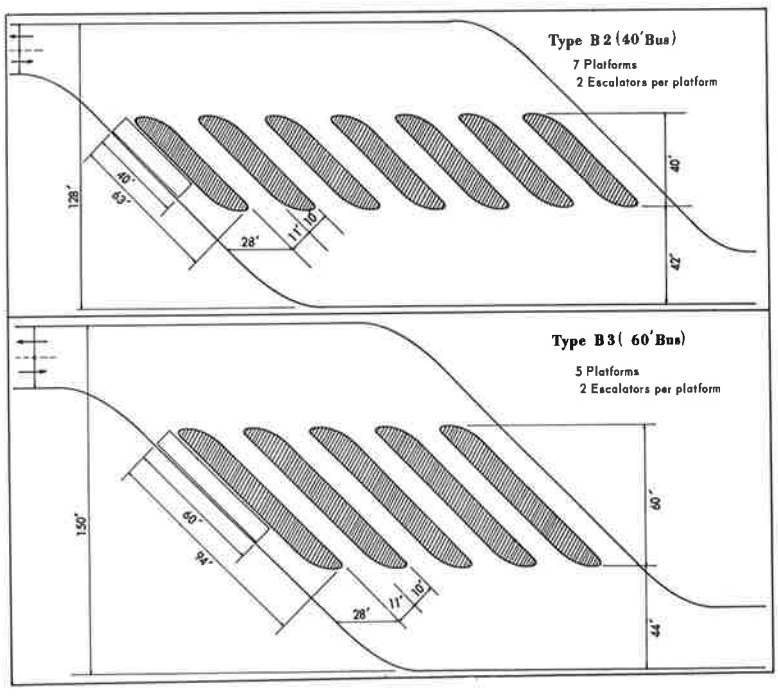

Figure 4B. Typical busway station layouts (suggested by Mayer, Kain, and Wohl in The Urban Transportation Problem).

costs plus necessary provisions for station agents, communications and control systems, and maintenance-of-way and structures. Where staffing of a similar nature was required for both modes, e.g., station agents, equal costs were used.

Rail vehicles were assumed to cost $185,000 each and were amortized at 6.5 percent annually for 30 years. The 40-ft bus was costed at $45,000, and the 60-ft bus at $70,000. Both types of buses were amortized at 6.5 percent for 15 years.

Scheduling

Annual miles and hours for costing purposes were determined for rail as follows: The number of peak-hour passengers at the maximum load point was divided by the assumed maximum train frequency (30 per hour) to produce the requisite number of seats per train. This number of seats was divided by seats per car (72), and the number of cars per train was determined. To obtain off-peak values, the peak-hour volume was divided by 6.2 (the average peak hour was assumed to have 6.2 times more passengers than the average off-peak hour), then divided by minimum frequency (12 trains per hour) to determine the number of seats required per train. Because the off-peak load factor was assumed to be 75 percent of seats, a maximum of 54 passengers per car was assumed ($0.75 \times 72 = 54$). The number of seats required was divided by 54 to produce cars per train. When these train consists had been determined (never fewer than two cars per train), the requisite trains were scheduled over the individual systems to determine train hours and car miles for one peak hour and one off-peak hour.

A similar procedure was followed for buses except that bus frequency was determined by dividing the proper number of passengers per hour by the given bus capacity.

For both rail and bus systems, turnbacks were provided at the 9-mile station from the CBD, and turnbacks were permitted at that point as long as headways did not exceed 5 minutes at any point along the system. Turnbacks were not contemplated on the 6-mile systems.

These parameters were used to construct operating schedules and to derive vehicle miles and train or bus hours.

Annualization

Annual vehicle miles and train or bus hours were determined by the following means: A weekday was assumed to consist of 4 peak and 17 off-peak hours, a Saturday of 21 off-peak hours, and a Sunday and a holiday of 10.5 off-peak hours (Saturday divided by 2). A year contains (normally) 255 weekdays, 52 Saturdays, and 58 Sundays and holidays. Therefore, the following formula was derived:

$$\text{Annual Miles} = 255(4P + 17B) + 52(21B) + 58(10.5B)$$

where

P = peak-hour miles, and
B = off-peak-hour miles.

Substituting hours for miles in this formula will give annual hours. When the appropriate costs per mile and hour were applied, annual costs for each system were determined.

SUMMARY OF ASSUMPTIONS USED IN BUS-RAIL COMPARISONS

Assumptions used in this analysis can be classified into three main groups: (a) constant assumptions, or those applied equally to all modes for all cases; (b) variable assumptions, or those applied equally to all modes but varying for different cases; and (c) special assumptions, or those applying uniquely to each vehicle type tested.

Constant Assumptions

Operating Methods—Rail cars and buses were operated identically: all vehicles stop at all stations, run from terminal to terminal on grade-separated roadways, and restrict

their movements to within the closed system, i.e., busway buses did not at any point operate on local streets. One exception was made to this: one-half of all buses on the 12-mile tests were turned back at the 9-mile station. This provides operating economies to the bus. However, the 5-minute maximum headway standard prohibited the turnback for the 60-ft bus in some instances. It is this same standard that keeps the rail vehicle from being turned back except in the case of higher volumes and then only in the peak hours. All fares were collected off the vehicles. Each test was for a single line with one CBD station and a variable number of outlying stations.

Station Spacing—Stations were assumed at 1.5-mile intervals.

Passenger Traffic Patterns—All line stations (outside the CBD) were assumed to handle equal volumes of passengers. Seventy percent of all passengers trips were assumed to begin or end in the CBD. The other 30 percent were distributed equally to non-CBD stations. Travel in the 4 peak hours was assumed to be approximately 60 percent of the total day.

Passenger Access to the System—Passengers were assumed to reach the stations of either rail or bus systems by walking, driving automobiles, or riding in feeder buses. No analysis was performed for costs of feeder service. Comparisons are for trunk-line service only.

Equal Comfort—So that similarity of service between modes was ensured, seats in all vehicles were assumed to be the same size (41 inches wide by 34 inches, back to back). This dictated 72, 40, and 57 seats in the rail, 40-ft bus, and 60-ft bus, respectively. All vehicles were assumed to be air conditioned. Escalators were at all stations. Maximum passenger loadings were 100 percent of seats during the peak hours and 75 percent of seats during the off-peak periods.

Headways—Maximum headways were assumed to be 5 minutes for all modes. This is a critical assumption. If a 10-minute maximum had been assumed, it could have made the rail system relatively more favorable. During low-volume conditions the larger rail units could have carried loads adequately at 10-minute headways, but the 40-ft bus would have required 3-minute service. Clearly the service differential between 3- and 10-minute headways is not negligible. Thus, a 5-minute maximum headway was assumed.

Variable Assumptions

Line Lengths—Analyses were made for lines 6 miles (5 stations) and 12 miles (9 stations) in length.

Passenger Volumes—It was assumed that there were passenger loadings of 12,000 and 4,000 at the maximum load point of the line for the peak hour, peak direction.

Station Stop Time—Both bus and rail vehicles were assumed to operate with equal dwell times for equal line loadings and line lengths. This was possible by assuming (and including in the cost estimates) that there were high platforms, equal door widths (per passenger carried), equal space (per passenger), and off-vehicle fare collection.

Wage Levels—Separate estimates of operating costs were prepared using today's wage levels and those expected to prevail 15 years hence (1.67 times today's levels).

Costs of Capital—Separate estimates of annual capital cost were prepared using 4 percent and 7 percent annualization rates.

Proportion of Line in Subway—Separate analyses were prepared for lines having no subway (90 percent at grade and 10 percent aerial), and those having 20 percent subway (70 percent at grade and 10 percent aerial).

Special Assumptions

Vehicle Specifications—The specifications for each vehicle tested are given in Table 1; note in the table that even during off-peak periods at least two 70-ft car units were assumed to be coupled to form a 140-ft train. One-car units could theoretically be used but were not for this analysis nor are they generally used in practice for the following reasons:

1. There generally is an operating console only in one end of a car. To operate in either direction this requires either a loop track at the ends of each line or two cars coupled with a console at opposite ends.

TABLE 1

VEHICLE SPECIFICATIONS

Item	Rail	40-Ft Bus	60-Ft Bus
Maximum speed	70 mph	50 mph	50 mph
Acceleration rate (initial, before taper)	3.0 mphps to 30 mph	2.0 mphps to 30 mph	2.0 mphps to 30 mph
Length, vehicle	70 ft	40 ft	60 ft
Width, vehicle	10.5 ft	8.5 ft	8.5 ft
Width, door	2, 54 in.	1, 30 in. and 1, 50 in.	1, 30 in. and 2, 50 in.
Seat spacing (back of seat to back of seat)	34 in.	34 in.	34 in.
Double-seat width	41 in.	41 in.	41 in.
Number of seats	72	40	57[a]
Passenger loading:			
Peak hour	100% seats	100% seats	100% seats
Off-peak hour	75% seats	75% seats	75% seats
Headways			
Maximum	300 sec	300 sec	300 sec
Minimum	120 sec	—	—

[a]Articulation unit occupies equivalent of three seats.

2. To supply an operating console at each end of a car costs more and requires some space otherwise available for passengers.

3. There are few hours per day where volumes are low enough to allow one car operations if the seating and headway standards are met.

4. Savings would be nominal because operating two cars in light periods requires the same number of operators, station personnel, and administrative costs. Power savings would be nominal because the so-called "demand" or peak-hour charge would not change. Some maintenance would be saved, but additional hostlers would be required to uncouple and couple cars.

Speed of Operation—Acceleration rates and maximum speed limitations caused the buses to make the trip from terminal to terminal on the 12-mile line 4 minutes slower than rail, although the differential for most riders would be less than half that. Buses, being smaller, operated at shorter headways for most volumes, and this tends to offset the speed disadvantage. Also, although it was not assumed in this analysis, buses are capable of operating skip-stop with little loss of service because of their very frequent headways at most volumes.

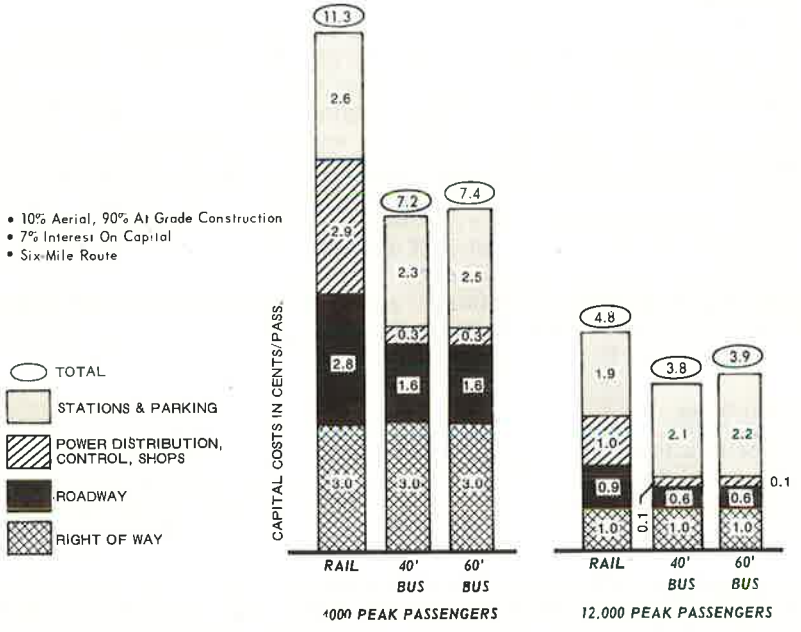

Figure 5. Comparison of rail and busway capital cost (cents per passenger).

CAPITAL COST ESTIMATES

Capital costs for either a bus or a rail system may be broadly classified into four main categories: (a) right-of-way; (b) roadway, including grading, drainage, structures, ballast, tunneling, track or paving, guardrails, yards, and shops; (c) power distribution, control, and communications systems; and (d) stations and parking lots. Vehicle costs are included with operating costs for these analyses.

Figure 5 shows that costs of stations and rights-of-way are about equal for bus and rail for either high or low volumes. (It should be noted that this so-called high volume, 12,000 peak direction, is less than one-half of the volume carried on a number of rail transit lines in North America. Rail is clearly superior for these higher loads.) However, the costs of power distribution and control systems are more than five times as great for rails. Also, costs for track and ballast for rails are greater than are those for paving for buses. The overall capital costs are 50 percent greater for rail than for buses at the 4,000-volume level and 25 percent greater at the 12,000-volume level.

The cost per passenger for almost all cost items is substantially lower for the high-volume level, illustrating the easier task of justifying express transit systems where significant traffic can be generated. However, the cost per passenger for bus stations decreases very little for the high-volume levels. High-volume bus stations require multiple platforms, extra escalators, and other added costs, almost in direct proportion to added passengers.

Capital costs for the 12-mile line are almost all twice the cost of the 6-mile line, and thus are not graphically illustrated. Capital costs for the route with 20 percent subway are over 50 percent greater than those for the route without subway, illustrating the high cost of underground construction. Figure 6 indicates that roadway costs (including tunneling) are 12 to 18 percent higher for buses than for rail. Clearly, as the proportion of the line involving subways increases, the more roadway costs will transcend other

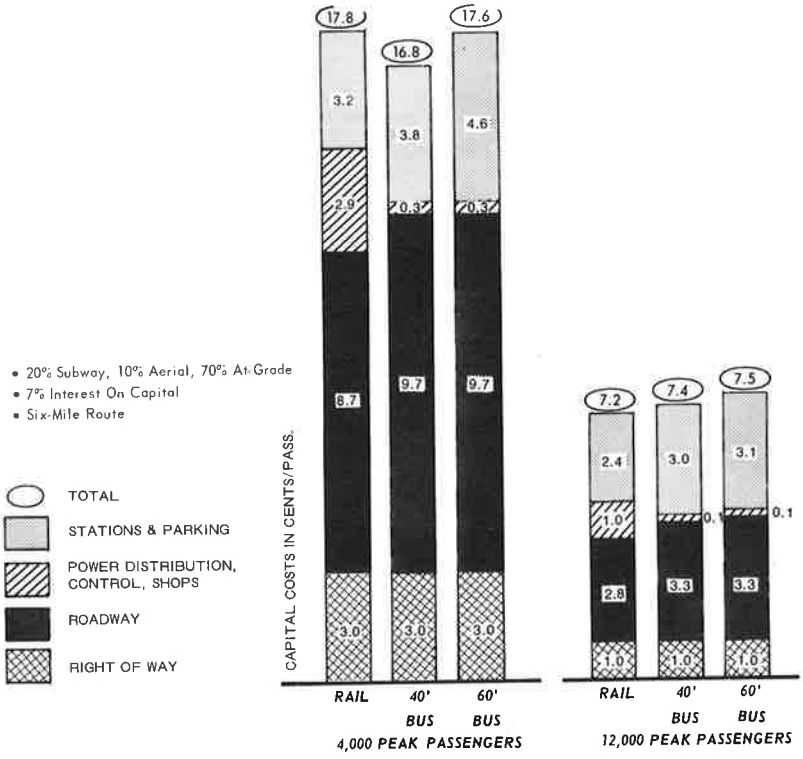

Figure 6. Comparison of rail and busway capital cost (cents per passenger).

cost elements, and roadway cost differentials between modes will become decisive. Even with 20 percent subway, roadway costs make up almost one-half of the total capital cost of the line.

The impact of interest rates on capital costs is significant. The increase from 4 percent to 7 percent over the 60-year period increases capital costs by 50 percent on an annual or per-passenger basis (see Tables 2 through 7).

TABLE 2

COST SUMMARY—RAIL TRANSIT
(Route Length: 6 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	12.7	7.5	20.2	8.0	3.2	11.2
		High	12.7	11.3	24.0	8.0	4.8	12.8
	1983	Low	16.7	7.5	24.2	9.8	3.2	13.0
		High	16.7	11.3	28.0	9.8	4.8	14.6
20% subway	1968	Low	12.7	11.9	24.6	8.0	4.8	12.8
		High	12.7	17.8	30.5	8.0	7.2	15.2
	1983	Low	16.7	11.9	28.6	9.8	4.8	14.6
		High	16.7	17.8	34.5	9.8	7.2	17.0

TABLE 3

COST SUMMARY—BUSWAYS (40-FT BUS)
(Route Length: 6 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type of Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	12.5	4.8	17.3	9.7	2.5	12.2
		High	12.5	7.2	19.7	9.7	3.8	13.5
	1983	Low	17.6	4.8	22.4	13.0	2.5	15.5
		High	17.6	7.2	24.8	13.0	3.8	16.8
20% subway	1968	Low	12.5	11.2	23.7	9.7	4.9	14.6
		High	12.5	16.8	29.3	9.7	7.4	17.1
	1983	Low	17.6	11.2	28.8	13.0	4.9	17.9
		High	17.6	16.8	34.4	13.0	7.4	20.4

TABLE 4

COST SUMMARY—BUSWAYS (60-FT BUS)
(Route Length: 6 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type of Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	11.4	4.9	16.3	8.6	2.6	11.2
		High	11.4	7.4	18.8	8.6	3.9	12.5
	1983	Low	15.9	4.9	20.8	11.3	2.6	13.9
		High	15.9	7.4	23.3	11.3	3.9	15.2
20% subway	1968	Low	11.4	11.7	23.1	8.6	5.0	13.6
		High	11.4	17.6	29.0	8.6	7.5	16.1
	1983	Low	15.9	11.7	27.6	11.3	5.0	16.3
		High	15.9	17.6	33.5	11.3	7.5	18.8

TABLE 5

COST SUMMARY—RAIL TRANSIT
(Route Length: 12 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type of Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	19.9	14.8	34.7	12.5	6.1	18.6
		High	19.9	22.3	42.2	12.5	9.2	21.7
	1983	Low	26.4	14.8	41.2	15.8	6.1	21.9
		High	26.4	22.3	48.7	15.8	9.2	25.0
20% subway	1968	Low	19.9	23.3	43.2	12.5	9.3	21.8
		High	19.9	35.0	54.9	12.5	14.0	26.5
	1983	Low	26.4	23.3	49.7	15.8	9.3	25.1
		High	26.4	35.0	61.4	15.8	14.0	29.8

TABLE 6

COST SUMMARY—BUSWAYS (40-FT BUS)
(Route Length: 12 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type of Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	19.5	9.1	28.6	14.7	4.7	19.4
		High	19.5	13.7	33.2	14.7	7.1	21.8
	1983	Low	27.5	9.1	36.6	20.5	4.7	25.2
		High	27.5	13.7	41.2	20.5	7.1	27.6
20% subway	1968	Low	19.5	21.9	41.4	14.7	9.4	24.1
		High	19.5	32.9	52.4	14.7	14.1	28.8
	1983	Low	27.5	21.9	49.4	20.5	9.4	29.9
		High	27.5	32.9	60.4	20.5	14.1	34.6

TABLE 7

COST SUMMARY—BUSWAYS (60-FT BUS)
(Route Length: 12 Miles)

Other Variables			Costs (cents per passenger)					
			4,000 Passengers (peak hour)			12,000 Passengers (peak hour)		
Type of Construction	Wage Level (year)	Cost of Money	Operating	Capital	Total	Operating	Capital	Total
No subway	1968	Low	17.8	9.3	27.1	13.0	4.8	17.8
		High	17.8	14.0	31.8	13.0	7.2	20.2
	1983	Low	25.0	9.3	34.3	17.5	4.8	22.3
		High	25.0	14.0	39.0	17.5	7.2	24.7
20% subway	1968	Low	17.8	22.7	40.5	13.0	9.7	22.7
		High	17.8	34.1	51.9	13.0	14.6	27.6
	1983	Low	25.0	22.7	47.7	17.5	9.7	27.2
		High	25.0	34.1	59.1	17.5	14.6	32.1

OPERATING COSTS

Figure 7 shows comparisons of operating costs for rail and busways based on the assumption that future wage rates are 67 percent above today's. For low-volume routes operating costs vary only 5 percent between modes. Surprisingly, costs for the 60-ft bus are even lower than those for rail.

On low-volume routes and off-peak periods as many operators are required for rail as for bus if the minimum of 12 trains per hour (5-minute headway) is to be maintained. For higher volumes, however, extra passengers are carried simply by adding cars to trains, and then more operators are required for buses. Costs for bus, excluding those for operators' wages, are equal to or higher than those for rail except that costs for vehicle maintenance are higher for 40-ft buses because more of them are needed.

Operating costs for the 12-mile line (see Tables 2 through 7) are about 55 percent higher than those for the 6-mile line for all modes. This is because of economies inherent in operating larger systems (spreading overhead), the lower number of

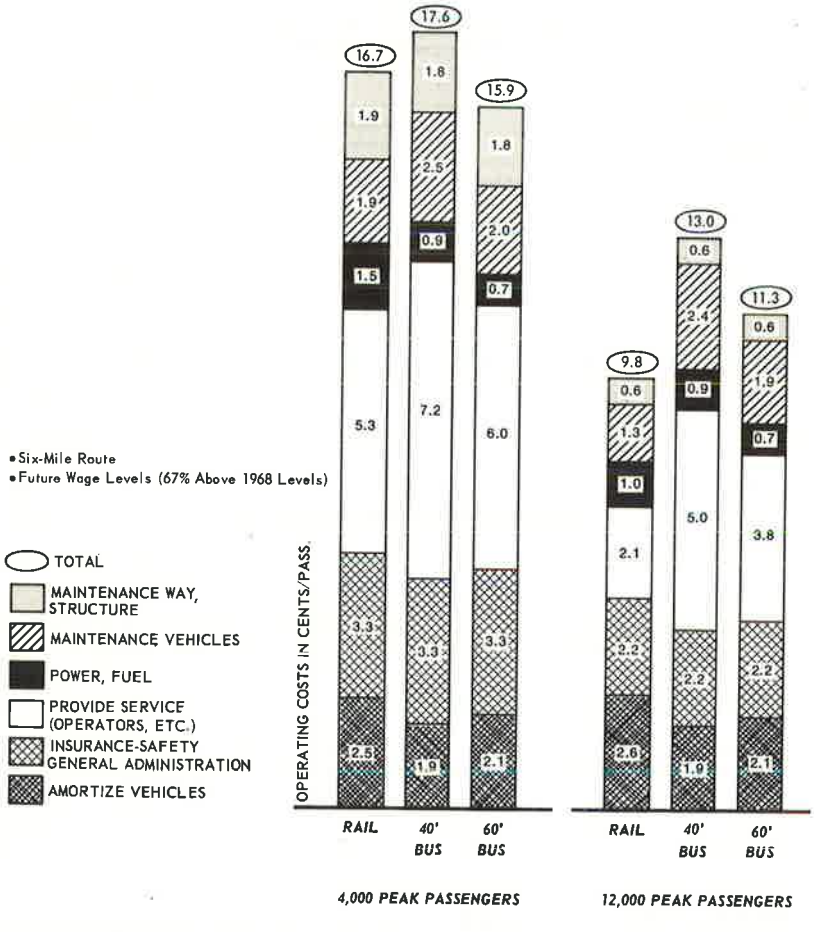

Figure 7. Comparison of rail and busway operating cost (cents per passenger).

passengers handled per station, and reduced layover as a percentage of running time in longer systems. The impact of increased wages on bus operating costs can be seen in Figure 8. Biggest increases are found in operators' wages and in maintenance. Vehicle amortization and fuel costs are unaffected.

TOTAL COST

When the cost per passenger associated with capital cost is added to the operating cost, the total cost per passenger can be estimated for each of the various cases studied. Figure 9 shows total cost comparisons of the 6-mile line where 7 percent interest on capital and future wage rates are assumed.

For cases involving 20 percent subway, both construction and operating costs are approximately equal, although rail is slightly less costly for the higher volume cases. Doubtless the relative cost efficiencies with rail would grow at volumes above 12,000 per hour because additional volumes can be accommodated by simply lengthening trains and stations. Bus stations, on the other hand, get increasingly complex, and operating costs would soar with added drivers. Lines with greater than 20 percent subway would also tend to show cost efficiencies in favor of rail because larger tunnels and expensive ventilation systems are required for buses.

The relative costs of bus or rail with 20 percent subway are not particularly sensitive to assumptions about interest rates or wage levels. All systems have about the same capital intensiveness and/or labor intensiveness, i.e., higher interest or wage rates would increase costs of rail or bus almost equally.

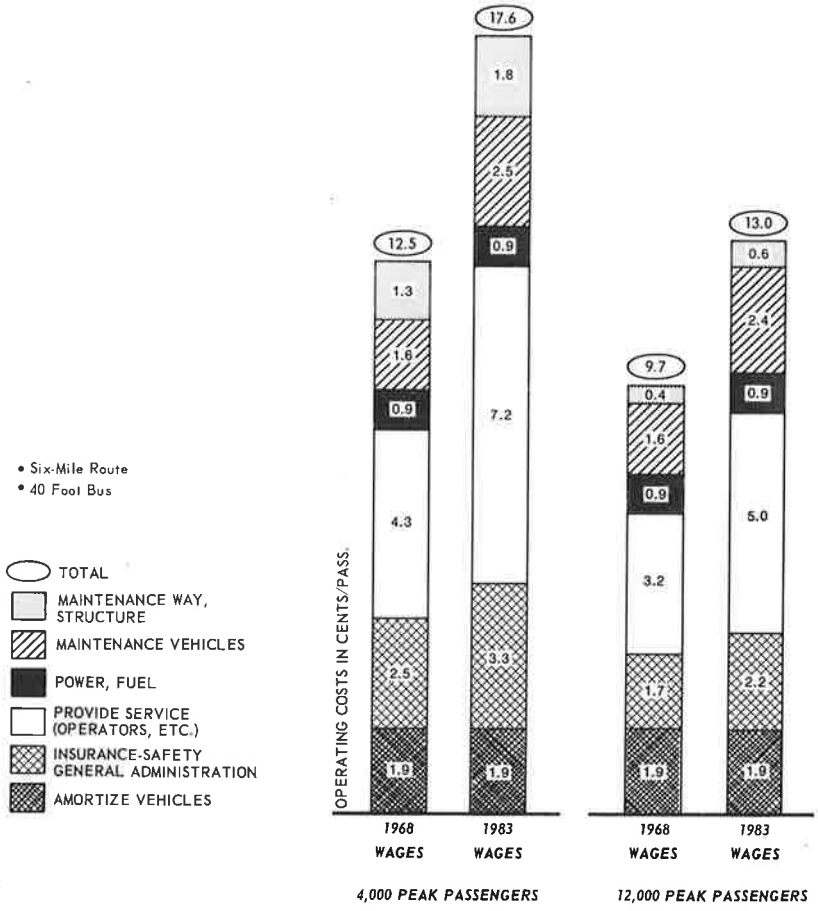

Figure 8. Busway operating cost variations (cents per passenger).

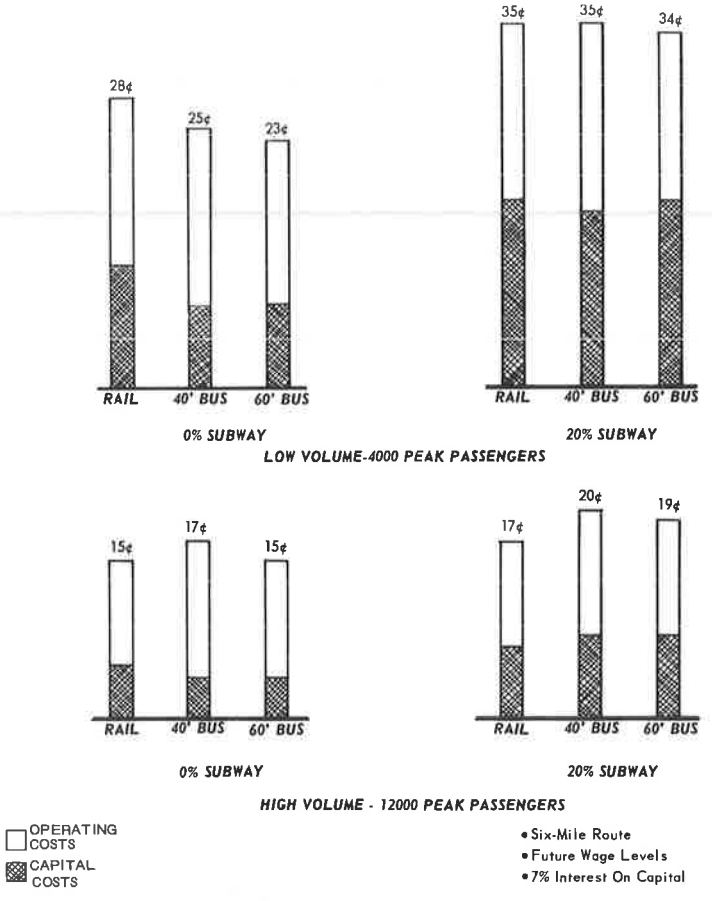

Figure 9. Total rail and busway costs (cents per passenger).

Without subways and with volumes of 12,000 passengers per hour, there appears to be no great cost advantage of one mode over another. Tables 2 and 4 show costs of rail to be slightly less (14.6 cents per passenger) than those for the articulated bus (15.2 cents) in this case. Doubtless the relative efficiencies of rail at higher volumes would show more clearly at volumes above 12,000. Relative costs for the 12-mile line and for various assumptions concerning wage escalation and interest rates can be found in Tables 5 through 7. Comments noted above are generally applicable to cases with high volumes and no subways.

Cost differentials, which appear to be significant, can be observed for nonsubway, low-volume cases (Fig. 9). Operating costs for buses and rail are about equal for this case, but the higher capital cost of rail tips the balance in favor of buses. Savings of 17 to 22 percent can be observed for buses (see Tables 2 through 7), depending on the line length, wage, and interest assumptions.

Caution must be exercised in applying these findings to other situations. Buses have never been used in a system such as that assumed in these studies. There are risks in developing an untried operation. Further, there is the belief in some quarters that busways cannot gain public support or acceptance as easily as rail. This may have some validity because the public knows buses only as presently operated, i.e., slow, subject to traffic delays, and used primarily by lower income people. Sensitivity to weather might be a factor weighing against buses in some environments.

Finally, estimates of cost were made in this study on a prelimianry basis for only one community. Before results are applied to other communities, operating and capital

cost estimates should be developed for the particular operational types and project envisioned. Yet the same assumptions and unit costs were applied to all modes; one must change the assumptions radically to get different relative cost values. Most of the cases tested showed insignificant cost differentials. However, for low volumes in situations where surface or elevated rights-of-way can be obtained, the lack of need for power distribution and train control systems for buses provides a cost advantage that appears to be significant. (Why a rail system requires a control system to avoid vehicle collisions and a bus does not is a matter that seems debatable. Control systems make up about 30 percent of the costs of "power distribution control and shops" shown in Figures 5 and 6. Yet the assumptions used in this study in this regard correspond to what would happen if busways or rail were built today.)

CONCLUSIONS

1. There are various ways to operate a busway. Any one method may be superior to another in cost or service, depending on the operating environment. Systems using the same vehicle for feeder service and trunk-line operation tend to serve the CBD well at the expense of non-CBD destinations.

2. Where 20 percent or more of a line must be in subway, the costs of subway construction become so large that they dominate other cost elements. Subway construction costs less for rail systems than for buses. Thus, if subway construction is required, rail can be considered superior to the bus.

3. On systems where 20 percent subway is required, capital costs (construction and right-of-way) represent less than one-half the total annual costs. Where no subway is involved, capital costs represent less than one-third under some conditions. This suggests that planning studies and feasibility analyses for systems of this type should put at least as much emphasis on estimates of operating costs and revenues as on capital costs.

4. Articulated buses have 40 percent more seats than the conventional bus and can provide for cost reductions of 10 to 12 percent in total capital and operating costs in some instances. Research and development programs should be inaugurated to refine such a vehicle for busway use. Three-element articulated units could conceivably be used to even greater advantage.

5. Where no subway is required on a line, volumes as high as 12,000 passengers (peak hour) can be accommodated as cheaply on buses as on rail, if large articulated buses are used. As volumes above 12,000 are reached, rail systems show increasing cost savings over bus.

6. Where no subway is required and where volumes are in the vicinity of 4,000 passengers equivalent (peak hour), either 40-ft or 60-ft buses can provide service equivalent to that of rail at cost savings of 15 to 20 percent.

7. Increasing wage rates in future years will tend to increase costs of bus operation more than those of rail, but not significantly. A 67 percent assumed future wage increment increased bus operating costs only about 1.5 cents per passenger more than it increased rail costs (for low volumes). This 1.5 cents is about 4 percent of total costs. assumptions that increase the cost of borrowing capital tend to increase rail costs more than bus. An assumed change of borrowing rates from 4 percent to 7 percent applied to both modes increases rail costs such that increased future wage rate assumptions are approximately offset; i.e., estimates made assuming today's wage rates and low interest costs will not be significantly changed by assuming future wage rates and high interest rates.

8. Many considerations other than cost are involved in the bus-rail decision in any particular community. Bus systems may be considered more risky in view of the fact that they have not been used on exclusive right-of-way systems to date; that they might provide more troublesome problems in bad weather; that they may not be as safe because collision avoidance control systems are required for rail but not for bus systems; and that public acceptance may be more difficult to obtain for bus than for rail. On the other hand, buses provide more opportunities for tailoring service to demands and for developing a system gradually rather than all at once.