COMPARATIVE ANALYSIS OF URBAN TRANSPORTATION COSTS

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This paper develops the methodology and compares door-to-door trip characteristics of some urban transportation modal combinations that are currently in use, are being considered, or appear to hold near-term promise for corridor travel in large U.S. cities oriented to the central business district. The cost and travel time of various options are developed separately for residential, line-haul, and downtown trip components. Then they are combined selectively to explore relative merits of door-to-door alternatives. The analysis addresses the many possible variations in corridor length, central business district size, daily volume level, and temporal flow pattern. Furthermore, the sensitivity of costs with respect to changes in design sepcifications, operating policy, automation, and nature of construction is explored. A case study compares various options for Metro in the Washington, D.C., metropolitan area. The marginal costs of busway-based systems are lower than those of systems based on rail rapid transit. Automation is not likely to lower rail rapid transit operating costs dramatically. High-performance, exclusive busways require substantial initial investment but are less costly and faster than rail rapid transit in almost all environments and volume levels. Residential collection with jitneys costs only a little more than residential collection with buses and provides much better service. Car pools provide the least expensive service and attractive door-to-door time.

•COMPARISONS are made separately for total costs (including fixed and variable costs) and door-to-door travel time (both in-vehicle time and out-of-vehicle time such as walking, waiting, and transfer time). Cost and service characteristics for various modes first are developed separately for the 3 trip components (residential collection, line-haul, and downtown distribution) and then are combined. This is important because residential and downtown components of urban travel have been dealt with superficially by most analysts. The problem of residential access could be critical to the success of a well-designed, high-capacity line-haul system especially because of the sprawling living patterns common in urban areas. Analysis of downtown systems requires careful consideration of available street capacity, parking space, and the possibility of underground construction.

A variety of modes may be used for the different trip components. Automobiles provide door-to-door, no-transfer, direct, and personalized service to the destination. However, a host of problems may be encountered by automobiles, especially in congested downtown areas. Automobiles also can be used for line-haul access; park-and-ride and kiss-and-ride are popular modes for residential collection. Car pools show significant improvement over automobiles from the standpoint of costs and congestion because of their higher occupancy even though substantial route diversion is required at the residential end in picking up riders. And car pools allow little schedule flexibility.

Rail rapid transit provides fast line-haul service with underground downtown distribution that helps ease congestion and its associated adverse effects. However, rail

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rapid transit lines must be fed by other modes, and rail rapid transit trips require transfers. Buses are somewhat more flexible because they provide relatively inexpensive service in mixed traffic or on reserved lanes at both the residential and central business district (CBD) ends, and they can be used to provide high-speed, high-capacity line-haul service on mixed traffic expressways or exclusive busways. Completely integrated, no-transfer service is feasible. In addition, underground busways, although they are expensive, can provide good downtown distribution without causing congestion on streets.

Jitneys make up another mode that may have potential in feeder service but has not received sufficient attention in the past. Jitneys can operate along fixed routes as buses do, or they can provide more flexible taxicab-type service for both residential collection and downtown distribution. Most downtown areas can accommodate large numbers of jitneys either in mixed traffic or on reserved lanes.

Collection and distribution modes generally share residential street space with local traffic, and exclusive right-of-way seldom is needed. Reserving lanes for bus or jitney service, however, may be desirable, especially in downtown areas. Also, because streets in urban areas are in place or will be provided, only a small user charge, rather than a charge for roadway costs, generally is assigned to the surface modes.

For a corridor with unusual physical characteristics, flow patterns, or flow levels, cost and service characteristics can be somewhat different. Because costs are based on average factor prices and unit costs, some caution is warranted in their use for policy analysis.

Rail rapid transit in this paper refers to the conventional heavy rail rapid transit systems such as those in service in New York, Chicago, Boston, Cleveland, and San Francisco and under construction in Washington, D.C. Light rail transit is not included. This does not imply that light rail transit cannot be an attractive mode. It means that sufficient reliable data on its costs and performance were not available to permit inclusion and comparison at the same level of accuracy as for heavy rail rapid transit.

REDUCTION OF FIXED COSTS TO EQUIVALENT DAILY COSTS

The fixed costs of facility and vehicles (which are incurred at 1 time) first must be reduced to equivalent annual costs and then to equivalent daily costs by assuming the number of days of operation per year. (I have assumed 250 days of operation per year. Many analysts have suggested that 300 days would be more appropriate, especially for highways. Because annual costs of all modes are factored down by this common figure of 250, the relative costs will not be much affected.) This study uses a 10 percent discounting rate.

RESOURCE COSTS AND PERFORMANCE MEASURES

Records of existing system facilities and operations were reviewed and analyzed to obtain the current estimates of unit resource costs and performance measures. This research has been summarized elsewhere (2).

For the most likely volume levels (300 to 600 buses/h), 1 bus lane would be sufficient to carry all peak-hour traffic. In any case, this study generally has assumed 44-ft-wide (13.4-m-wide) busways that, in effect, provide 2 lanes in each direction. Similarly, rail track capacity of 50 trains/h appears to be higher than that achieved for existing operations. Such high capacities probably can be achieved with completely automated systems that run reasonably short trains (4 to 6 cars). Again 1 track in each direction would be ample for flows in most urban corridors.

Highly skilled bus drivers can sustain fast line-haul speeds on exclusive busways. In fact, in most situations, bus volumes will be low enough to achieve speeds faster than those on mixed-traffic expressways. The highest achievable speed for rail rapid transit is of little concern because interstation time will be governed by the spacing of stations, and, even for a 2.0-mile (3.2-km) spacing, trains cannot achieve more than 60 mph (96 km/h).

The user time components (wait, walk, transfer, and overall in-vehicle time) are based on extensive analysis reported elsewhere (2). In-vehicle travel time depends on speed characteristics as well as vehicle, facility, and volume characteristics. Waiting time has been assumed to be equal to half of the headway but not more than 15.0 min. Routes were designed to achieve the walking times given in Table 1. Each transfer was assumed to take 1.0 min.

Unit costs have been estimated for a variety of facilities. The estimates for this paper include the following cost items:

1. Fixed costs associated with facilities (right-of-way acquisition and construction of guideway, downtown terminal parking, stations, garage and service facilities, and park-and-ride facilities);
2. Fixed costs associated with vehicles (vehicle acquisition or ownership);
3. Variable costs associated with facilities (operation and maintenance of facilities including guideway, CBD terminal and parking facilities, stations, and park-and-ride facilities);
4. Variable costs associated with vehicle operation (equipment maintenance and repairs including those for the garage, operator, conducting transportation less operator costs, power, administration, and general).

The data given in Tables 2 through 5 summarize these costs for the various modes. The costs are based on the most recent available cross-sectional data. The estimates are 1973 figures obtained by adjustment of estimates available for recent past years. Consumer price, road construction, heavy construction, and other indexes were used in the adjustment.

Expressway and arterial facility costs were obtained from 1968 nationwide data collected by the Federal Highway Administration as part of its study on national highway needs. Rail transit facility costs are based on actual recent cost figures from Washington, D.C., and San Francisco and were corroborated by using costs of rail projects for the past 20 years in North America.

Surface and elevated busway construction costs were estimated from recent facility costs and about a dozen planning and design studies. Underground busway costs were extrapolated from underground rail construction costs and corroborated with the results of a recent study (11). Busway costs include costs of ventilation.

Errors in unit cost estimates obviously can affect the relative costs of involved modes. The overwhelming cost component for busway and rail rapid transit is underground construction cost. However, because underground busway costs are based on extrapolations of rail cost data, the cost differential between these 2 systems is not likely to be affected greatly by errors in estimates. There also may be some uncertainty regarding ventilation costs for underground busways. However, because these costs constitute only a small percentage of total construction costs [costs exclusive of ventilation are on the order of $40 million to $50 million/mile ($25 million to $30 million/km)], the overall impact would be small. Also, because the driver costs for bus systems constitute only a part of the total cost, the overall impact of increased driver wages would not be dramatic.

In calculating the operating costs of public transportation modes, I have assumed that current administrative structures for the various industries concerned will prevail. This directly affects the costs of the modes. For example, major reasons for the attractively low feeder jitney costs (only 10 to 20 cents per passenger trip more than the feeder bus) are that bus driver wages, benefits, and other payments typically amount to $6 or $7/vehicle h and taxicab or jitney driver expenses amount to about $3/vehicle h and because overhead expenses per trip are up to 4 times higher for bus companies. If large-scale jitney service is provided, these costs could go up substantially and make overall jitney costs much greater.

Table 1. Walking times (4).

	Time (min)	
Mode	Residential	CBD
Automobile	1.00	1.50
Car pool	1.00	1.50
Jitney		
2-block spacing	1.83	2.25
3-block spacing	2.50	3.00
Bus in mixed traffic		
3-block spacing	2.50	3.00
4-block spacing	3.33	3.75
6-block spacing	4.84	6.00
Rail rapid transit	–	7.20
Bus on busway	–	7.20

Table 2. Automobile and car pool unit costs.

	Operation and Maintenance						Vehicle Ownership Costs[a] (dollars/car)		Fixed Costs			
	Vehicles[a] (cents/car mile)		Way (dollars/ lane mile/ year)		Parking (dollars/ space/year)				Way (dollars/lane mile)		Parking (dollars/space)	
Trip	Auto-mobile	Car Pool	Auto-mobile	Car Pool	Auto-mobile	Car Pool	Auto-mobile	Car Pool	Auto-mobile	Car Pool	Auto-mobile	Car Pool
Residential	8.7	9.0	–	–	–	–	–	–	–	–	–	–
Line-haul												
Expressway	5.2	5.4	4,600	4,600	–	–	–	–	1,550,000[b] 1,200,000[c]	1,550,000[b] 1,200,000[c]	–	–
Arterial	7.5	7.7	1,750	1,750	–	–	–	–	800,000[b] 600,000[c]	800,000[b] 600,000[c]	– –	– –
CBD	8.8	9.2	–	–	150	150	–	–	2,000,000	2,000,000 to 5,000,000	4,500	4,500
Overall	–	–	–	–	–	–	3,610	3,820	–	–	–	–

Note: 1 cent/mile = 0.625 cent/km. $1/mile = $0.625/km.

[a]Costs for car pool are larger than they are for automobile because a size mix involving a smaller number of subcompacts has been assumed for car pools.
[b]For miles 0 to 5 (kilometers 0 to 8), which are in areas with average intensity of development.
[c]For miles 5 to 15 (kilometers 8 to 24), which are in areas more sparsely developed than miles 0 to 5 (kilometers 0 to 8).

Table 3. Feeder mode unit costs.

Mode	Service Cost	Residential	CBD
Feeder bus	Operating, dollars		
	Per vehicle mile	0.39	0.39
	Per vehicle h	7.00	7.00
	Vehicle acquisition, dollars/vehicle	45,000	45,000
	Fixed (yards and shops), dollars/vehicle	13,700	13,700
Jitney	Operating, dollars		
	Per vehicle mile	0.012	0.012[a]
	Per vehicle h	4.56	4.56
	Vehicle acquisition, dollars/vehicle	3,500	3,500
Park-and-ride	Operating, dollars		
	Per car mile	0.087	–
	Per parking space/year	20.0	–
	Ownership, dollars/car	3,610	–
	Fixed (parking), dollars/space	1,960	–

Note: $1/mile = $0.625/km.

[a]Road user charges.

Table 4. Rail rapid transit unit costs.

Costs	Line-Haul	CBD
Operating, dollars/car mile	1.57[a]	1.57[a]
Vehicle acquisition, dollars/car	260,000	260,000
Fixed, dollars		
Way, per mile of 2-track facility		
Underground	45,200,000[bc]	61,500,000[c]
Elevated	9,200,000[bc] 5,500,000[cd]	
At grade	3,600,000[cd]	
Stations, per 2-track station		
Underground	6,750,000[b]	9,000,000
Elevated	2,910,000[b] 2,500,000[d]	
At grade	1,680,000[d]	
Yards and shops, dollars/car	29,000	29,000

Note: $1/mile = $0.625/km.

[a]Of this, $0.22 is the cost of the train crew.
[b]From 0 to 5 miles (0 to 8 km) along the corridor (average intensity).
[c]Costs for the line portion of the facility excluding stations.
[d]From 5 to 15 miles (8 to 24 km) along the corridor (sparse intensity).

COMPARATIVE ANALYSIS

Long-run average total costs were compared because the objective of the study is to provide guidance toward better investment decisions. The costs presented later in this section are for providing a system where no facility exists.

Bus-based systems or systems based on rail rapid transit can be designed to operate in many different ways. However, after exploring various operating options and service capabilities, I assumed a particular method of operation for each. Rail rapid transit is assumed to operate in the typical manner with each train stopping at line-haul and CBD stations without skipping any stations. On the other hand, the bus is assumed to operate nonstop along the line-haul facility after it has accessed a particular ramp.

The line-haul facility is accessed at each residential zone by means of a station or a ramp placed at the center of the zone. This implies that stations or ramps are spaced 1 mile (1.6 km) apart. This is quite comparable with the Cleveland rapid transit and Washington, D.C., Metro [stations spaced 1.1 mile (1.8 km) apart]. A larger spacing would improve level of service and costs for line-haul but at a detriment to residential level of service and costs.

The costs are shown for corridor lengths of 5 and 10 miles (8 and 16 km). [Average widths of these corridors are assumed to be about 2.5 and 4.5 miles (4 and 7.2 km) respectively.] These are the most typical sizes in large U.S. cities. Only Chicago, Los Angeles, Detroit, Houston, and Saint Louis have 1 or 2 longer corridors. A downtown of 1 mile^2 (2.6 km^2), which is a typical situation in most U.S. cities today except Manhattan in New York City and Washington, D.C., also has been assumed in this study.

A study in the 1960s (8) indicated that volumes in CBD-oriented corridors in most large U.S. cities without rail rapid transit in the early 1960s did not exceed 150,000 trips/day. In the last decade, the radial trip volume has not increased dramatically. This range has been included in this study. (The range of trip volumes most appropriate for large U.S. cities is indicated by shaded areas on the cost figures in this paper.)

Costs are developed for 2 specific daily flow patterns; one resembles the observed transit travel pattern (flow 1), and the other resembles the observed automobile pattern (flow 2). Both assume that daily travel is confined to the period between 6 a.m. and 12 midnight. Flow 1 assumes a 2-h peak period in the morning and afternoon and that 15 percent of the daily volume is in each of the peak hours and 2.86 percent of the daily volume is in each of the off-peak hours. Flow 2 assumes 2.5-h peak periods, each of which has 8 percent of the daily volume per peak hour and 4.62 percent of the daily volume per off-peak hour. Generally, the costs associated with flow 2 are lower because flow 2 results in more efficient use of fixed facilities and fleet. Peak-period trip time, on the other hand, is somewhat better for flow 1 because of the higher average frequency of departures. Off-peak trip time is worse for flow 1.

For convenience, it was assumed that all flow in peak hours is in the primary direction (no reverse flow). This assumption is not as restrictive as it sounds because the flow in the minor direction can be served at near 0 incremental costs by bus- and rail-based modes. In any case, the flow in reverse direction in peak hours has been observed to be only a small fraction of the total flow. [A study in 1964 (8) suggested that reverse direction flow generally was 10 to 15 percent of the primary direction flows. The relative magnitude probably has increased since then but is likely to be not more than 25 to 30 percent as indicated by recent planning studies in Washington, D.C. (6); Atlanta; and Baltimore.] Along-the-line flow, which, in this analysis, is assumed not to be served by express bus modes, also is very small. Along-the-line service, however, can be provided by additional buses at small incremental expense (as little as 10 cents/along-the-line trip), which would result in an overall system cost increase of roughly 1 cent.

For the purpose of this study, it was assumed that an automobile carries 1 passenger, a car pool vehicle carries 4 passengers, and a jitney carries a maximum of 5 passengers. For rail rapid transit cars and buses, it seems desirable to assume loading standards that are roughly comparable. It was assumed that all passengers are seated with identical maximum loading per vehicle-floor unit of area. This requirement implied that the typical 70-ft (21-m) rail rapid transit car must have 110 seats to be comparable with the typical 40-ft (12-m) bus with 50 seats [roughly 5.0 ft^2/seat (0.5 m^2/

seat)]. Table 6 gives vehicle occupancy data.

Bus and jitney routes have respective station spacings of 3 and 2 blocks in both CBD and residential zones. Stops are provided along the route at each cross street. This structure keeps the average walking distance at both ends to less than 3 blocks. CBD underground busway and rail loops and station spacing also conform to this requirement.

There are many modes and facilities that travelers can use along any of the 3 trip components. Their amount of use of each will depend on the perceived costs and service levels of alternate modes. But, because this study aims to compare the alternatives from the supply side only, I have assumed that only 1 mode will be used by all travelers for a particular trip component.

Residential Service

The time difference among modes, especially the difference between times for bus and other modes (because of the substantial difference in waiting times), is marked at low volumes. At higher volumes this difference is much smaller. Travel time on jitney service is better than that on bus service. Car pool time is much higher than automobile time because substantial route deviation is required to pick up riders. The advantage of automobiles and car pools is that little walking is required compared with the amount of walking time required for use of jitney or bus.

The costs for 5- and 10-mile (8- and 16-km) corridors with average residential zone widths of 2.5 and 4.5 miles (4 and 7.2 km) are given in Table 7 for flow 1 characteristics. These approximate transit peaking characteristics. Park-and-ride costs are very high because the daily car ownership and parking facility costs are spread over only 2 residential trips. Kiss-and-ride costs also are large. Automobile cost is the lowest of the 3 and is lower than jitney cost even after ownership costs are included. Car pool costs are very low because they are spread over 4 occupants. Bus service is the most attractive mode from the standpoint of cost. Jitney costs are higher than bus costs although jitneys provide much better service in terms of walking time and waiting time (especially at low volumes).

Line-Haul Service

The fixed facilities in this report are designed with typical existing or most likely specifications in terms of the mix of various types of construction, widths, and station size. Passenger volumes entering each station or ramp are assumed to be equal to reduce the complexity of analysis.

In-vehicle travel time by busway and expressway is substantially lower than in-vehicle travel time by rail rapid transit primarily because rail rapid transit service involves multiple intermediate stops and the other modes operate express and nonstop service to downtown fringe areas. Busway times are slower than expressway times because highly skilled drivers can sustain higher speeds on high-performance uncongested busways. Expressways provide substantially faster service than arterial streets.

Figure 1 shows line-haul costs for the 2 corridor lengths for the transit flow pattern. The rail rapid transit line is assumed to be made up of underground construction over the first 5 miles (8 km) starting from the downtown fringe and is assumed to be elevated over the next 5 miles (8 km). The busway is elevated over the first 5 miles (8 km) and at grade over the outer 5 miles (8 km). The term expensive busway refers to a construction mix similar to rail transit; the term inexpensive rail refers to busway-type construction. Inexpensive rail rapid transit construction is acceptable, and the costs approach busway-based-system costs (with comparable residential and downtown services) but are not lower in most situations. Similarly, if the expensive busway were compared with a typical rail system, then its costs would be lower still in most realistic situations. Figure 2 shows these comparisons. It should be reemphasized that further cost reduction is possible in busway-based systems because 44-ft-wide (13.4-m-wide)

Table 5. Rapid bus unit costs.

Costs	Residential	Line-Haul Busway	CBD
Operating, dollars			
Per vehicle mile	0.39	0.33	0.39
Per vehicle h	5.3	7.00	7.00
Per day/mile of 2-lane facility	—	10,000	—
Vehicle acquisition, dollars/vehicle	50,000	50,000	50,000
Fixed, dollars			
Per mile of 2-lane facility			
Underground	—	51,000,000[ab]	82,500,000[b]
Elevated	—	6,400,000[a] 6,400,000[c]	—
At grade	—	4,400,000[c] 3,500,000[d]	—
Stations, per platform	—	—	1,186,000[b]
Terminals, per platform	—	181,000	716,000
Yards and shops, per vehicle	13,700	13,700	13,700

Note: $1/mile = $0.625/km.

[a]From 0 to 5 miles (0 to 8 km) along the corridor.
[b]Includes ventilation costs.
[c]From 5 to 10 miles (8 to 16 km) along the corridor.
[d]From 10 to 15 miles (16 to 24 km) along the corridor.

Table 6. Vehicle occupancy.

	Passengers/1-Way Vehicle Trip			
	Peak Period		Off-Peak Period	
Mode	Primary Direction	Secondary Direction	Primary Direction	Secondary Direction
Automobile	1	—	1	—
Car pool	4	—	4	—
Jitney	5	0	2.5	2.5
Bus[a]	50	0	25	25
Rail rapid[a]	110	0	55	55

[a]These loading standards provide equivalent floor space per passenger.

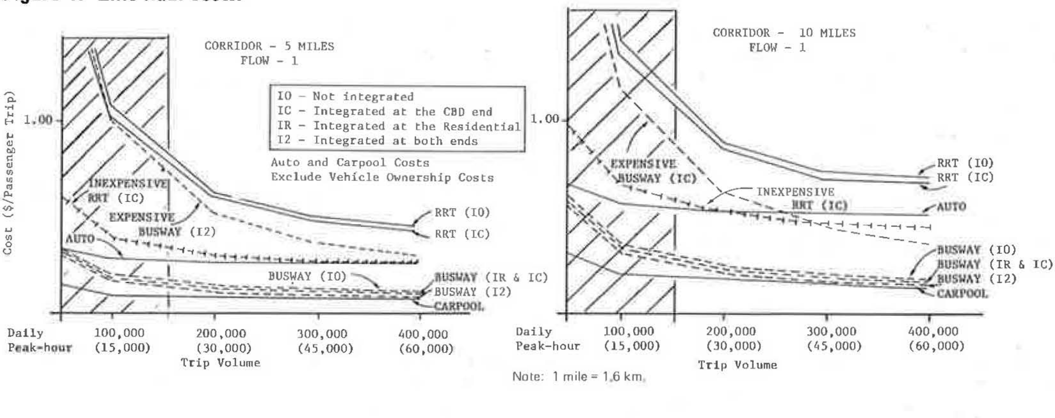
Table 7. Costs of residential service for all volume levels.

	Dollars/Trip			Dollars/Trip	
Mode	5-Mile Corridor	10-Mile Corridor	Mode	5-Mile Corridor	10-Mile Corridor
Park-and-ride	0.92	0.96	Integrated bus	0.09	0.13
Kiss-and-ride	0.72	0.76	Automobile[a]	0.07	0.12
Jitney	0.19	0.28	Car pool[a]	0.05	0.06
Feeder bus	0.09	0.14			

Note: 1 mile = 1.6 km.

[a]Automobile and car pool costs do not include car ownership costs, which are shared by all 3 trip components and would be accounted for in overall trip costs.

Figure 1. Line-haul costs.



Note: 1 mile = 1.6 km.

busways are assumed. Fixed costs can be reduced substantially by providing narrower busways over outer sections of the line-haul facility where volumes are low.

Expressway trip costs are roughly similar to arterial cost per trip. Car pool and busway costs are very low compared with rail rapid transit system and automobile costs. Even at extremely high volumes, rail costs are higher than car pool, busway, and automobile costs. Comparison of costs of busways and rail rapid transit systems shows that busway transit is likely to be cheaper than both the typical and inexpensive rail rapid transit in most situations.

Downtown Service

The underground busway and rail rapid transit distribution loops for the 1.0-mile^2 (2.6-km^2) downtown (12 × 12 blocks) are 2.5 miles (4 km) long and have 8 stations each. Two distinct designs were considered: a single-track (lane) facility providing service in 1 direction only over the closed loop and a 2-track (lane) facility providing service in both directions over the closed loop.

Automobiles and car pools offer the fastest service of all modes, and jitney service is not far behind these 2 modes. The trip times of busways and rail rapid transit are similar because the loops are identical and the speeds are similar.

The costs of the downtown modes are shown in Figure 3. Costs of surface bus service are much lower than costs of underground busways and rail rapid transit service primarily because of the heavy investment required for the latter 2 modes. Jitney service, on the other hand, is quite attractive, and its costs are not too much higher than those of the surface bus service. By comparing underground busways and rail rapid transit, one can see that the high-performance 44-ft-wide (13.4-m-wide) busways are likely to cost more to construct than rail rapid transit primarily because the actual bore size will be much larger for busways and because busways require an expensive ventilation system. Underground busway stations, however, cost less than rail rapid transit stations because busway stations are smaller in size on the average. The overall total cost for busways would be higher than that for rail rapid transit. The cost differential would be enhanced for a larger CBD because a longer distribution loop would be required.

In most situations, 33-ft-wide (10-m-wide) busways would be quite sufficient for a CBD because speeds are low and buses stop at all stations thus avoiding high-speed merging problems. [Even 24-ft-wide (7.3-m-wide) 2-lane busways would suffice for volumes of around 50,000 to 100,000 trips/day.]

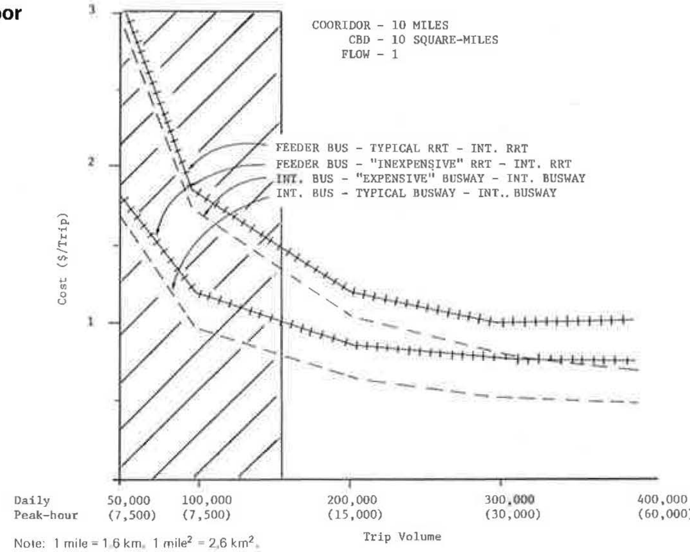
Overall Trip Costs and Service

The residential, line-haul, and CBD modes discussed in the preceding sections can be put together in various modal combinations to provide door-to-door service in a corridor. Each combination has its own set of cost and service characteristics. Table 8 gives the combinations for door-to-door travel chosen for this study.

Figures 4 and 5 show door-to-door costs and total door-to-door peak-period times for a 10-mile (16-km) corridor with a 1-mile^2 (2.6-km^2) downtown for flow 1. The 1-way trip costs for a typical 10-mile (16-km) corridor with a 1-mile^2 (2.6-km^2) downtown vary from about \$0.50 for car pool and busway with CBD surface bus to about \$1.50 for rail rapid transit line-haul and CBD systems to about \$2.00 for single-occupancy automobile for a volume level of 150,000 trips/day in the corridor. In general, the automobile is the most expensive mode followed by rail rapid transit, bus, and car pool.

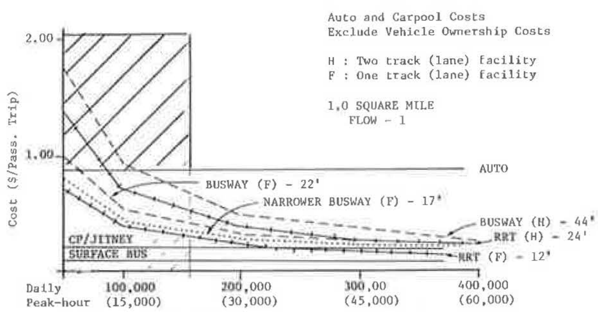
Trip time is shortest for the automobile. Car pool time also is reasonably attractive, and bus-based modes generally are faster than rail-based options. Even though nonintegrated services involve transfer at the interface with another mode (and terminals to provide transfer and turnaround facilities), the high penalty attached to waiting time associated with integrated services can be avoided, especially at low

Figure 2. Door-to-door costs.



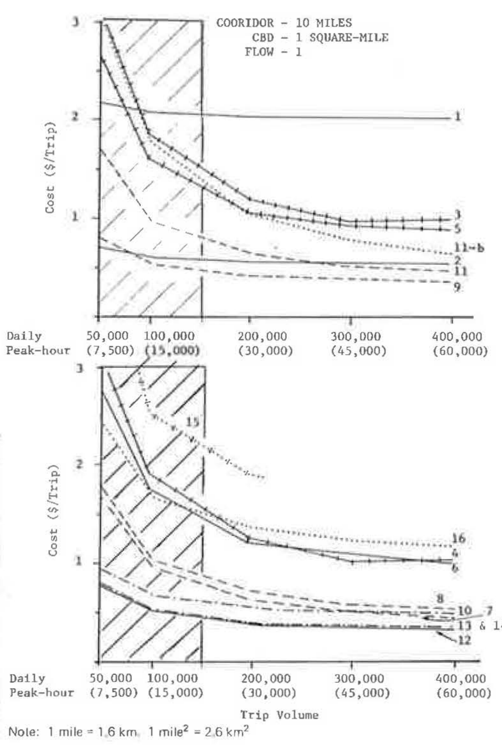
Note: 1 mile = 1.6 km. 1 mile² = 2.6 km².

Figure 3. CBD costs.



Note: 1 mile² = 2.6 km². 1 ft = 0.305 m.

Figure 4. Door-to-door trip costs.



Residential	Linehaul	CBD
1. Integrated Auto	Expway	Integrated Auto
2. Int. Carpool	Expway	Int. Carpool
3. Feeder Bus	RRT	Integrated RRT
4. Feeder Jitney	RRT	Integrated RRT
5. Feeder Bus	RRT	Surface Bus
6. Feeder Jitney	RRT	Jitney
7. Feeder Bus	Busway	Int. Busway
8. Feeder Jitney	Busway	Int. Busway
9. Feeder Bus	Busway	Surface Bus
10. Feeder Jitney	Busway	Jitney
11. Integrated Bus	Busway	Int. Busway
12. Integrated Bus	Busway	Surface bus
13. Feeder Bus	Busway	Int. Surf. Bus
14. Integrated Bus	Busway	Surface Bus
15. Park-and-Ride	RRT	Int. RRT
16. Park-and-Ride	Busway	Int. Busway
11-b -- 11 with "Expensive" Busway Design		

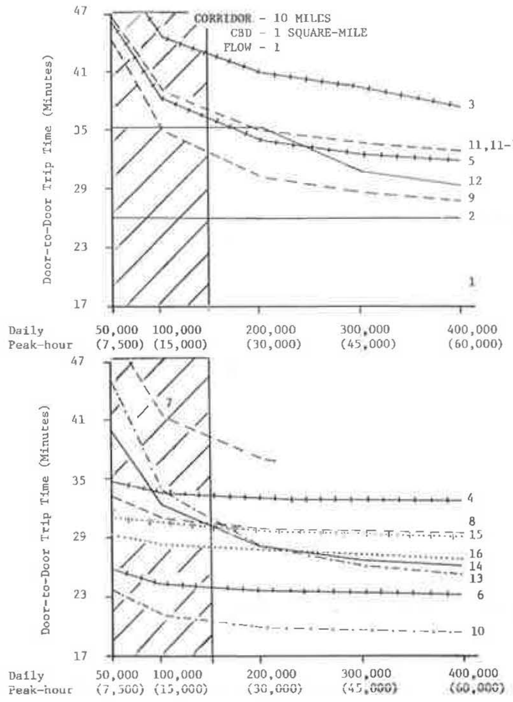
Note: 1 mile = 1.6 km. 1 mile² = 2.6 km²

Table 8. Modal combinations for door-to-door trip.

System	Residential	Line-Haul	CBD
Automobile based	Integrated automobile	Automobile expressway	Integrated automobile
	Integrated car pool	Car pool expressway	Integrated car pool
Rail rapid transit based	Feeder bus	Rail rapid transit	Integrated rail rapid transit
	Feeder jitney	Rail rapid transit	Integrated rail rapid transit
	Feeder bus	Rail rapid transit	Surface bus
	Feeder jitney	Rail rapid transit	Jitney
Bus based	Feeder bus	Busway	Integrated busway
	Feeder jitney	Busway	Integrated busway
	Feeder bus	Busway	Surface bus
	Feeder jitney	Busway	Jitney
	Integrated bus	Busway[a]	Integrated busway
	Integrated bus	Busway	Integrated surface bus
	Feeder bus	Busway	Integrated surface bus
	Integrated bus	Busway	Surface bus
	Park-and-ride	Rail rapid transit	Integrated rail rapid transit
	Park-and-ride	Busway	Integrated busway

[a]Expensive rather than typical design.

Figure 5. Door-to-door trip time for peak period.



Residential	Linehaul	CBD
1. Integrated Auto	Expway	Integrated Auto
2. Int. Carpool	Expway	Int. Carpool
3. Feeder Bus	RRT	Integrated RRT
4. Feeder Jitney	RRT	Integrated RRT
5. Feeder Bus	RRT	Surface Bus
6. Feeder Jitney	RRT	Jitney
7. Feeder Bus	Busway	Int. Busway
8. Feeder Jitney	Busway	Int. Busway
9. Feeder Bus	Busway	Surface Bus
10. Feeder Jitney	Busway	Jitney
11. Integrated Bus	Busway	Int. Busway
12. Integrated Bus	Busway	Surface bus
13. Feeder Bus	Busway	Int. Surf. Bus
14. Integrated Bus	Busway	Surface Bus
15. Park-and-Ride	RRT	Int. RRT
16. Park-and-Ride	Busway	Int. Busway
11-b -- 11 with "Expensive" Busway Design		

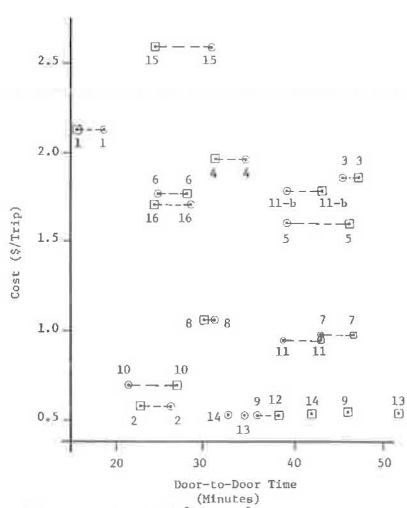
Note: 1 mile = 1.6 km. 1 mile^2 = 2.6 km^2.

Figure 6. Door-to-door costs and time when trip volume = 100,000.

⊙ - Peak
⊡ - Off-peak

CORRIDOR - 10 MILES
CBD - 1.0 SQUARE MILE
FLOW - 1

Residential	Linehaul	CBD
1. Integrated Auto	Expway	Integrated Auto
2. Int. Carpool	Expway	Int. Carpool
3. Feeder Bus	RRT	Integrated RRT
4. Feeder Jitney	RRT	Integrated RRT
5. Feeder Bus	RRT	Surface Bus
6. Feeder Jitney	RRT	Jitney
7. Feeder Bus	Busway	Int. Busway
8. Feeder Jitney	Busway	Int. Busway
9. Feeder Bus	Busway	Surface Bus
10. Feeder Jitney	Busway	Jitney
11. Integrated Bus	Busway	Int. Busway
12. Integrated Bus	Busway	Int. Surf. Bus
13. Feeder Bus	Busway	Int. Surf. Bus
14. Integrated Bus	Busway	Surface Bus
15. Park-and-Ride	RRT	Int. RRT
16. Park-and-Ride	Busway	Busway
11-b ←→ 11 with "expensive" Design		



Note: 1 mile = 1.6 km. 1 mile^2 = 2.6 km^2

volumes, because waiting time strongly depends on the number of distinctly unique routes serving a unique set of origin-destination pairs for integrated services.

Figure 6 shows a comparison of door-to-door costs and times for the 16 modes at a typical volume level of 100,000 trips/day for flow 1 characteristics.

Jitney costs are not too much in excess of surface bus costs. The service level for surface bus, however, is likely to be poorer, at least in terms of total time (although the walking requirement is smaller than that for underground rail transit or busway). The cost differential, however, is likely to be so great that use of surface bus may be worth the drop in service level particularly in other than 10 or 15 of the largest U.S. cities.

Figure 7 shows a breakdown of different cost components for 4 selected modes (integrated automobile and car pool, rail rapid transit with residential feeder bus, and busway integrated in downtown subway with integrated feeder bus). Figure 8 shows the breakdown of time components for these modes.

A sufficient number of ramps must be provided for line-haul busways and expressways that feed CBD surface streets. At very high volume levels, local street capacity can be strained by the incoming line-haul vehicles. For example, a volume level of 100,000 trips/day implies a peak-hour flow of 15,000 (15,000 automobiles or 300 buses entering the downtown area per peak hour). This would require 25 lanes for automobiles, 6 lanes for car pools, or 3 reserved lanes for buses. This is not beyond the capability of downtown street systems in most urban areas. In extreme cases, it may become necessary to provide a special downtown automobile expressway for proper distribution. Such a system would increase automobile cost by 10 to 20 cents/trip. Parking requirements should be checked against parking availability. A maximum of about 10 to 12 city blocks may be required for a volume level of 100,000 automobile trips/day.

Automation often has been suggested as a means of reducing rail rapid transit costs. However, automation would involve greater fixed facility costs. The important point is that, for rail rapid systems, the costs associated with the train crew are only a small proportion of total operating costs (about 10 to 15 percent). In fact, doing away with the train crew in the rail rapid transit operations costed in this paper would result in a maximum line-haul cost savings of only about 2 and 4 cents/trip for 5- and 10-mile (8- and 16-km) corridors respectively. The saving in CBD distribution costs would amount to an additional 0.5 cent/trip. Similarly, running longer trains would require longer platforms and would increase fixed costs and bring about only small savings in operating costs. Moreover, such a policy would increase headways and waiting times.

As mentioned previously, seating with the same floor space per seat for every passenger is provided for both bus and rail transit. Trip costs per passenger can be reduced dramatically by packing more people in a vehicle than there are seats. A certain amount of forced crowding is possible in both buses and rail cars. Similarly, automobile costs can be reduced dramatically by increasing occupancy figures from the assumed value of 1.0.

CASE STUDY

Scope

The case study compares door-to-door trip costs for some transportation options in a real urban environment. The Washington, D.C. , metropolitan area was selected because extensive planning and cost information was at hand. Washington, D. C., is one of the largest cities in the United States without a high-performance transit system. Therefore, the observations from the case study can provide substantive guidance about the relative costs of bus, rail, and car pool systems for other areas of comparable or smaller size. Existing planning reports were explored to obtain the necessary travel information. According to a planning study, a total of 959,000 trips will be served in the year 1990 by Metro, which will operate in 7 major corridors (the Shirley corridor will not be served by Metro) (6). (In the aggregate, 53 percent of the trips are expected

Figure 7. Door-to-door trip cost components.

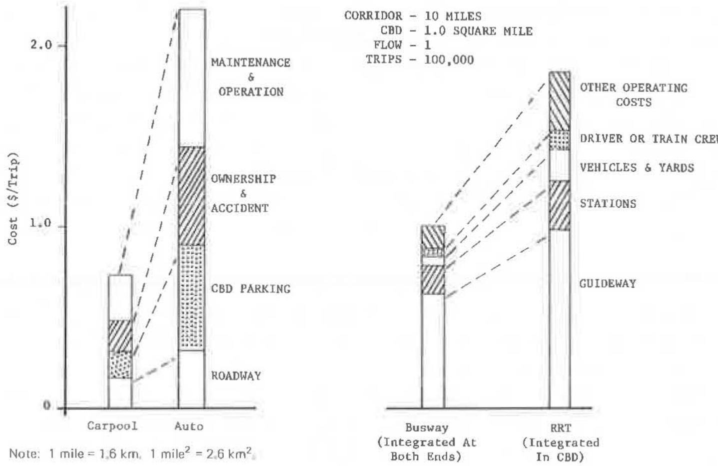


Figure 8. Peak-period time components for door-to-door trip.

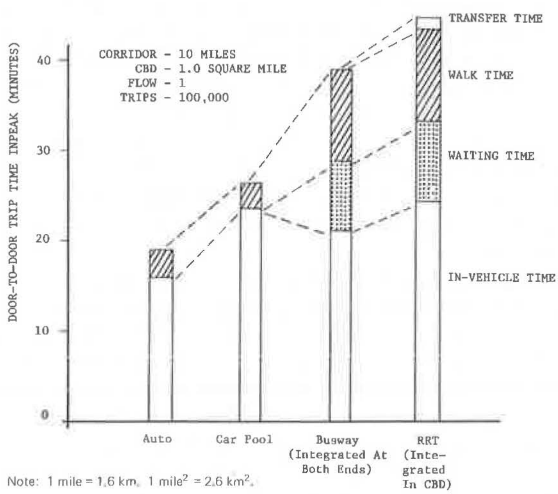


Table 9. Modal combinations.

Option	Residential	Interface	Line-Haul	Interface	CBD	Total Number of Transfers[a]
1	Feeder bus, walk, park-and-ride, kiss-and-ride[b]	Transfer	Metro rapid rail transit	Integrated	Metro rapid rail transit	1.6
2	Feeder bus, walk, park-and-ride, kiss-and-ride[b]	Transfer	Metro busway[c]	Integrated	Metro busway	1.6
3	Feeder bus, walk, park-and-ride, kiss-and-ride[b]	Transfer	Inexpensive busway[c]	Integrated	Metro busway	1.6
4	Car pool on streets	Integrated	Car pool expressway	Integrated	Car pool on streets	0.0
5	Feeder bus	Transfer	Metro rapid rail transit	Transfer	Feeder bus	2.6
6	Feeder jitney	Transfer	Metro rapid rail transit	Transfer	Feeder jitney	2.0
7	Feeder jitney	Transfer	Inexpensive busway[c]	Transfer	Feeder jitney	2.0
8	Surface bus	Integrated	Inexpensive busway[c]	Integrated	Surface bus	0.6[d]
9	Automobile on streets	Integrated	Automobile on expressway	Integrated	Automobile on CBD loop and streets	0.0

[a]Home to CBD trips.
[b]Relative usage patterns for these modes were obtained from Washington, D.C., Metropolitan Area Transit Authority (6).
[c]In peak periods both express nonstop and local multiple-stop services to the CBD fringe are operated, but in off-peak periods only the complete multiple-stop service from the route extremity to the CBD is provided.
[d]Incorporates the fact that 60 percent of trips with downtown destinations require transfer from one line to another in the CBD.

to be made in 4 peak hours; 15 percent of these trips will be along-the-line trips. The flow in the reverse direction is expected to be about 30 percent of the total in the peak period and 50 percent in the off-peak period.)

The construction detail and costs for the rail rapid transit options are based on actual numbers provided by local officials. The busway construction costs are based on extrapolations of costs of underground rail rapid transit lines and expressway cost projections. Car pool facility costs are based on expressway cost estimates. Current costs of purchasing rolling stock are adjusted for the assumed midyear of purchase (1980). Rail operating costs are derived from a Washington, D.C., Metropolitan Area Transit Authority report (6) and adjusted for 1990 operations. All other operating cost estimates are from a research study (4) and have been adjusted for 1990 operations.

System Specifications

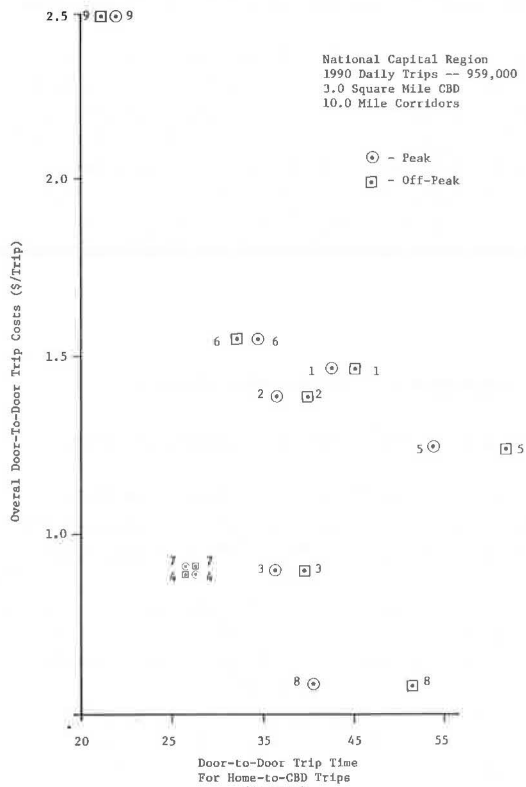
Table 9 identifies the 9 options or modal combinations that have been studied.

1. Option 1 is the 98-mile (156.8-km) Washington, D.C., Metro Adopted Regional System (ARS).
2. Option 2 is the 98-mile (156.8-km) bus system operating on exclusive busways located exactly along the Metro ARS lines. It is assumed that the type of construction will be the same as that for Metro. For example, the busway would be underground where Metro is underground.
3. Option 3 is based on exclusive busways in the same 7 corridors as those in options 1 and 2 and has an identical CBD underground system. Line-haul portions of busways are designed and located in the most optimal manner to take advantage of local setting. Bus lines do not overlap the Metro system exactly except in the CBD.
4. Option 4 consists of 7 exclusive car pool line-haul expressways located within the 7 corridors of interest. Downtown streets are used for distribution. Car pool expressways radiate outward from the downtown fringe and go as far as the Metro line in each corridor.
5. Option 5 is much like the commuter operation in which the line-haul rail rapid transit lines radiate outward to the suburbs in the 7 corridors starting from the CBD fringe terminals. Feeder bus is used for residential service. CBD distribution is through surface bus.
6. Option 6 is identical to option 5 except that jitneys instead of buses are used as feeder modes at either end of the trip.
7. Option 7 is similar to option 6 except that line-haul service is provided on exclusive busways instead of on rail rapid transit commuter lines. Jitneys are used as feeder modes at either end of the trip.
8. Option 8 is a line-haul busway service similar to that of option 7, but complete integrated service is provided by the line-haul vehicle at each end. This provides no-transfer, origin-to-destination bus service.
9. Option 9 is the conventional automobile option requiring expressways in the 7 corridors to provide service for trips that would otherwise use Metro. CBD streets already are congested; therefore, this option is feasible only if a downtown distribution expressway is provided. Costs for this option are likely to be high.

Cost Comparisons

Cost comparisons are based on the assumption that each alternate mode would attract identical trip volume and pattern. The analysis of the bus-based options include additional along-the-line service at an additional cost of roughly 10 cents/along-the-line passenger. Bus-based options were designed to provide seating standards that are at least as good as those planned for rail rapid transit options. Residential collection systems were designed and costed under the assumption of a 10-mile (16-km) corridor length, which is the average approximate size of line-haul Metro corridors. A 3.0-

Figure 9. Trip time and costs.



Note: 1 mile² = 2.6 km², 1 mile = 1.6 km.

mile² (7.8-km²) CBD was assumed.

Figure 9 shows a summary of the costs and peak-period trip times for home-to-CBD trips by the 9 modal combinations under study at the projected 1990 volume level of 959,000 trips/day. (Costs for volume levels above and below 959,000 also were calculated, and the relative positions of modes were not affected greatly.)

Metro busway, which is designed to the same specifications as the rail rapid transit system, would cost about 8 cents/trip (or 5 percent) less than the rail-based system. Car pools would cost substantially less than Metro rail or busway systems. However, the least expensive mode is the judiciously designed line-haul busway system with integrated surface bus systems on residential and downtown streets. It would be 60 percent cheaper than Metro on a per trip basis. The automobile is the most expensive, although the fastest, mode.

Rail-based modes generally have the longest total trip times (except for the line-haul system fed by jitneys at both ends) and require transfers. A line-haul busway with feeder jitney at both ends would be even faster although it would require transfers. An integrated bus system shows long trip times even though no transfers are required. Long waiting times are responsible for this. Generally, bus-based modes seem less costly and faster than rail. A surface bus feeder system, when compared with underground services, seems to be a reasonable downtown alternative. The costs are much lower and trip time is not greatly inferior. Car pools offer no-transfer service and trip times that are almost as good as those for the 2-transfer bus service and at costs that are comparable. Even though CBD streets have sufficient capacity to carry the car pool vehicles, they will be congested. Also up to about 28 city blocks may be required for parking facilities. The automobile option is extremely costly and could require up to 100 city blocks for parking.

In summary, the systems based on rail rapid transit appear to be expensive options with poor door-to-door time. Busway-based systems are much more cost attractive and provide comparatively quicker service. Downtown surface distribution costs much less than underground service and would be quite feasible with sophisticated street usage techniques. Car pools, although they sustain congestion downtown, are shown to be the least costly and the quickest mode. Jitneys also are shown to have potential as a feeder mode at either end of a trip.

CONCLUSIONS

This study has confirmed some of the current notions about the costs associated with the different modes. At the same time, some of the observations are perhaps contrary to currently accepted ideas.

1. Park-and-ride and kiss-and-ride are very expensive feeder modes.

2. Car pools may require substantial route deviation at the residential end of the trip.

3. The automobile is a relatively expensive mode for commuter trips except at very low trip volumes although it does provide no-transfer, comfortable, and the quickest door-to-door service.

4. Car pools can provide the least expensive and the fastest no-transfer door-to-door service except for the automobile, but they allow little schedule flexibility.

5. Surface bus service is much cheaper than underground busway, but the busway has a better service level.

6. Automobile and car pool costs are almost independent of trip volume, and bus- and rail-based systems show rapid decline in trip costs per passenger as trip volumes increase.

7. Expressways are less costly and quicker than mixed traffic arterial streets for line-haul automobile and car pool travel.

8. Feeder jitney costs per passenger trip are only 10 to 20 cents more than (about twice as much as) those for the residential bus. However, jitneys provide service that is far superior to that of the bus in terms of waiting and walking time.

9. Even though line-haul express buses do not provide along-the-line service as rail transit does, such extra service can be provided easily with small incremental costs.

10. Overall typical, door-to-door costs are substantial for most systems—4 cents/passenger trip mile (2.5 cents/passenger trip km) for car pools and line-haul busways with downtown surface distribution to about 12 cents/passenger trip mile (7.5 cents/passenger trip km) for rail rapid transit to about 16 cents/passenger trip mile (10 cents/passenger trip km) for single-occupancy automobiles.

11. For the range of alternatives and volume levels studied, high-performance exclusive busways require heavy investments (underground busways are more expensive to build than underground rail rapid transit lines) but are less costly overall and provide better door-to-door times than rail rapid transit does for most urban environments and trip volumes.

12. Automation of rail rapid transit systems will not dramatically bring down the total costs per trip, and bus-based systems are still likely to be less costly.

13. For busway-based and rail-rapid-transit-based systems with comparable loading standards, the marginal costs per passenger are likely to be lower for busways than for rail systems.

Busway-based systems not only appear to be less costly and faster than systems based on rail rapid transit but also provide greater flexibility. For example, van and car pools or even automobiles can share a facility designed originally for exclusive use by buses. It also would be relatively easy to alter the mode of bus operations to provide along-the-line local or skip-stop services.

ACKNOWLEDGMENT

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DISCUSSION

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This discussion reviews the basically sound format of Bhatt's presentation but confronts the unrepresentative and unlikely calibration of the cost models used. The findings and conclusions of Bhatt's paper are found to change and actually reverse when more typical and accurately calibrated cost data are applied to the model. This discussion also points to the problem created when cost modeling is undertaken in the abstract without consideration of the important element of revenue or income generated by costs. When both accurate calibration and revenue generation are taken into account, one discovers that Bhatt's conclusion that busway-based transit systems are not inherently lower in cost than rail-based transit systems will not hold true. In fact, the reverse is often, and more likely, true. The importance of proper calibration with proper assumptions relative to the real world is emphasized.

Bhatt has attempted to construct a precise model for costing certain alternatives for the provision of home-to-work commuter journeys over 5- and 10-mile (8- and 16-km) distances. He quite properly identifies costs and prices, sunk costs and opportunity values, the nature of costs, joint-use and shared cost, and the reduction of fixed costs to equivalent daily costs. He limits his comparison to heavy, automated rail rapid transit and fixed busways of the Shirley Busway type, and jitney or other feeder bus service as a supplement to the rail mode. Bhatt's paper is a generalization and as such is quite parallel to the Institute for Defense Analyses work for the U.S. Department of Transportation done in 1973 by Boyd, Asher, and Wetzler. Bhatt properly points out that light rail transit is not included because it may have different characteristics.

Bhatt rightly points out in an extended version of his paper (4) that

> cost comparisons have only a limited value to the decision maker, if no attempt is made to incorporate the aspects of demand .... Modal comparisons based solely on cost are valid only if it is assumed that the benefits associated with each mode are identical, or that each mode does attract the same volume, and that each shows equivalent comfort and convenience characteristics.

I do not agree that equality is achieved by arbitrarily setting what Bhatt believes to be equal service levels. The experience of the marketplace is the only measure of what is equal, and such experience does not rate bus and rail service equally as indicated by Tennyson (12, Table 5) and Vuchic and Stanger (13). With arbitrarily set service equality, it is possible and likely that one mode will actually out-haul another mode and thus vastly affect the resultant cost per passenger mile (kilometer) depending on load factors actually achieved.

In practice, the demand for the type of rail service estimated by Bhatt will be approximately 50 percent greater than the demand for the "equivalent" bus service. There are 4 basic or prime reasons for this. First, the rail model provides passenger stops along the line, which permits various local trips to be made in addition to CBD trips. Where the bus service as modeled would, of necessity, serve primarily CBD trips (95 percent by experience), the rail model would add an additional one-third trips to the intermediate stations but never the CBD. Second, the rail model has a feeder bus system that not only feeds the rail line but also provides superior crosstown service as a useful byproduct. This adds patronage to the system or reduces cost of rail feeders, depending on the calculations. Third, there is all-weather dependability and safety because rail services capture some permanent converts when highways are seriously impeded by ice and snow storms. Fourth, there is comfort and speed of loading. The larger size of rail vehicles and their freedom from fumes and unexpected swerving or "stone wall" deceleration rates are comfort factors recognized by riders when they choose modes.

SUNK COSTS

In an extended revision of his paper (4), Bhatt assumes the highways are a sunk cost: "Lanes for exclusive use by express buses and/or carpools can be set aside." In almost every situation requiring a separate right-of-way, highways are saturated. If a 1,800-vehicle lane is removed from general expressway use, 3 lanes of arterial street will be needed to replace it. The cost of this severely congesting policy must be calculated, or the cost of an added highway lane must be charged to express buses. Rail rapid transit, on the other hand, removes vehicles from traffic while creating another channel equivalent to many additional expressway lanes. This benefits those who continue to drive as well as those who switch to rail transit. If the cost of 2 added freeway lanes or 2 added arterial lanes (1 in each direction) were assigned properly to the bus operation that preempted them, the bus investment for a 10-mile (16-km) urban line would increase from $40 million to $100 million or more.

ANNUALIZATION

The use of 250 days as an annualization factor is not too unreasonable for the type of express bus operation proposed (255 would be more accurate), but the type of rail facility proposed could be expected to have an annualization factor of 280 because of the provision of intermediate station service. This similarly impacts the weekday peak-to-base ratio for the same reason. For example, Shirley Highway and the Philadelphia A-Express have 25-to-1 peak-to-base ratios; the Broad Street Subway or the Lindenwold Line (both in Philadelphia) have 10-to-1 peak-to-base ratios. In Buffalo, only 1 or 2 expressway bus trips/day/route can be justified because of the low patronage generated by nonstop service. Stops are essential to patronage even though passengers detest any but their own. The speed versus stops dilemma is very real, but without stops no one can enjoy the speed. The impact of varying peak-to-base ratios on capital costs is tremendous because annual volumes are so different for the same peak-hour volume. Even peak-hour volumes from the same service area are different by mode, as evidenced by the impact of service changes (12, Figure 2).

The Lindenwold Line carries 12 million passengers annually and has an 8,000-person peak hour in 1 direction (1,500:1); the A-Express bus (or the Route 18 bus on Shirley

Highway) carries 1.5 million passengers annually and has a 1,667-passenger peak hour in 1 direction (900:1). The Buffalo example would be much worse. I realize that specific examples may be atypical, but I believe that reasonably comparable examples have been chosen. The only sure way to improve the bus peak-to-base ratio is to carry a smaller portion of the peak-hour travel, which is what has been happening because bus riding has declined over the years by 70 percent.

Bhatt states that, "for the most likely volume levels (300 to 600 buses/h), 1 bus lane would be sufficient to carry all peak-hour traffic." This is true only if no stops are made, but, if buses are to perform a service, they must make stops, at least in the CBD. Experience has shown that, with 120 buses/h/lane, schedule speeds fall to between 3 and 4 mph (4.8 and 6.4 km/h) where stops are made. For more than 150 buses/h, 2 lanes are necessary. For 300 buses/h, which is the minimum Bhatt suggests, 3 lanes will be needed for reasonable but slow service. In bad weather, it is doubtful that the service could function at all. Most transit texts rate buses at 9,000 passengers/h maximum, and this is about 120 buses/h at the outdated 150 percent load factor, which was a leftover from streetcar days. The assumption of 50 rail trains/h has never been met in practice if station stops are included unless the trains are very short. Loading problems limit practical, effective, reliable movements to 34 trains/h. Automation has little to do with capacity. Philadelphia has run 1-car trains in subway since 1907 on 27-s headways with some lapsing of signal protection not used for buses anyway and on 105-s headways for 6-car trains with full safety-signal override.

Bhatt's assumption that busways can be underground has not been proved in practice. Newark and Providence have operated short bus subways in tunnels for light volumes, but the overpowering underground odor is neither desirable nor acceptable to passengers even with ventilation. It is inconceivable that additional money would be invested to build such an inferior facility.

WALKING TIMES

Bhatt's assumptions for walking access times are not typical of real situations. The typical bus rider will have 0.15 mile (0.75 km) to walk, which will amount to about 3 min at each end of the trip. This is based on experience and verified by the theory of 0.5-mile (0.8-km) route spacing that has been well proved in practice. Because rail rapid transit has fewer stops and greater attraction, walks will average 4.5 min at both the residential and CBD ends of the trip. The 7-min penalty is excessive except for a poorly designed system. Jitneys are no less costly to operate than buses, as Atlantic City has seen over the years; therefore, no economic reason exists to differentiate them from buses. Few CBDs have automobile parking at all-day rates within 1.5 min of major attractive centers.

Bus line spacing in the CBD is irrelevant to walk time. At home, a person walks to the nearest bus line, but in the CBD, he or she must walk to the bus line that goes to his or her home, not the nearest one. These unlikely assumptions do much to distort the model because time values are so important.

UNIT COSTS

Variable costs associated with vehicle operation have omitted injury and damage liability costs, which average 5 to 6 percent of the total for bus systems and 2 percent to 3 percent of the total for rail rapid transit. It also should be noted that no park-and-ride costs are assumed for buses. This is tacit admission that automobile owners are not likely to patronize bus service. If they do, park-and-ride facilities must be provided.

It does not appear that Bhatt meant $4,500/automobile space/year in Table 2. The figure $4,500 is a lump sum capital cost for life. CBD automobile costs, in reality, should exceed considerably the residential area cost because of stop-and-go conditions. At least 2 cents/mile (1.25 cents/km) should be added.

BUS AND JITNEY COSTS

In Table 5, Bhatt has assumed 39 cents/bus mile plus $5.30/h for bus operating costs. For cities likely for rapid transit, these costs are unreasonably low. For the typical 11-mph (17.6-km/h), 30,000-mile/year (48 000-km/year) city bus, this comes to only $9.60/h, 87 cents/mile (54.4 cents/km), or $26,000/year. Actual costs, excluding those for New York City and Boston, are much higher than this and average $15/h, $1.36/mile ($0.85/km), or $45,000 per year (12, Tables 2 and 3). Adding the necessary 50 percent to bus operating cost will have a heavy effect on the conclusions.

Bhatt's jitney costs are even more absurd. Federal transit legislation and labor laws require protection for displaced transit workers. Accordingly, jitney drivers are guaranteed the same wages as those received by bus drivers in the same system. Jitney maintenance will be more, not less, than diesel bus maintenance as almost all operators of small buses have learned to their dismay.

Park-and-ride costs have no allowance for kiss-and-ride. Distance costs will double, which will add 50 cents/day; fixed costs will decline $2/day, and parking lot operation will decline 8 cents/day. The net saving of $1.58/day will mean much to rapid transit costs where access by automobile is a major factor.

RAIL RAPID TRANSIT COSTS

Unlike bus costs (Table 3), rail operating costs (Table 4) are too high. The $1.57/car-mile ($0.98/car km) used will average from $47,000 to $63,000/car/year whereas bus costs were estimated at only $26,000/year. Tennyson (12, Tables 2 and 3) found actual results for each kind of vehicle to be about the same ($45,000). Rail costs can no more be estimated realistically by the mile (kilometer) than bus costs can be. Rail costs vary with frequency of stops (stations). If we assume a 20-mph (32-km/h) rail service, costs will be 80 cents/mile (50 cents/km) plus $15.40/h, or $31.40/car h. The 20-mph (32-km/h) speed allows for turnaround and recovery time at terminals.

BUS RAPID TRANSIT COSTS

These costs not only contain the errors of bus feeder costs but also fail to account for driver and bus time paid for but not worked. The very high peak-to-base ratio of CBD express bus travel requires 10 or 12 drivers at peaks for every 1 working at noon. Improvements in working conditions require penalty time for drivers who start at 6 a.m. and finish at 6 p.m. Bhatt makes no allowance for very low CBD speed costs although he takes credit for speed on the busway. A typical express bus will operate 60 miles/day (96 km/day). That is all the productive work that can be found. For a year, only 16,000 miles (25 600 km) of use is likely. Bhatt's assumptions would cost this out to only 1,040 h/year or $5,512 of hourly cost and $5,920 of distance cost, which is a total of only $11,432/year. Against this small estimated total weighs the fact that a driver must be guaranteed $12,000 plus $3,500 in fringe benefits, which is $4,000 more than the total estimated cost, and costs of fuel, maintenance, administration, busway cleaning and plowing, injuries, and damages have not yet been considered. To obtain correct estimates for such a busway operation, hourly costs must be boosted to $15.90 and distance costs to $0.59. By using these more realistic figures, one determines that express busway costs will approximate $26,000/bus, which is still a third less than average. To speed buses, station fare collection and cleaning may be necessary. This will add still more to bus costs.

Table 5 also overlooks the problem of bus volume in a 2-lane underground bus station. To serve 500 buses/h from the Lincoln Tunnel exclusive bus lane, the Port Authority of New York and New Jersey requires 76 bus stops, and more are needed. The cost of 76 underground bus stops in a single station is outside the national debt limit in a developed, congested area.

Bhatt is correct when he points out that bus drivers draw $6 or $7/vehicle h although he used only $5.30 to compete with rail rapid transit. A taxicab driver at $3.00/vehicle h also draws 50 percent of the fare as commission plus tips. No one would work for the $3 figure in a metropolitan city. Section 13c of the National Mass Transportation Assistance Act of 1974 would preclude such wage scales in any event. Bhatt admits in an extended version of his paper (4) that his rail costs include "both peak and off-peak service while bus operating costs are based on operations biased heavily towards peak service."

COMPARATIVE ANALYSIS

It is artificial to separate transit costs into residential collection, line-haul, and CBD distribution. Many passengers walk from home to rapid transit and from rapid transit to the office, which means they use only line-haul service. Many others use park-and-ride or are dropped off, which means that they also use only line-haul service. On Philadelphia's suburban Lindenwold Line, which has poor feeder bus acceptance, off-center CBD distribution, and high ridership, 83 percent of the passengers are line-haul-only passengers as far as transit is concerned. If park-and-ride is added, there is still little CBD distribution other than by the line-haul mode. The same is true on most other lines. Rail transit costs are overstated grossly by this pseudoanalytical technique pioneered by Meyer, Kain, and Wohl.

Bhatt's assumption that all rapid transit trains will be all-stop locals but that all buses will offer nonstop express service is not realistic. The efficient method for such a rail service would be to have peak-hour local and express trains and have locals cover only ⅔ of the length of the line. With only 2 tracks, only 2 min can be saved by each express on a 6-min headway, but each local will save 8 min by cutting short the trip. This reduces fleet and personnel requirements, conserves energy and money, and pleases the riders. True, the average wait increases from 1.5 to 3 min, but express riders save 2 min. Morning local riders get a seat they would not get otherwise. For more than 20 trains/h, this system is impractical; therefore, a skip-stop system becomes necessary, but the short turnback a half hour before the peak of the peak period is still a major economy.

If a 10-mile (16-km) line with 100,000 passengers/day is assumed for illustration, there may be 18,000 peak-h passengers in 1 direction. This will require 168 large cars in 21 trains. However, if express and local turnback operation is employed, adding express to 4 stations, then only 80 cars will be needed in 10 express trains and only 64 cars will be needed in 8 local trains, thus saving 3 trains and 24 cars at $260,000 each ($6,240,000) plus $45,000/car ($1,080,000) in operating expenses. These savings make a great difference in comparative analysis, and they are not highly theoretical. Many rail systems use short turnbacks.

The assumption that 15 percent of all travel will occur in the peak hour is valid only for a short urban rapid transit line. Peaking is proportional to line length. For a 10-mile (16-km) line, that 20 percent of all travel will occur in the peak hour is more common. For an express busway, 30 percent should be assumed in the peak hour, which doubles costs and adds no revenue. This is based on experience with the Shirley Busway, Route A on the Schuylkill Expressway in Philadelphia, the Saint Louis and Marin County, California, rapid buses, and most others.

The assumption that there is no reverse flow for either rail or bus systems is a heavy penalty for rail to bear because it is costed to provide reverse commuting service to all local stations along the way. Buses, with no intermediate stops, and hence no demand, are not similarly penalized although they are unproductive. In the real world, at least 2,000 persons/h would be carried in the reverse direction by a 20,000-passenger peak-hour rail line. This would save $1.8 million/year in the operation of 40 surface local buses or would generate that much more revenue.

Table 7 lists the cost of automobile residential service at only 7 cents/mile (4.4 cents/km), but Table 2 lists the same cost at more than 8 cents/mile (5 cents/km). This should be reconsidered.

The assumption that jitneys provide better service and thus could charge 10 to 20 cents more is unfounded. If this were true, the United States would be full of successful jitney operations even if they were operated by old line transit authorities. The nation went through this just after World War I, and it did not work out well. An extra 20 cents on a city fare will frighten many riders away; experience has shown so repeatedly.

Figure 1 costs are based on the extremely biased idea that a rail facility would require 5 miles (8 km) of subway and 5 miles (8 km) of elevated railroad. If buses are substituted, however, no subway is used and at-grade right-of-way is used for half the distance. It is not at all apparent why a rail line cannot use the busway alignment and save $164 million. Such unequal assumptions defy comparative analysis. Bhatt's claim to the contrary is based on grossly distorted operating costs as has been shown.

DOWNTOWN SERVICE

Bhatt has assumed a 25-mile-long (4-km-long) downtown subway to serve a 1-mile^2 (2.6-km^2) downtown. Good rail design would run trains through to the other side of the city, avoid any loop, and limit distance to 1 mile (1.6 km). However, if a dead end must be assumed, the area can be served by a 1.75-mile (2.8-km) hook route within 0.25 mile (0.4 km) of any location in the area. The difference of 0.75 mile (1.2 km) is $38 million.

Bhatt grossly underestimated the operating cost of downtown surface service by bus. If one uses actual 3- to 4-mph (4.8- to 6.4-km/h) CBD bus speeds, costs will be 2½ times that estimated by Bhatt and ridership will be proportionately less. A 0.5-mile (0.8-km) CBD bus ride will cost 8 cents instead of 2 cents as estimated by Bhatt [$5.30/h + 0.39 mile (0.62 km) ÷ 25 passengers]. A 2-cent bus ride is obviously untenable.

The statement that "underground busway stations . . . cost less than rail rapid transit stations because busway stations are smaller in size on the average" is quite incorrect. A rail station requires 18,000 ft^2 (1674 m^2) per track for a line capacity of up to 40,000 passengers/h. For only 20,000 passengers/h, a busway station would need 15,000 ft^2 (1395 m^2) plus an extensive ventilating system. This assumes very slow weaving operation. At rail speeds, a bus station could not be built feasibly.

OVERALL TRIP COSTS AND SERVICE

The assumption that a 24-ft (7.3-m) busway would suffice for 10,000 daily trips is erroneous. Such volume suggests a capacity of 30,000 passengers/peak h for bus service. But, even for a capacity of 20,000 passengers/peak h, this would require 400 buses according to the data given in Table 6. With a bus every 9 s, stopping, unloading, or loading is not possible and neither is operation in snow or ice. Even with an extra lane, loading and required weaving will choke up the movement.

The data given in Table 8 ignore walking to the rail transit stations. Park-and-ride and drop-off also are ignored. The gross distortion caused by these assumptions writes off 30,000 passengers/day or 6,000/peak h. Conversely, it adds several million passengers per year to rail transit feeder costs, which is neither necessary nor realistic.

The assumption that the automobile is the fastest mode is not borne out by experience. The data given in Table 37 of the Penn Jersey Transportation Study show that rail commuter service was 25 percent faster door-to-door than automobile travel was. With 0.5-mile (0.8-km) station spacing, a subway-elevated system was slower, but since then, the Lindenwold Line has inaugurated service that, although it is rapid transit, is as fast as or faster than commuter rail service or the automobile.

No one should designate car pools as a form of transit because casual travelers cannot avail themselves of car pools. Car pools are a form of automobile, not transit, travel.

Figure 4 does not list park-and-ride rail or busway travel, but curves are presented for them. It is totally illogical that they should show high cost except for the aberrations already cited.

Bhatt claimed in the extended version of his paper (4) that along-the-line rail rapid transit, which is not available by busway, can be replaced by a 7-cent bus service.

Current bus fares should prove the invalidity of this "case study." If a 5-mile (0.8-km) local bus line that operates on a 1-h round-trip cycle (which is typical) is assumed, it will cost $15/round trip. Buses in urban service on good routes pick up 4 to 5 passengers/mile (2 or 3 passengers/km) or 40 to 50 passengers/round trip as an all-day average. This will cost 30 to 37.5 cents/ride and not 7 cents as Bhatt claimed. With free transfers included, it would require a 50-cent fare, which has been demonstrated to be necessary

The assumption made by Bhatt in the extended version of his paper (4) that "per passenger trip costs can, needless to say, be dramatically reduced by packing twice or three times as many people as there are seats in a vehicle" is grossly fallacious. A 50-passenger bus cannot realistically carry 100 people and cannot physically carry 110, let alone 150, people. A 110-seat rail car, however, can readily carry 210 and can be jammed to 250 in emergencies because of the design and shape of the vehicle. More important, prospective riders will not pay to ride that way.

SUMMARY OF FINDINGS

Bhatt's findings are devoid of validity. The case study finds an 8-cents/trip saving with busways, but it has been shown that bus costs are 33 percent lower than they would be to be realistic. If this is corrected, a huge advantage accrues to rail rapid transit. The finding that car pools are least costly is also erroneous because no highway investment has been included to serve the 30,000 peak-h riders that a transit way can carry. At 3 persons/vehicle (or a 100 percent increase), 10,000 vehicles/h corridor would be needed, which would require 6 expressway lanes in each direction and 18 lanes/corridor of CBD distributor streets. The ecological, sociological, and financial cost of such a facility would be prohibitive now that urban freeways often exceed $50 million/mile ($31.25 million/km).

By using Bhatt's methodology but correctly calibrating the models, one can readily see that rail rapid transit will collect the most riders and move them at lowest cost, as shown by the data given in Table 10. The computation of the data given in Table 10 is oversimplified because the complete data calculations were not available, but I believe that this computation realistically presents the difference between the methods used. Comparison with actual experience should verify the calculations. Rail costs can be further reduced by using express service as explained in this Discussion.

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12. E. L. Tennyson. Economic Relationships Among Urban Transit Modes. Transportation Research Record 552, 1975, pp. 19-30.
13. V. R. Vuchic and R. M. Stanger. Lindenwold Rail Line and Shirley Busway: A Comparison. Highway Research Record 459, 1973, pp. 13-28.

Table 10. Bhatt's data versus corrected data.

System	Line Length (miles)	Subway Miles	Investment (dollars)	Volume: Passengers/ Peak Hour	Volume: Passengers/ Day	Required Number of Vehicles	Operating Cost: Dollars/ Vehicle/ Year	Operating Cost: Dollars/ Passenger	Capital Cost (dollars/ passenger)	Total Cost (dollars/ ride)
Busway										
Bhatt[a]	10	0	56,000,000	20,000	140,000	467	11,432	0.14	0.12	0.26
Corrected	10	1	132,000,000	20,000	66,667[b]	467	26,000	0.69	0.52	1.21
Rail Rapid Transit										
Bhatt[a]	10	5	332,000,000	20,000	140,000	364[c]	50,000	0.45	0.47	1.02
Corrected	10	1	140,000,000	20,000	120,000	255[c]	53,000	0.39	0.28	0.67

Note: 1 mile = 1.6 km.

[a]Estimated from data in the extended version of Bhatt's paper (4). [b]Low because no along-the-line access is provided. [c]Includes feeder buses.

AUTHOR'S CLOSURE

In his discussion of my paper, Tennyson almost totally misses the point. In trying to show that rail rapid transit is less expensive and faster than bus rapid transit, Tennyson compares costs of rail rapid transit systems with costs of local bus service upgraded with "bells and whistles" rather than approaching the comparison from the first principles set out in my paper. There are internal inconsistencies in Tennyson's arguments, and eventually he compares heavily overcrowded rail systems with currently inefficient bus services. In other words, he compare apples to oranges. I will try to point out the inconsistencies and invalid assumptions in Tennyson's discussion.

Tennyson stated that, "in practice, the demand for the type of rail service estimated by Bhatt will be approximately 50 percent greater than the demand for the 'equivalent' bus service." It is hard to accept how, "in practice," the demand for rail service will be 50 percent greater than for "equivalent" bus service when the bus would be faster and less expensive (if one allows for lower fares), would require fewer transfers, and would have a loading standard (crowding) that is at least as good as that for rail service.

Tennyson stated that the rail model would increase trips to the intermediate stations by about 33 percent. Along-the-line travelers probably would increase the trip total by 10 to 15 percent rather than 33 percent. The bus system also provides superior crosstown service because the feeder bus for both modes is nearly identical. Express bus service also can capture some permanent converts when highways are impeded by ice and snow.

On sunk costs, Tennyson missed my point. I did not assume that line-haul highway costs are sunk, and I provided for added lanes. Similarly, the costs of providing new exclusive busways have been included.

Tennyson also missed my point on annualization. I was not trying to compare one particular existing operation with another specific system but was designing systems to operate in a similar manner to serve identical demand levels and peaking patterns.

When Tennyson stated that bus riding has declined over the years by 70 percent, he should have pointed out that this decline is for local, conventional bus operations and not for express bus services.

Tennyson's comment about 120 buses/h/lane at 3 to 4 mph (4.8 to 6.4 km/h) is valid for local buses in mixed traffic with on-line stations. I suggested exclusive bus lanes for surface distribution. More important, the busway mode, which is comparable to rail service, provides CBD distribution along an underground, weather-protected, exclusive facility with off-line stations. Thus much greater flow capacity and speeds would be allowed. One lane would be ample. [I provided 22-ft-wide (6.7-m-wide) busways for service in each direction.] Automation will increase capacity of rail rapid transit lines.

Tennyson stated that the odor from buses operating underground even with ventilation is neither desirable nor acceptable to passengers. But the underground busway designs suggested in my paper included expensive ventilation systems. Therefore, the environment in the underground facility will not be "overpowering."

When he discussed walking times, Tennyson once again missed the purpose of my paper. There is no typical bus rider walk requirement. Walk is a function of route design in both the residential zones and the CBD. My study considered specific route designs for various access and egress modes. I also would like to add that, currently, jitneys are less expensive to operate than buses. The costs for automobile parking in the CBD were based on the assumption that the needed parking would be provided. And bus line spacing in the CBD is not irrelevant to walk time. My study design accounted for the need to walk and wait for the appropriate bus for home.

In the section of my paper on unit costs, I developed costs for rail and bus systems, both of which are fed by park-and-ride, jitney, or bus modes, because I was trying to compare equivalent modes. The figure of $4,500 for parking facility cost in Table 2 was, as Tennyson indicated, a lump sum capital cost for life.

Tennyson had a few points to make about the section on bus-jitney costs. He took issue with my use of $5.30/h for bus driver costs. In the study, a figure of $7.00/h is now used for bus driver cost; this figure is based on recent data. In the study, the distance traveled per bus is an output of the model and not a constant as suggested by

Tennyson. Actual figures in the study were higher. Therefore, with a revised cost of $7.00/h, the actual annual costs per bus would be greater that the $26,000 suggested by Tennyson. New York and Boston, which show costs of $48,000/bus/year, are hardly typical U.S. cities as Tennyson suggested. The jitney costs given in my paper are not absurd. They are real figures based on taxicab operations. I encourage readers to put in their own wage rates.

The rail operating costs I used are not too high. They were based on statistical analysis of actual figures from various North American rail rapid transit systems and normalized by the same cost index (wage rate) as that used for bus costs. If they are anything, they are low. A glimpse at U.S. rail rapid transit systems will confirm this. Tennyson's figures are without any theoretical basis and are not based on in-depth statistical analysis of cross-sectional data.

In the section on rapid bus costs, the bus costs did include effects of idle bus driver time. Tennyson's suggestion that services show a peak-to-base ratio of 10 or 12 to 1 is way off the mark. In my analysis, the actual ratio is closer to 2.5 or 3 to 1. Contrary to Tennyson's contention, a typical express bus in my study operates 200 miles/day (320 km/day), 50,000 useful miles/year (80 000 useful km/year), and 1,750 useful vehicle h/year. These figures indicate $12,250 in hourly costs and $18,000 in distance-related costs. Tennyson's method of obtaining busway costs is inaccurate and misses the point. Tennyson criticized Table 5 in my paper because it "overlooks the problem in a 2-lane underground bus station." The bus station that I used is not a 2-lane facility; a sufficient number of off-line platforms are provided. Regarding bus driver costs, the study was revised to show $7.00 instead of $5.30 as hourly costs. Contrary to what Tennyson feels, taxicab drivers in U.S. cities have been working for about $3.00/h.

In the comparative analysis, it is not artificial to separate transit costs into the 3 components of residential collection, line-haul, and CBD distribution. Park-and-ride access to rail or bus is expensive. In my paper, the rail transit costs generally are grossly understated (for example, the Lindenwold Line analyses leave out park-and-ride costs). Tennyson gets carried away in calling the Meyer, Kain, and Wohl study "pseudoanalytical." Why is it so? How is Tennyson's approach better?

The service suggested by Tennyson would have many standees, which is onerous to travelers; waiting time would increase; and service providing more than 20 trains/h would not be feasible. My assumption that there is no reverse flow for either rail or bus systems is not a heavy penalty for rail. Reverse flow can be served at near-incremental costs, and along-the-line flow in both directions can be served very cheaply (about 1 cent/system rider).

I would like to point out to Tennyson that jitneys do not exist today because they were outlawed, not because they were unsuccessful. They were outlawed because they were successful. And an extra 20 cents on city fares will frighten some, not many, riders away.

Some of the busway modes shown in Figure 1 do have underground distribution downtown (those labeled "busway" in the CBD column); Tennyson stated that no subway would be used if buses were substituted for a rail facility. The impact of designing the line-haul facilities with specifications that are identical for both rail and busway is shown in Figure 2 and by option 11b in Figure 4. I might add that the operating costs have not been grossly distorted as claimed by Tennyson.

In criticizing my section on downtown service, Tennyson defines "good" rail design. However, what "good" rail distribution should look like is not agreed on. Bus distribution can be designed exactly as rail distribution and it would still be better. Remember that a smaller undergound distribution will favor a bus system over a rail system.

My overall average surface bus speeds downtown would not be the 12-mph (19.2-km/h) average road speed that Tennyson assumed it would be because the analysis also includes slowdown effect due to acceleration, deceleration, loading, and unloading [which are included in Tennyson's unrealistically low figures of 3 to 4 mph (4.8 to 6.4 km/h)]. Also ridership will not necessarily be proportionately less even for slower speeds because the elasticity would not be 1.0. I also would like to point out that the surface bus costs shown in my paper are about 10 cents/trip, not 2 cents/trip as indicated by Tennyson.

Off-line bus platforms have been assumed in my paper, and they, indeed, require less space and construction than rail stations. A 600-ft (183-m) rail station requires 15,000 ft^2 (1395 m^2) of space for platforms in addition to the space for the line portion of the station. A bus station will require roughly 2,800 ft^2 (260 m^2) of additional space per platform where each platform can handle 150 buses/h if only a few passengers load and unload per station.

Under the assumed peaking pattern in my study, 100,000 daily trips imply a peak-hour flow of 15,000, which would require 300 buses. Stopping, loading, and unloading are possible if off-line multiple-platform stations are provided. Also, for underground operation, snow and ice should hardly cause any concern. Weaving and loading will not choke up the movement if operations are designed properly.

People can walk to bus stations. Tennyson missed the point that my analysis looks at 1 access mode at a time. Park-and-ride can be provided for both rail and bus services but would be a very costly option. The assumptions have identical impact on both rail and bus services; therefore his comments on Table 8 are totally irrelevant.

Tennyson disagrees that the automobile is the fastest mode, but other studies have shown that this is often so. The automobile will be the fastest if sufficient line-haul capacity is provided as was done in my study.

Tennyson says that "no one should designate car pools as a form of transit." We have a semantic problem here. Car pools are a paratransit mode.

Tennyson is mistaken totally in saying that park-and-ride access is not costly. It is not costly to the transit company. But in terms of economic costs, which are the concern of this paper, park-and-ride is the most expensive feeder mode.

Tennyson disagreed with my claim that along-the-line rail rapid transit can be replaced by a 7-cent bus service and stated that current bus fares would prove the invalidity of my claim. But fare has nothing to do with costs. Also the suggested along-the-line service can be designed in a better than typical form to run efficiently on 44-ft-wide (13.4-m-wide) busways at the cost of 7 to 10 cents/passenger trip. The "typical" figures given by Tennyson are irrelevant because they do not apply to the service being treated. The additional cost over the system ridership will be only 1 to 2 cents/trip because the 10-cent cost will be spread over the entire system. (The curves will go up by only about 1 cent.)

Tennyson's contentions that my findings are devoid of validity are baseless. The findings are valid for the modes and the operations studied. The bus does not cost 33 percent more than I have shown. Huge advantage does not accrue to rail rapid transit if proper analysis is done. In fact, the operating costs for rail service included in the study were unrealistically low. Car pool costs do include highway investments to serve 15,000 peak-h riders/corridor. If 4 persons/vehicle are assumed for car pools, then less than 4,000 vehicles/h/corridor will be needed, which would require only 2 expressway lanes in the primary direction and 1 lane in the opposite direction. Costs for 3-lane urban freeways do not often exceed $50 million.

Irrelevant methodology and inconsistent assumptions have been used to develop Table 10. Use of different demand levels as shown is conceptually and methodologically without any basis. The corrected busway system data are totally incorrect. Comparison with real-world experience will, indeed, expose the errors in the numbers used in the table.

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