Analysis of Nationwide Demand for Urban Transportation Tunnels

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For the purpose of determining estimates of the amount of transportation-related tunneling activity likely to occur to 1990, a methodology was devised whereby the conditions necessary to justify the application of tunnel segments for mass transit facilities were identified and matched against the number of situations in which these conditions are likely to be fulfilled. A corollary outcome of the analysis is an appraisal of factors that affect the preference of one type of mass transit system over others and an understanding of the sensitivity of preferred system choice to these factors. A technical evaluation of supply and demand for alternative types of mass transit systems was conducted to determine the future viability of such systems for cities that do not have them. Results of city-by-city application of the methodology developed revealed that, with current construction costs and property values, three cities currently without mass transit systems—Detroit, Cincinnati, and Denver—would meet necessary conditions for tunneled systems by 1990. At the other extreme, tunnel distance was computed for conditions in which tunnel construction costs in real terms were postulated to fall to 40 percent of today's cost and right-of-way values to rise by 5 percent/year. Other sensitivity results for the preference of tunnels to new right-of-way and for the forecast of nationwide tunnel construction under other assumptions are also reported.

A tunnel is used by transportation planners as a device to bypass obstacles that obstruct or otherwise make more costly the movement of freight and passengers. Justifying the use of this expensive technique to solve transportation problems involves consideration of the direct and indirect benefits and costs unique to the particular obstacle to be bypassed. The intent of this paper is to summarize a research methodology (1) to identify the underlying economic, demographic, and technological forces that jointly influence the decision to tunnel in urban areas and to present estimates of the likely extent of tunneling in the future based on this methodology. Emphasis is placed on tunnels used in conjunction with urban mass transit systems where the major obstacles to be bypassed are centers of high-density activity and where right-of-way costs and system capacity requirements and costs may call for tunneling as a solution.

The following procedure was used in the study:

1. Develop an analytical framework to indicate conditions in terms of ridership, cost for new rights-of-way, facility costs, operating characteristics, and social costs where alternative bus or rail modes with surface and subsurface guideways are preferred.
2. Develop estimates for future values of these variables, and identify the location and extent of justifiable urban transit systems (both bus and rail) with tunnel segments.
3. Base forecasts of future tunneling on alternative assumptions of urban growth for estimates of ridership, cost of new tunnel construction, and cost of new right-of-way for future at-grade systems.

First, ridership forecasts made at various census boundaries emanating from the central city for each of the 35 largest U.S. standard metropolitan statistical areas (SMSAs) are presented. Transit ridership is explained in terms of residential and employment distribution by using statistical regression techniques. The supply side of the analysis is next concerned with establishing, through parametric costing techniques, the conditions by which bus or rail transit is preferred to alternative surface and subsurface guideway options. Finally, the results of the analysis of transit demand and supply are merged with forecasts of urban population growth, construction costs, and costs for new right-of-way to provide a nationwide forecast of warranted system distance for tunneled segments. These results are useful (a) in assisting designers and planners in establishing criteria for system specification under existing and future conditions and (b) in framing the impacts that may result from federal policies toward urban growth patterns and research and development expenditures to alter or reduce costs for new tunnel construction.

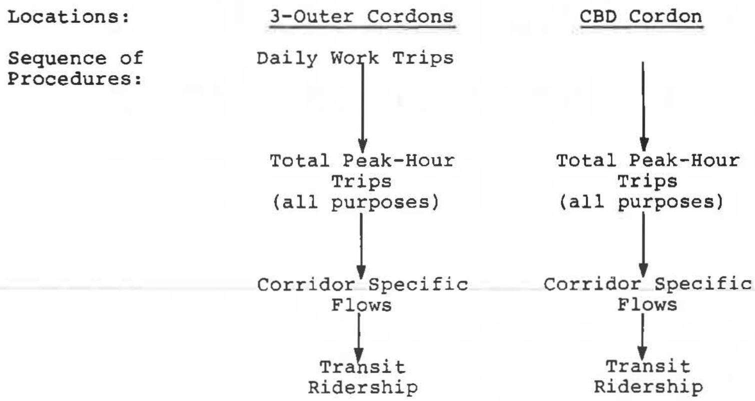
FORECASTS OF URBAN TRANSIT RIDERSHIP

Paramount among the factors that influence the choice of preferred urban transit systems is the prospective level of ridership. The level, geographic dispersion, and time distribution of demand must be known to dimension system capacity, which in turn is the basis for costing system capital and operating expenses for each alternative considered. The methodology for demand forecasting is designed to produce estimates of peak-hour, primary-direction transit ridership at each of four geographic boundaries. The estimation procedure is evaluated under two alternative assumptions for the distribution of urban growth: (a) that historic population trends for the central city and the suburbs will continue and (b) that current population distribution will prevail in the future.

The procedure for demand estimation, shown in Figure 1, consists of two components: the determination of daily primary-direction work trips at three outer cordons and the determination of total peak-hour flows at the central business district (CBD) cordon. In the first instance, daily primary-direction work trips are converted into total peak-hour trips and, for both components, total primary-direction, peak-hour trips are converted first into corridor-specific flows and then into transit ridership. The need for separate treatment of CBD traffic flows and flows at other boundaries reflects the unique nature of the CBD as the geographic center of an urban area and the consequent use of the CBD as a conduit for traffic that neither originates nor terminates in the CBD.

Daily work trips crossing the three outer cordons in 1970 (corresponding to the concentric census boundaries called rural and scattered urban, urbanized area, and central city except CBD) can be derived from a recent publication of the U.S. Department of Transportation (2). This publication presents for each of the 35 largest SMSAs 1970 census data for the journey to work in the format of an origin-destination table in which trip origins and terminations correspond to the five concentric census rings. From this data source, primary-direction radial work trips at the other three cordons can easily be found by summing at each outer cordon boundary the number of trips that originate outside the boundary and

Figure 1. Procedure for demand estimation.



terminate in an inner census ring. A conversion process to translate daily primary-direction radial work trips to peak-hour trips for all purposes was then developed by using two average factors: peak-hour trips as a percentage of total daily work trips (factor 1) and peak-hour work trips as a percentage of total peak-hour trips (factor 2). These adjustment factors, applied to daily work-trip flows, provide peak-hour trips for all purposes. These two factors, which cover a total of six cities, are (a) factor 1, 21.87 percent (standard deviation 2.77); and (b) factor 2, 73.35 percent (standard deviation 3.48) (3, 4).

For the critical CBD cordon, a more involved procedure was used since it is well known that a significant fraction of CBD traffic neither originates nor terminates in the CBD. Meyer, Kain, and Wohl (5) cite pre-1960 data for a small sample of cities that suggest that from 30 to 70 percent of CBD traffic is of this nature. A statistical procedure was developed to provide a relation for estimating total peak-hour CBD cordon crossings based on the total number of work-trip terminations in the CBD, the number of intraring work trips in rings adjacent to the CBD, and the distance of these intraring trips.

Data for peak-hour CBD cordon crossings were assembled for 19 out of the 35 largest SMSAs together with values for the city-specific explanatory variables listed above. In many instances, data for CBD cordon crossings were for other than census years; interpolation was thus required to provide consistent data observations.

Regression equations were computed in linear and log-linear form by using the following as explanatory variables: CBD workers, intraring work trips in rings adjacent to the CBD starting with the nearest adjacent ring and adding more distant rings, and the radial distance from midpoint to midpoint of the adjacent rings. The theory being tested was that traffic across the CBD was explained by both CBD attraction and through-trip generation and that the greater intraring traffic is and the shorter the distance represented by radial trips through the CBD is, the more CBD trips occur.

Preliminary results that used CBD workers as the single explanatory variable indicated that the inclusion of New York City in the data set was unduly affecting the results (New York City had a peak-hour flow nearly as large as the combined values of 15 out of 19 remaining cities) and, consequently, this data point was dropped from further regressions. Furthermore, these preliminary results indicated that CBD workers explain a large fraction of the variability of peak-hour CBD cordon crossings; the dependent variable appeared to be elastic with respect to CBD workers. Larger cities show a higher elasticity, which indicates that peak-hour traffic increases more than proportionally to the number of CBD workers as the city becomes larger and probably reflects a greater proportion of white-collar employment. A final statistical check was used to test whether the error term was systematically increasing with increasing values of the dependent variable since large variability of the independent variables is present in the sample. A ratio test that compared the sum of squared residuals for separate regressions fit to large and small values of the dependent variables revealed the presence of heteroscedasticity for the linear specification but not for the log-linear formulation. Consequently, a log-linear specification was selected.

Regressions that use first intraring trips and radial distance for the closest ring adjacent to the CBD and then the next adjacent ring were then computed. Only trips within the closest adjacent ring (central city) proved to be statistically significant, so the process was stopped at this point. The regression results, which consider first CBD workers and then add the closest intraring and corresponding radial distances, are given below (t-statistics in parentheses):

$$\log(Y) = -0.187 + \underset{(6.89)}{1.044}\log(X_1) \qquad R^2 = 0.736 \tag{1}$$

$$\log(Y) = -0.135 + \underset{(5.63)}{0.934}\log(X_1) + \underset{(2.89)}{0.437}\log X_2 - \underset{(-4.05)}{1.013}\log D_2 \qquad R^2 = 0.876 \tag{2}$$

$$\log(Y) = -0.546 + \underset{(5.31)}{0.999}\log(X_1) + \underset{(3.0)}{0.534}\log X_2 - \underset{(-2.43)}{1.624}\log D_2 - \underset{(-1.16)}{0.197}\log X_3 + \underset{(0.84)}{0.779}\log D_3 \qquad R^2 = 0.888 \tag{3}$$

where

Y = peak-hour CBD cordon flow,
X_1 = CBD workers,
X_2 = trips that originate and terminate in the central-city ring,
D_2 = radial distance from midpoint to midpoint of the central-city ring,
X_3 = trips that originate and terminate in the urbanized area, and
D_3 = radial distance from midpoint to midpoint of the urbanized area.

On the basis of statistical properties, the second regression equation was used for forecasting purposes. The results of this equation suggest that peak-hour CBD cordon flows increase nearly in proportion to increases in CBD workers, that work trips within the ring adjacent to the CBD have a positive but less than proportionate effect on peak-hour CBD cordon crossings, and that the impact of through traffic is directly proportional to the radial distance across the next adjacent ring to the CBD. Nearly 88 percent of the variability of CBD peak-hour crossing is explained by this relation.

The peak-hour cordon flows developed above can be used to generate estimates of future traffic flows once residential and employment patterns—the explanatory variables—are themselves projected. Historic trends reveal that an increasing share of the U.S. population resided in metropolitan areas until 1970, at which point relative growth rates for urban and rural areas equalized. Within metropolitan areas, central-city populations have declined on a relative basis. After 1970, absolute declines in central-city populations were observed. Employment trends generally follow the same pattern. A universal tendency for population to reside close to the place of employment was observed. In the five largest SMSAs, between 61 and 67 percent of workers reside and work in the same census ring. In the five smallest SMSAs, the comparable percentages range from 53 to 58 percent. The average for the entire 35-city sample is 55 percent.

To forecast employment and residential levels and distribution, we first projected employment by census ring and assumed that the probability of a worker residing in ring i, given that that worker is employed in ring j, remains unchanged from the probability of 1970. Levels and distribution of employment are thus assumed to determine residential decisions; employment levels are forecast by using the assumption that historic rates of growth among census rings remain unchanged:

$$E = E_1 + E_2 \quad (4)$$

$$\Delta E/E = (E_1/E)(\Delta E_1/E_1) + (E_2/E)(\Delta E_2/E_2) \quad (5)$$

$$(\Delta E_1/E_1)/(\Delta E_2/E_2) = \alpha \quad (6)$$

where E is employment and α is historic relative growth rates.

By way of illustration, total metropolitan employment consists of employment in rings 1 and 2 (E_1 and E_2 respectively). Projected overall growth in employment $\Delta E/E$ equals the weighted growth in each ring $\Delta E_i/E_i$ where the weights are base-period shares E_i/E and are found after correction for changes in geographic boundaries attributed to annexation. By using Equations 5 and 6, each ring's growth rate can be found from α, E_i/E, and $\Delta E/E$ for the projected area. The third value was obtained from U.S. Department of Commerce projections (6).

A second forecast was also prepared that assumed uniform growth rates in each census ring or that the distribution of employment remains unchanged. Note that this assumption is equivalent to setting $\alpha = 1$ in Equation 6.

Employment projections that use historic trends show 32 out of 34 cities to have higher suburban employment growth relative to central-city growth. The exceptions—Pittsburgh and San Antonio—will therefore show higher forecasts of traffic flow when trends are used than when the forecast that assumes uniform growth in all census rings is used. Thus, in general, forecasts that assume uniform growth will produce higher CBD and central-city boundary flow rates than the comparable rates obtained by assuming continuing historic relative growth. Two SMSAs—Houston and Dallas—have the highest central-city growth rates and the most balanced growth between the central city and suburban rings. For these two cities, forecasts of traffic flow under the two alternative assumptions can be expected to be similar.

The forecasts of residential and employment levels by SMSA are next substituted into the previously developed peak-hour relations. The distribution of peak-hour primary-direction flows into corridor-specific flows is based on the number of existing corridors in an SMSA and their existing share of traffic. A mode assignment to transit is also based on existing observations that show higher transit shares as the absolute volume of peak-hour traffic increases.

COST ANALYSIS OF URBAN TRANSIT SYSTEMS

A cost analysis was performed to identify critical levels of demand, property values, and tunneling construction costs at which tunneling could compete in cost with the best surface alternative.

A three-step procedure was used:

1. System specifications were prepared to reflect the major competing transit system types under consideration.
2. Cost parameters were obtained for all of these systems.
3. A parametric cost model was used to solve for a locus of property values and tunnel construction costs that define conditions in which tunneling should be used.

Results were obtained by parametrically varying ridership to cover the range encountered in American cities.

Specifications

The systems to be discussed all consist of a line-haul and a CBD component. All would require feeder lines but, since tunneling is improbable for a feeder route, no feeder systems were costed. Bus and rail rapid transit systems, the two major urban transit alternatives currently in use, are compared.

The roadway options included in the study are tunnel, aerial, and three surface options—dedicated lanes, acquisition of new right-of-way, and median strip of an existing roadway. Comparative analysis was eventually limited to new right-of-way versus tunnel. Station spacing was set at an average of 0.5 km (0.33 mile) in the CBD and 2.4 km (1.5 miles) in the line-haul. This spacing approximates that of systems currently under construction.

To normalize for differences in the speed of operations between the modes, bus service is taken as half express and half local whereas rail service is strictly local. Provision of only one track in each direction simplified computations and allowed adequate passenger-carrying capacity for all cities currently without rail transit. Service is provided 20 h/d on weekdays (with two peak hours each morning and evening) and 18 h/d on weekends and holidays. Demand is based on peak-hour major-direction passengers per hour, and secondary directions or off-peak, one-way flows are set at 15 percent of the peak flow. Minimum service frequency is 15 trains or buses/h at the peak and 6 at the off-peak. A train has a maximum of eight 23-m (75-ft) cars in married pairs or 182 m (600 ft) of length.

Although bus and rail systems were required to provide similar performance for purposes of cost comparisons, it did not seem realistic to make seating standards or speeds identical. The purpose of the analysis is to predict tunnel construction based on systems that will actually be in use in the next decade or two. Instead, the number of seats per length of railcar was equated to standards of a 12-m (40-ft) bus or 50 seats/bus and 94 seats/railcar. At peak, some standing is allowed for railcars (30 percent of seating) and local buses (20 percent of seating since there is less standing room in the narrower bus) but not for express buses, which remain full for the entire route. Average speeds for buses vary from 19 km/h (12 mph) in the CBD on dedicated lanes to 61 km/h (38 mph) on the line-haul for an express bus on a special busway. Rail speeds average 60 km/h (37 mph) on the line-haul and 32 km/h (20 mph) in the CBD.

Bus and rail differ in two other respects that do not affect service but do affect costs. First, bus stations may be larger (i.e., have more platforms) in the CBD than in the line-haul where fewer buses may be stopping provided the minimum service frequency is met. However, rail stations must always accommodate one train at the platform; station costs have therefore been based on 182 m of length. Second, buses on special busways can make the return trip on local streets by using excess local street capacity so that only one-way capacity is required, whereas rail always has one track in each direction.

Costs

System costs, like system specifications, are intended to be representative rather than specific to any one city. Operating and capital costs were derived from the past experience of existing systems and modified by expected future trends in technology and prices. Other costs—externalities to nonusers, travel time, accidents, damage to property during construction, and property values—cannot easily be documented and were either estimated or treated as parameters for sensitivity analysis.

Operating costs were based on the American Transit Association (ATA) reports of bus and rail transit companies (7). Costs were divided into costs per vehicle mile, costs per vehicle hour (chiefly drivers' wages), and maintenance costs per vehicle, per station, or per lane mile.

Costs of operation and maintenance of underground busway and rail or bus stations were not available from ATA reports. The major cost element for operation of underground busways is ventilation; lighting, washing, and signaling also contribute to the total. A rough estimate of $0.12/bus-km ($0.20/bus-mile) was used to cover these costs.

Station operating costs were derived from a report prepared for the Washington, D.C., Metro system (8). For underground stations, almost half the cost of operation is for electricity, and about half of that is for lighting. Underground stations are twice as expensive to operate as surface stations.

Costs of construction of vehicles, roadway, and stations were also obtained from the current experience of several systems. Bus stations were included in bus systems to make them comparable to rail but, since there is little current cost experience with bus stations for local urban transit, it was necessary to estimate bus platform costs at a tenth of the cost of a rail station per platform. The factor of one-tenth was based on both the physical size of the platform and passenger use.

All capital costs were annualized by using a discount rate of 10 percent and lifetimes similar to those used by other authors (5, 9). The lifetimes are given below:

Item	Life (years)	
	Rail	Bus
Line		
Surface	50	35
Underground	50	50
Stations	50	50
Yards	50	40
Vehicles	30	12
Land	∞	∞

Tunnel costs were obtained for three types of tunnels: earth (soft), rock (hard), and cut-and-cover. In reality, an infinite variety of tunneling conditions can be encountered, and these three types were intended to be representative of the relevant ranges. Since Washington, D.C., and San Francisco have conducted a great deal of recent tunneling construction, the cost figures relied heavily on data from these two systems. Supplemental data were, however, obtained from other cities (10, 11, 12).

The final figures cited below include all extras and all stages of construction—engineering, administration and contingencies, track, signaling, and ventilation for bus tunnels as well as all other categories—in 1975 prices (1 km = 0.62 mile):

Tunnel Type	Cost ($000 000)			
	Per Rail-Line-km	Per Bus-Line-km	Per Rail Station	Per Bus Station Platform
Cut-and-cover				
CBD	29	36	17	1.4
Line-haul	27	34	15	1.1
Earth				
CBD	21	23		
Line-haul	20	22		
Rock				
CBD	14	15	22	2.0
Line-haul	13	15	22	1.6

The table compares costs of three kinds of tunnels and underground stations for bus and rail systems. Bus and rail route costs are given for double-track (lane) kilometers; rail station costs are per station, and bus station costs are per platform (a station may have many platforms). A total cost comparison is therefore possible only by using this table with estimates of the level of passenger demand. No earth stations are listed since stations are generally cut-and-cover in soft conditions. Note that, although cut-and-cover line is more expensive than other alternatives, the stations are cheaper so that station frequency will determine which alternative provides the lowest cost.

The following table (10, 11, 14, 15) shows the percentage breakdown of tunneling costs by various components:

Category	Cut-and-Cover Tunnels (%)	Round Tunnels (%)
Route construction	88-92	86-90
Mobilization	3-7	2-10
Excavation and mucking	24-36	40-66
Utility relocation	4-16	0-5
Underpinning of buildings	4-16	0-5
Traffic maintenance and street decking	4-16	0
Lining and structures	30-50	24-40
Backfill and restoration	4-8	0
Guideway	2-3	3-4
Signaling	2-7	3-8
Electrification	2-3	3-4

The distribution of costs for the different categories is only illustrative and may vary substantially in different tunneled segments. Bus terminals have an additional cost component of $4 to $9 million/km ($6 to $14 million/mile) for ventilation (13). The smaller number is for round tunnels (earth or rock), which are able to use part of the tunnel cross section above and below the roadway for transverse ventilation structures. Ventilation of cut-and-cover tunnels requires construction of additional ducts and is more costly given present technology.

Total costs were adjusted for accidents, damage to property during construction, and noise-shielding devices. These costs generally do not account for more than 6 percent of total costs. They therefore do not play a decisive role in preferences of one mode over another. The value of passenger time, on the other hand, can be a major cost component. Time was valued at \$1.94/h at the peak and \$0.97/h at the off-peak. The peak figure is 40 percent of the average hourly wage for 1975 and is typical of time values found by other researchers (8). When costs of travel time are included in improved evaluation of systems on a more comparable basis, they account for as much as half of total costs depending on which system alternative is specified.

Parametric cost analysis was used to find the critical property value at which tunneling becomes feasible. Tunneling should proceed from the center of the city out to the point where estimated property values drop below this critical value. A gradient of land values was consequently estimated for each city.

Unfortunately, little evidence is available about patterns of land values in American cities. Data on the assessed value of land and improvements were collected from city assessment directories for 85 properties each in Washington, D.C., and Baltimore. The assessed values were converted to market values according to assessment practices in these cities (the ratio of assessed to market value is 0.55 in Washington and 0.50 in Baltimore). A regression on these data yielded the following coefficients, with t-statistics in parentheses (these equations were formulated in U.S. customary units; therefore, no SI equivalents are given):

$$Y = -683 - \underset{(4.70)}{0.187}\, X_1 - \underset{(10.96)}{0.758}\, X_2 - \underset{(3.25)}{0.126}\, X_3 \qquad R^2 = 0.69 \tag{7}$$

where

- Y = $\log_{10}$ property market value (CBD property value, $\$/ft^2$);
- X_1 = $\log_{10}$ residential density (CBD worker density/ $mile^2$);
- X_2 = $\log_{10}$ (distance to CBD, miles); and
- X_3 = dummy variable (1 if Baltimore, 0 if Washington).

CBD property values for other cities were calculated as follows. Rental values per unit of area of floor space in many cities were obtained from realtors in each city. Floor space per CBD unit of area was then estimated for each city based on CBD worker density. Next, rental values were capitalized into property values by a conversion based on monthly rent equal to 1 percent of property value. Finally, these CBD property values were used to obtain property-value gradients by applying the regression equation (with the dummy equal to 1 for small cities and 0 for large cities). Property values of \$376/m² (\$35/ft²), a critical value for tunnel feasibility found from sensitivity analysis with the parametric cost model, would be found at 0.6 km (0.4 mile) from the CBD of small cities and 1.3 km (0.8 mile) from the CBD of large cities. Air rights costs were computed at 75 percent of surface acquisition costs (16).

This method is admittedly crude, but some measure of urban property-value gradients is necessary to gauge tunnel applicability. It should be noted that explicit values for right-of-way acquisition were necessary to produce a definitive tunnel forecast. However, the identification of required right-of-way values by use of the parametric cost model is itself an important planning factor.

Results of Cost Analysis

The cost analysis computed costs of alternative systems for a 16-km (10-mile) line-haul and a 1.2-km (0.75-mile) CBD component for a range of values of capacity ridership, tunnel construction costs, and property values. The comparisons were based on annual totals rather than on peak-hour costs alone, which avoided the issue of proper allocation of capital costs to peak and off-peak users. Tunnel construction costs were a "basic" cost (average of earth, rock, cut-and-cover) of \$18.6 million/km (\$30 million/mile) of double track and \$17 million/rail station. Tunneling costs were, however, treated as a parametric variable that ranged from 0.25 to 1.30 times the base case costs; this represents different geological tunneling conditions encountered across U.S. cities given current technology as well as possible future advances in technology.

Figure 2 shows how CBD system preference depends on the level of demand. All values for this illustration were computed by using a property value of \$1076/m² (\$100/ft²). Tunneled systems may be competitive for ridership levels greater than 8000 to 10 000 passengers/h depending on tunneling costs. The next best option is rail aerial, but many cities have chosen to exclude this alternative. Note that the sensitivity of system costs to levels of tunnel construction cost is identified by the tunneling cost index, which measures the proportion of base case costs included in those systems that have tunnel components.

The program also computed property values above which tunneling is preferred. First, the cheaper tunnel option (bus or rail) was selected for the particular level of peak-hour ridership. The program then solved for the property value that made the cheaper tunnel option equal in cost to the best (cheapest) surface alternative.

Figures 3 and 4 show these trade-offs for tunnels versus surface systems on new right-of-way. Asterisks are placed at levels of ridership for which rail tunnels are preferred to bus tunnels. In the line-haul, bus tunnels are preferred because bus stations are smaller and only one-way capacity is provided. In the CBD, rail tunnels are preferred for a peak demand of 8000 to 12 000 (or more) passengers/h/corridor. At current construction costs (1.0 in Figures 3 and 4), tunnels compare favorably with surface systems in the CBD when surface systems require new right-of-way that costs more than \$1076 to \$1184/m² (\$100 to \$110/ft²). This level of necessary right-of-way costs remains constant for systems that are required to meet peak-hour capacity greater than 8000 passengers/h in a corridor. Further, increases or decreases in tunnel construction costs produce right-of-way values to justify tunnels that rise and fall roughly in proportion to the relative changes in costs. However, dramatic reductions in tunnel construction costs to 40 percent of today's value would make tunnels compare favorably with surface systems in the CBD for a right-of-way value of only \$161/m² (\$15/ft²). For the line-haul, a comparison between tunnel and surface systems that require new right-of-way shows that tunnels are preferred when right-of-way costs approach \$376 to \$430/m² (\$35 to \$40/ft²). Proportionate changes in the costs of tunnel construction appear to produce proportionate changes in the right-of-way value required to favor tunnels.

The major cost categories that affect tunnel competitiveness in the CBD are given in Table 1. It can be seen that the cost of acquisition of new right-of-way dominates the cost of surface systems on new right-of-way and the cost of roadway and stations dominates the cost of underground routes. Stations represent the following fraction of overall (line and station) tunneling costs: line-haul rail, 29 percent; line-haul bus, 11 percent; CBD rail, 75 percent; CBD bus, 41 percent. Thus, a one-third reduction in station costs would reduce overall tunnel construction costs for CBD rail by about 25 percent.

Figure 2. Cost per passenger of CBD transit systems (1975 costs in 1975 dollars).

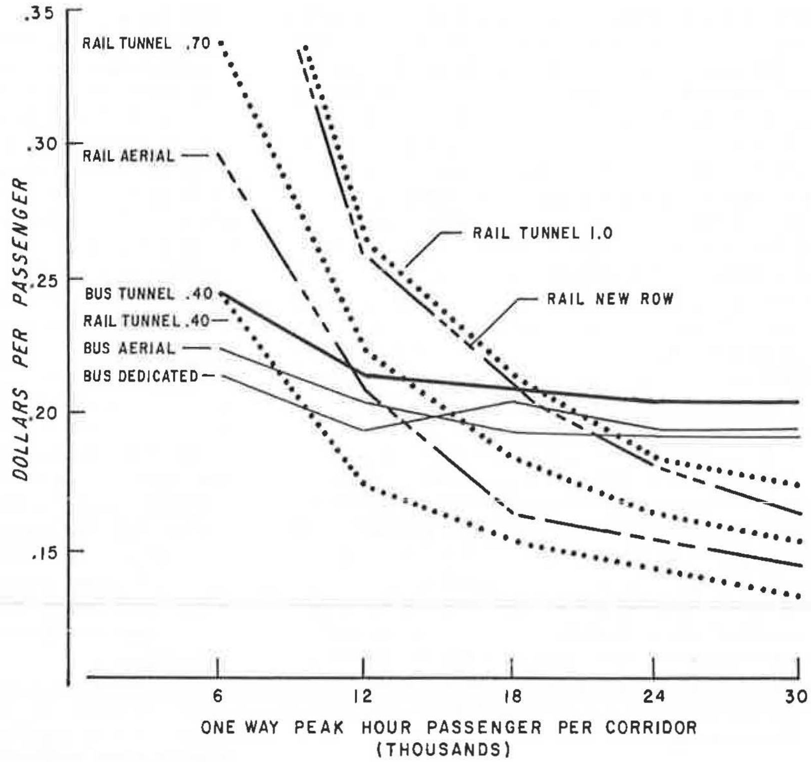


Figure 3. Critical property values: tunnel versus new right-of-way for CBD.

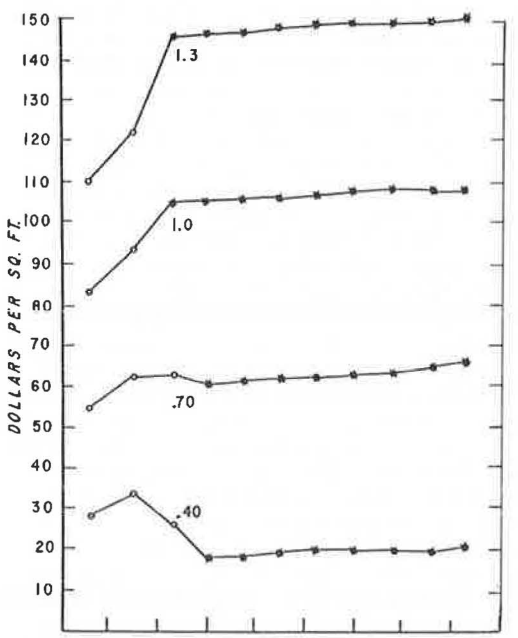
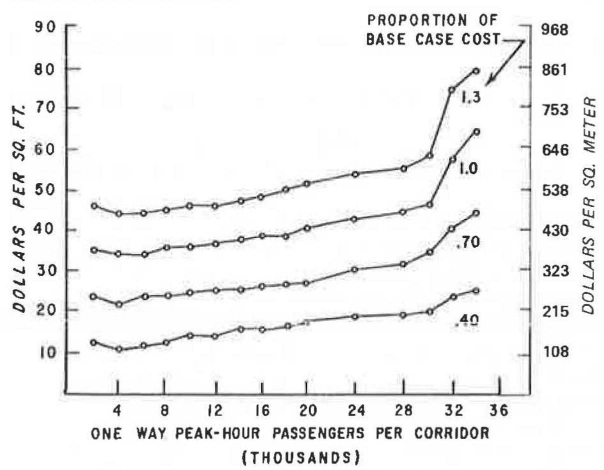


Figure 4. Critical property values: tunnel versus new right-of-way for line-haul.



There is a striking difference between the cost of underground roadway for bus and rail in the CBD. This can be accounted for in three ways. First and most important, there will be two lanes in each direction for bus traffic. A lane capacity of 200 buses/h was used in this computation, so the corridor peak demand of 12 000 passengers/h is close to the marginal level of adding an extra lane. In fact, estimates of bus-lane capacities by other writers and from actual experience vary considerably (17). Second, bus tunnels are more expensive. Third, bus stations are off line whereas rail stations are necessarily on line, and two 182-m stations/km (three 600-ft stations/mile) in the CBD means that much less distance is required in the roadway category for rail.

FORECAST OF TUNNELS TO 1990

A procedure was used to integrate the results of the preceding sections to identify (a) where tunneling is a suitable alternative and (b) the extent of tunneled construction activity that is justified under a cost-effectiveness criterion. Projections for three critical factors are used to forecast the 1990 level of justifiable tunnel kilometers: the average level of tunnel construction costs, the rates of peak-hour transit use in the two heaviest corridors, and property values along corridors as a proxy for surface right-of-way costs.

The method used to integrate these factors for each forecast was to determine from the results of the cost model the minimum necessary or critical property value that must be satisfied to justify either a bus or rail subsurface segment when the least costly tunnel mode is compared with the least costly surface system. Critical property values are found by using the cost model for both CBD and line-haul given the level of transit use (ridership) and the level of tunnel construction cost assumed in the particular scenario. The critical property values are then superimposed on estimated city-specific property value tapers—property values versus distance from the center city, today and after 5 percent annual shifts to 1990—and the amount of justifiable tunnel mileage is identified. This technique is shown in Figure 5.

An identification of justifiable tunneling mileage was conducted across the sample of 35 candidate cities for the following alternative scenarios:

1. A base case that uses current average costs of tunnel construction and the current level of property value estimates developed during the course of this study,
2. A moderate forecast in which average costs of tunnel construction are assumed to fall to 70 percent of the current level because of technological change and right-of-way costs are assumed to increase relative to other cost factors at a rate of 5 percent/year to 1990, and
3. An optimistic scenario in which average costs of tunnel construction are assumed to fall to 40 percent of the current level and right-of-way costs are assumed to increase at a relative rate of 5 percent/year to 1990.

Table 1. Total annual costs in 1975 dollars for 1.2-km (0.75-mile) CBD segment of four possible systems [demand of 12 000 passengers/h/corridor and property values of $1076/m² ($100/ft²)].

Category	Cost for Express Bus ($000)		Cost for Rail Rapid Transit ($000)	
	New Right-of-Way	Under-ground	New Right-of-Way	Under-ground
Roadway	597	6 056	506	1 450
Stations	443	3 275	1 212	4 640
Right-of-way	6 704	118	4 323	108
Vehicles	331	331	718	718
Operation	1 188	1 640	657	694
Time	2 444	2 440	1 955	1 955
Noise, accidents, and damages	746	1 015	642	747
Total annual costs	12 453	14 859	10 063	10 312

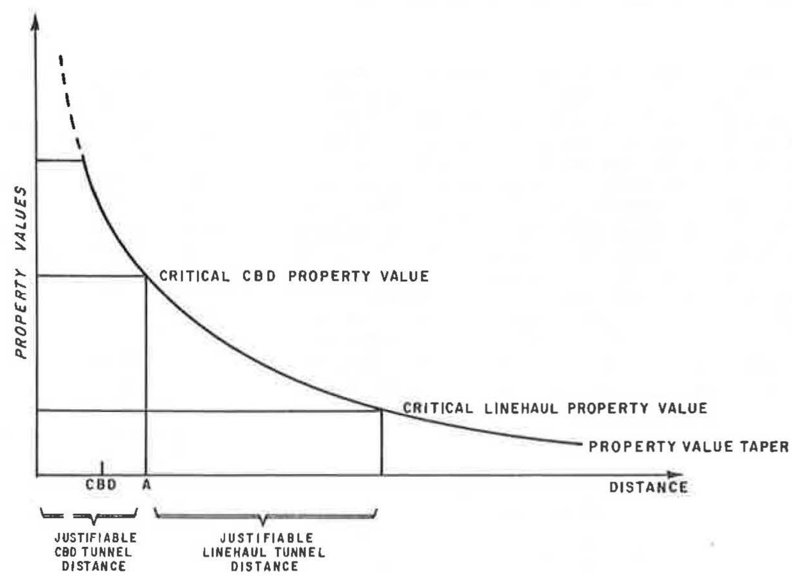
Results of city-by-city application of this methodology for the two heaviest corridors for the base case revealed that three cities currently without systems would meet necessary conditions for tunneled systems by 1990: Detroit, with 15.5 combined kilometers (9.6 combined miles) of tunnels; Cincinnati, with 7.7 km (4.8 miles); and Denver, with 5.5 km (3.4 miles). This gives a two-corridor total of 29 km (17.8 miles) of tunnels. When these additional system distances are combined with "hard" forecasts of tunnel distance for extensions to existing systems and systems under construction, they produce a total forecast of 223 km (138 miles) of tunnel by 1990. For the moderate scenario, the same procedure produced justifiable tunnel segments for all of the 35 candidate cities except San Jose and Tampa. In the heaviest corridor, all qualifying cities showed tunneled segments for the entire CBD. When it was combined with the line-haul distance, the overall justifiable distance amounted to 223 km of tunnels. In the second heaviest corridor, the overall distance increased slightly because of lower critical property values in certain instances caused by a switch from rail to bus in the comparison between lowest cost tunnel mode and lowest cost surface mode. The aggregate justifiable distance in both corridors amounts to 448 km (278 miles) in 1990. When the hard estimates for extensions and systems under construction are combined, the moderate forecast results in a total of nearly 645 km (400 miles) of tunnels by 1990.

For the optimistic scenario, all candidate cities qualified for some tunneling. This scenario produced a forecast of 976 tunnel km (605 tunnel miles) by 1990.

The table below gives kilometers of nationwide transportation tunneling under each scenario (1 km = 0.62 mile):

Category	Pessimistic Forecast 1990	Pessimistic Forecast If Plans Implemented	Moderate Forecast (1990)	Optimistic Forecast (1990)
Extensions to existing systems	90	90	90	90

Figure 5. Integration of supply and demand.



Category	Pessimistic Forecast		Moderate Forecast (1990)	Optimistic Forecast (1990)
	1900	If Plans Implemented		
Systems under construction	104	104	104	104
Forecast of additional systems	29	284	449	782
Total	223	478	643	976

Included in this table, under "if plans implemented," are 284 km (175.9 miles) of tunnel construction that would result if cities that have applied for federal grant money or have completed feasibility studies were actually to implement existing plans.

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Fracture Control in Tunnel Blasting

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This paper describes a procedure for achieving control of the fracture plane in construction blasting. The conventional drill-and-blast technique is modified in three ways. First, side notches that extend the length of the borehole are used to control the initiation site for the cracks that produce the fracture plane. Second, the pressure in the borehole is maintained between specified limits by using light and cushioned charges. Third, stemming length is increased to avoid venting that could produce premature arrest of the crack that produces the controlled fracture plane. The procedures suggested have been validated by using fracture mechanics computations, two-dimensional experiments in rock and polymeric models, and field tests in large rock boulders. Fracture control in tunnel blasting can reduce the time and equipment required to make the opening cut while increasing the size and improving the quality of the cut. Fracture control can also reduce the cost of contouring the walls and roof of a tunnel and at the same time improve tolerances and reduce structural damage to the remaining rock.

Excavation in hard rock is usually accomplished by a drill-and-blast procedure: A hole is drilled in the rock, packed with high explosive, and stemmed, and the explosive is detonated. The detonation pressures are extremely high, and an extensive amount of energy is dissipated in the process. Very little of this energy is used to create the specified fracture planes required for the excavation. Energy is expended in producing a radially outgoing stress wave that crushes the adjacent rock and in producing a dense radial crack pattern about the hole. These radial cracks arrest quickly and only about 8 to 12 randomly oriented cracks extend any significant distance from the borehole. The stress wave reflects from a free face and initiates an additional set of cracks at the location of flaws in the rock far removed from the borehole (1). The fracture pattern is largely random in this process, and very little control can be exercised in forming the specified fracture plane.

When control of the fracture plane is important, the conventional drill-and-blast process has been modified. Presplitting, postsplitting, and smooth-blasting procedures that offer some degree of control have been developed.

In presplitting, a row of closely spaced and highly