Development and Application of a Model to Evaluate Transportation Improvements in Urban Corridors

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This paper introduces the linear program model developed at the University of Pennsylvania for evaluating transportation improvements in a high-travel-demand urban corridor. Variables included in the linear program are discussed, and the linear objective function and the constraint equations of the model are outlined. Application to a radial travel corridor in Chicago, Illinois, illustrates the capability of the model; an analysis is made of existing corridor bus service and several corridor capital investments to improve that service. In the analysis of existing bus service, several alternatives to the existing price structure of bus transportation in the corridor were studied; the major result was an evaluation of the shift in mode choice caused by the different pricing schemes and the effects of a change in patronage on bus operating and capital costs. For the study of alternative capital investments, the corridor model computes the patronage attracted by the improvements and adjusts operating and bus capital costs of bus lines serving the corridor.

The overall purpose of the work described in this paper was to develop and test an analytical model for planning transportation improvements in a high-travel-demand urban corridor. The objective was to produce a technique that (a) incorporates anticipated travel demands and establishes air quality and noise standards and financial and energy limitations, (b) searches for transportation alternatives to satisfy those constraints, and (c) identifies alternatives generating the most benefits. This technique was to be an alternative to the sequential transportation models whose primary application is long-range regional urban transportation planning and to the very detailed analyses used in corridor location studies. The goal of the research was a corridor-level approach that could assess a large number of potential corridor transportation improvements and thus enable the determination of the trade-offs between alternatives.

The corridor model developed at the University of Pennsylvania (1) was applied in this research to a radial travel corridor in Chicago, Illinois. Application of the model to an actual planning problem was an important aspect of the corridor model project and was a joint effort of the University of Pennsylvania and the Chicago Area Transportation Study (CATS). The model was applied to the Chicago southwest corridor, the only major radial corridor in the Chicago region in which rapid transit facilities do not operate on exclusive right-of-way.

CORRIDOR PLANNING MODEL

The general form of the corridor transportation planning model used in the analysis is a linear program. The solution of a linear program is a set of variable values that satisfy a series of linear equations or inequalities and also optimize the value of a separate linear equation that is termed the objective function. Mathematically, in a linear program the objective function can be summarized as follows:

$$\text{Maximize (or minimize)} \sum_i c_i x_i \qquad (1)$$

subject to

$$\sum_i a_{ij} x_i \geq b_j \qquad j = 1, \ldots, m$$

$$\sum_i a_{ij} x_i = b_j \qquad j = m+1, \ldots, n$$

$$x_i \geq 0$$

where

x_i = choice variables to be evaluated,
c_i = objective function coefficient for x_i, and
a_{ij}, b_j = parameters of the constraint relations.

The model can thus be described by the variables, the objective function, and the constraints.

Choice Variables

In this model choice variables for the highway mode include

1. Volume of traffic on individual links in the highway network,
2. Capacity of individual links,
3. Corridor highway travel times during different periods of the day, and
4. Cost to the user of driving an automobile.

Public transportation choice variables are similar and include

1. Amount of patronage on bus-line segments,
2. Bus travel times, and
3. Bus user costs or fares charged.

But, for public transportation, frequency of service on the lines replaces capacity as a choice variable because frequency of buses on a line determines the number of individual units of capacity or line capacity.

Objective Function

The objective function is to minimize the weighted sum of the costs of providing corridor transportation service plus the vehicle emissions and fuel consumption of any alternative. In more detail, the objective function is composed of the following elements:

1. Capital costs—For highways capital costs are treated as a function of the capacity added to the highway or the improvement in travel time on the route. Capital costs for public transportation are based on the frequency of service during the peak period and any investments made to change line-haul travel times.
2. Public transportation operating costs—These costs depend on frequency of service, which controls vehicle kilometers operated. Travel time also enters this calculation because the number of times a vehicle can be put into service is determined by the time required

for one run of its route.

3. Highway user costs—This cost is calculated from vehicle kilometers of highway travel.

4. Travel time—Highway travel time is the sum of travel times on individual highway links; for public transportation, travel time is a function of link travel times and service frequency.

5. Vehicle emissions—Vehicle emissions are computed from total highway vehicle kilometers.

6. Fuel consumption—The amount of fuel consumed is again calculated from highway vehicle-kilometers.

Constraint Equations

The constraints are as follows:

1. Mode-choice relations—These equations calculate the number of trips for each corridor movement that will use public transportation and allocate the remaining trips to the highway mode. Mode-split fractions are calculated as a function of highway travel times, public transportation travel times and frequencies, and the cost to the user of traveling by either of these modes.

2. Minimum public transportation service levels—These equations relate the minimum frequency of bus service on a line in the corridor to the maximum volume on that line.

3. Summation of flows using a link—Modal flows determined in the mode-split equations are origin-destination movements within the corridor. This set of equations assigns those movements to public transportation and highway links.

4. Bus and highway link capacity—Maximum volumes on a highway link are constrained by these equations to the link capacity. In the case of public transportation, the maximum volume on a link is limited to the capacity of a bus times the number of buses traveling on the link.

5. Highway reverse peak and off-peak travel times—These constraints limit highway travel times in the off-peak period and, in the peak period, reverse direction to values that are consistent with peak-period performance.

6. Noise restrictions—By using these constraints, travel on a highway link can be limited to ensure that standards for maximum traffic noise will be met.

7. Budget restrictions—These constraints ensure that capital and operating costs can be held to specific levels.

The structure of the linear program model applied to the Chicago southwest corridor is shown in Table 1 in the form of a matrix in which an X indicates the use of a choice variable in either the objective function or the constraints.

APPLICATION OF THE MODEL

In the application of the model to the Chicago southwest corridor, travel demand in the corridor was first estimated. The estimate relied on data from a 1970 home interview survey of regional travel undertaken by CATS and the Northwestern Indiana Regional Planning Commission. Data from the home interview survey were supplemented by a mass transit usage survey of regional travel undertaken by CATS in 1974 and miscellaneous traffic counts taken on major corridor arterial highways.

The second phase of the application was to link this travel demand estimate to the linear program formulation of the corridor planning model. An operational test of the resulting linear program was made by using it to analyze the existing bus service in the southwest corridor. Several alternatives to the existing price structure of corridor transportation were studied. The major emphasis of the study was on the impact on choice of mode of these different pricing schemes. Of secondary interest was the question of how the costs of providing corridor bus service change with an increase in patronage.

The final portion of the Chicago application dealt with an evaluation of several capital investments to improve bus service. The alternatives studied included

1. An exclusive-bus-lane facility operating only within the Chicago central business district (CBD),
2. A connection between the CBD bus lanes and a short busway having a high level of service and extending 3.2 km (2 miles) into the southwest corridor,
3. CBD bus lanes and a longer nonstop busway running from the CBD facility to a point 10.5 km (6.5 miles) into the corridor, and
4. A 10.5-km (6.5-mile) extension from the CBD of an exclusive bus facility that serves intermediate corridor destinations.

The corridor model computed the amount of patronage attracted by the time savings of each of the above improvements and adjusted operating and bus capital cost requirements of the bus lines serving the corridor according to the savings accruing from each alternative. The corridor model was also used to investigate other impacts such as user time savings and environmental impacts of each of the four investments.

Existing Corridor Travel

Existing CBD-oriented bus service in the corridor is provided by six bus lines that are used, in a combination of express, limited-stop, and local service, to transport large volumes of passengers. Figure 1 shows the route structure as well as 1974 passenger volumes past selected points (summed over all routes passing that point) by direction during the 6:00 a.m. to 9:00 a.m. morning peak period (2). The total combined two-way daily flow at the maximum load point near Halsted Street is in excess of 27 000 persons/d. The Archer Avenue operation is unusual in its use of three different types of operations along a single route, in the amount of service offered, and in the patronage attracted.

Pricing Options

The corridor model was first applied to the question of how ridership would increase in the southwest corridor if fares were decreased. Using the linear program formulation of the model, this calculation was first done by assuming that frequencies remained at existing peak and off-peak levels. A $0.10 reduction in fare (from $0.45) resulted in a 1.9 percent increase in patronage in the peak and a 6.3 percent increase in the off-peak period. The effect was more dramatic in the off-peak period than in the peak period because of the high ratio of nonriders to Archer Avenue bus users during the off-peak period; even a small percentage change in the mode split between automobile and public transit in the off-peak period added a large number of public transit users.

During the peak period, however, the Archer Avenue bus lines operate nearly at capacity. Average occupancy per bus on the Archer Avenue limited and local service is in the range of 70 to 75 passengers/bus. Expressway lines average only slightly less, approximately 60 passengers/bus (3). Off-peak ridership is considerably less than capacity and averages around 30 percent of total line capacity, including standees, or slightly more than 40 percent of seating capacity. This peak-period capacity constraint means that any reduction in fares in the peak

Table 1. Structure of the linear program corridor model.

	Highway Choice Variables				Transit Choice Variables			
Objective Function	Volume	Capacity	Time	Price	Volume	Frequency	Time	Price
Minimize the sum of								
Capital costs		X	X			X	X	
Operating costs								
Bus						X	X	
Automobile	X							
Travel times			X			X	X	
Vehicle emissions	X							
Fuel consumption	X					X		
Constraints								
Mode-split relation			X	X		X	X	X
Minimum bus service					X	X		
Summation for link flows	X				X			
Bus and highway capacity	X	X			X	X		
Highway nonpeak times	X	X	X					
Noise restrictions	X		X					
Budget restrictions		X	X			X	X	

period must be accompanied by an increase in the peak-period capacity of the Archer Avenue lines. The model indicates that, for the buses in use, existing routes incur an approximate daily capital cost of $2200 and a daily operating cost of $21 000. These figures were calculated by using an operating cost of $0.98/km ($1.57/mile) for a bus (4) and a bus capital cost of $23.50/d (5).

Figure 2 is a composite of four plots developed from the corridor model showing the impact on operating and capital costs of diverting travelers from the automobile to the Archer Avenue bus lines. The axes for these plots are as follows:

1. Difference in user cost between bus transit and the automobile,
2. One-way patronage on the Archer Avenue bus lines,
3. Bus capital costs for the Archer Avenue service, and
4. Bus operating costs for the Archer Avenue service.

The intersection of the axes defines existing costs and patronage of the Archer Avenue bus service.

An example of the use of Figure 2 would be tracing the impact of a $1.00 increase in automobile user costs relative to bus fares. In the upper right quadrant of the figure, the impact of the cost change on patronage can be seen. Peak daily ridership would increase to around 9500 riders, and daily off-peak ridership would climb to about 11 500. At this level of peak-period ridership, additional buses would have to be obtained and bus capital costs would increase to approximately $2650/d (found by tracing costs across Figure 2 from the upper right quadrant to the upper left quadrant). New operating costs of $22 500/d can then be located in the lower left quadrant.

Capital costs of the Archer Avenue bus service vary directly with peak-period patronage because, at the time of the study, there was no excess peak capacity. The cost of additional garages or other related capital facilities for buses is not included in the calculation; if the number of buses added were small, there would probably be little effect on total garage requirements. This explains the linear capital-cost relation to patronage in the peak period. But operating costs are not linear, and the relation between operating costs and patronage shown in Figure 2 is kinked. This behavior is explained by the excess capacity available on the Archer Avenue bus lines in the off-peak period. As travelers are diverted to the bus mode, peak-period operating costs rise but new off-peak bus users are absorbed in the excess capacity. This continues until bus transit attains a cost advantage of approximately $1.00 over the automobile. Beyond this cost advantage, operating costs for the Archer Avenue bus lines increase at a higher rate because of added off-peak service.

Figure 3 shows how the costs of the Archer Avenue service vary with the cost advantage achieved by the service. The capital costs of the required additional buses are shown to be relatively unimportant. Because of the operating characteristics these total costs are not linear but kinked. In plotting the revenue that would be obtained from the existing $0.45 fare, Figure 3 also implies that the entire bus cost advantage is attributable to automobile cost penalties. Revenue climbs faster than total costs to the left of the point where capacity is exhausted in the off-peak period. As soon as added off-peak service must be provided, marginal cost exceeds an added fare. Revenue does not exceed costs at any point, and the service must always be subsidized. A $0.75 fare is the minimum fare that would allow revenue to exceed costs, but this would occur only when an additional cost penalty of $1.00/trip is applied to the automobile user.

Investment Options

The four capital investments proposed to improve the existing Archer Avenue bus service were evaluated with the model. The initial capital investment considered was an upgrading of bus service in the Chicago CBD that would separate bus operations from automobile and commercial traffic. For the running of the linear program, exclusive bus lanes were evaluated from 12th Street (Roosevelt Road) to Wacker Drive on the northern end of the CBD. This 2.17-km (1.35-mile) section within the Chicago CBD is congested and bus travel times are quite high. Scheduled bus travel times through this section are greater than 11 min during the morning peak period and more than 15 min in the peak direction during the more congested evening peak period (6).

The second investment alternative evaluated was an extension of the separate bus right-of-way from the end of the CBD bus lanes at Roosevelt Road to the vicinity of Halsted Street and Archer Avenue. One possible alignment for this extension would be along existing railroad right-of-way. This alternative would add around 3.2 km (2 miles) of exclusive bus right-of-way to the CBD bus lanes. It is assumed that the extension would offer a high level of service and that nonstop buses using it would travel at a top speed of around 80.5 to 88.5 km/h (50 to 55 mph).

The next alternative investigated concerned extending the busway of the second alternative to Pulaski Road. This segment, which could be constructed on available right-of-way in the median of the Stevenson Expressway, would lengthen the busway facility another 7.1 km (4.4

miles) west from Halsted Street. To maintain high speeds on this section of the busway no stops would be made. This would allow high-speed operation and improved service over the existing bus lines operated on the Stevenson Expressway.

The inability of the busway facility proposed in the two previous alternatives to serve trips to intermediate corridor destinations led to the development of the fourth and final alternative capital investment: an exclusive bus facility with stations or access points along its length. In coding this alternative into the linear program, it was assumed that stations would have to be located at approximately 0.8-km (0.5-mile) intervals to serve intermediate movements adequately. This alternative could be realized by (a) exclusive bus lanes on an existing street, (b) a low-design busway facility on which buses would pick up and discharge passengers while stopped, or (c) a higher design busway with stations separated from the through busway lanes to permit overtaking and passing. The third design would permit the facility to be used by the Archer Avenue expressway lines as well as the Archer Avenue limited-stop service. The bus facility would start at the end of the CBD bus lanes at Roosevelt Road and end at Pulaski Road. Given the range of design options, the speed of the buses on this alternative could vary substantially depending on the selected design. As a compromise, it is assumed in the linear program that average speeds of around 32.2 km/h

Figure 1. Peak-period bus routes, frequencies, and patronage in the southwest corridor.

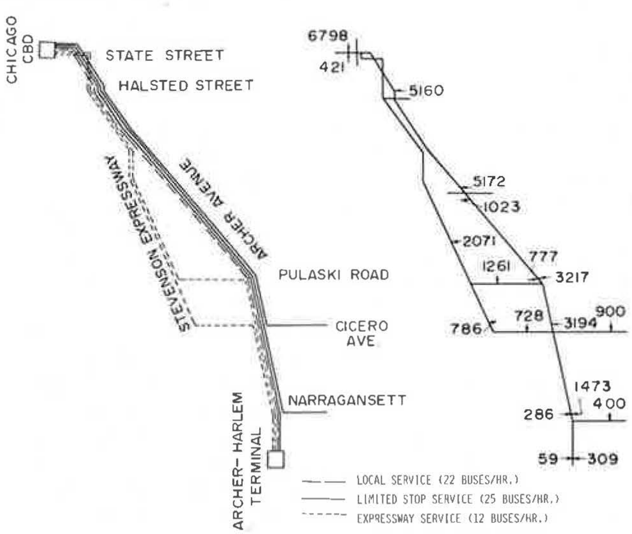

Figure 2. Bus patronage, operating costs, and capital costs versus automobile-cost disadvantage.

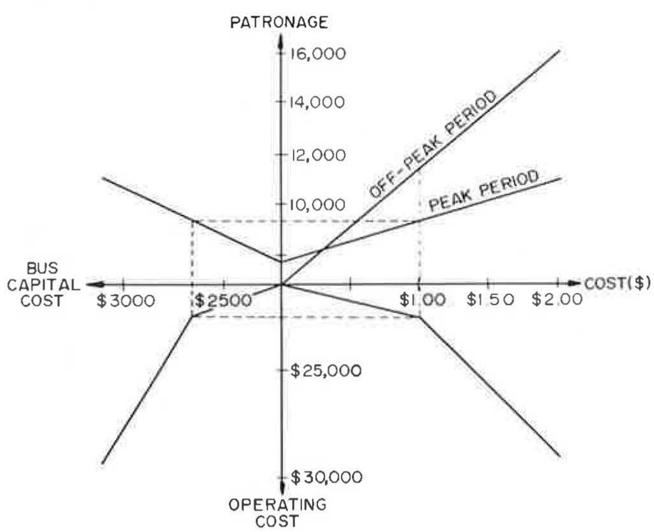

Figure 3. Daily costs and revenue of Archer Avenue bus lines.

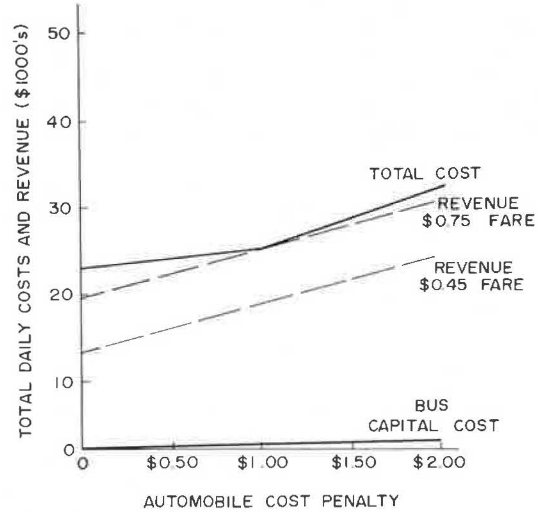

Table 2. Time savings for the four investment alternatives.

Trip Origin and Destination	Time Saved per Trip (min) CBD Bus Lanes Peak	CBD Bus Lanes Off Peak	Halsted Busway Peak	Halsted Busway Off Peak	Pulaski Busway Peak	Pulaski Busway Off Peak	Pulaski Bus Lanes Peak	Pulaski Bus Lanes Off Peak
Roosevelt Road to CBD	2.5	3.0	2.5	3.0	2.5	3.0	2.5	3.0
Halsted Street to CBD	2.5	3.0	7.5	7.5	7.5	7.5	5.0	4.0
Pulaski Road to CBD	2.5	3.0	8.0	7.5	12.5	7.5	2.5	3.0
Halsted Street to Roosevelt Road	0	0	5.0	4.5	5.0	4.5	2.5	1.0
Pulaski Road to Roosevelt Road	0	0	5.5	4.5	10.0	4.5	0	0
Pulaski Road to Halsted Street	0	0	0	0	4.0	0	3.5	2.0

Table 3. Patronage and costs of the investment alternatives for southwest corridor bus lines.

Item	Alternative Existing	CBD Bus Lanes	Halsted Busway	Pulaski Busway	Pulaski Bus Lanes
Peak load-point patronage					
Peak	7900	7950	8050	8090	8005
Off Peak	6900	7050	7310	–	7110
Daily bus capital costs ($)	2200	2050	1910	1890	1965
Daily bus operating costs ($)					
Vehicle-kilometers					
Peak	2330	2340	2370	2375	2365
Off Peak	4670	4670	4670	–	4670
Labor					
Peak	4670	4350	4060	4035	4135
Off Peak	9330	8425	7510	–	8010

(20 mph) would be maintained over the length of the route.

The estimated travel-time savings of the four alternatives for selected movements in the southwest corridor are shown in Table 2. All users of the Archer Avenue bus lines do not benefit equally from the different improvements. Only trips to the CBD are able to use the CBD bus lanes. Trips with intermediate corridor destinations are not well served by the nonstop busway alternatives between Roosevelt Road and Halsted Street and Halsted Street and Pulaski Road. An exclusive bus facility with a number of intermediate stops does not improve travel times to the CBD for users at the western end of the corridor who use the expressway lines. However, a busway (or bus lanes) with stops along its length could benefit through bus travelers as well as users having trip ends in the middle section of the corridor.

The following table shows the total daily person hours of user time savings that would result from implementing each of the investment alternatives.

Alternative	Person Hours Saved	Alternative	Person Hours Saved
CBD bus lanes	1020	Pulaski busway	4050
Halsted busway	3400	Pulaski bus lanes	2105

The alternatives are ranked by their approximate investment cost, and the travel time saved rises regularly with the increased cost of the alternative. In terms of incremental travel time saved, the busway extension that runs from Roosevelt Road to Halsted Street is most beneficial, although the nonstop busway extension from Halsted Street to Pulaski Road saves less user travel time marginally than the lower cost investments.

Patronage, Capital Costs, and Operating Costs

The construction of any of the alternatives would increase patronage by reducing travel times. Table 3 gives the calculated increase in peak and off-peak patronage for each of the alternatives. The mode-split equations in the linear program that predict this patronage change are based on the CATS mode-split model (7), which indicates that the fraction of trips made by transit is not very sensitive to transit travel time in the existing range of times in the corridor or in the range of times considered as alternatives in this analysis. This insensitivity accounts for the small ridership increases computed for the alternatives by the corridor planning model.

However, increased patronage would affect the capital and operating costs of the Archer Avenue bus lines in two ways: (a) These costs for the Archer Avenue service would tend to increase because of the increased peak-period use because these lines presently operate near capacity in the peak period, and the impact of increased peak patronage would be additional runs with added equipment; and (b) the exclusive bus right-of-way alternatives would also tend to cause economies in the operating and capital costs of the bus lines because a reduced peak-period cycle time would permit buses to make additional runs in the peak period and reduce the total number of buses required, thereby reducing bus capital costs. Fewer buses in operation also means that fewer operators would be needed and the labor element of bus operating costs would decline.

Table 3 summarizes the operating and bus capital costs for the Archer Avenue service with each of the four alternatives in place. Patronage is given for the peak load point near Halsted Street. The shortened cycle time tends to decrease daily bus capital costs, but these costs do not decrease in direct proportion to the cycle time because of increased peak-period patronage, which creates a need for added bus trips. Vehicle-kilometers refers to those operating costs of a bus that vary with the kilometers operated and account for about one-third of total operating costs; these costs increase in direct proportion to patronage increases in the peak period. The labor component of operating costs varies with the number of buses required for service and changes at the same rate as bus capital costs.

Bus operating and capital cost savings shown in these tables reveal that, as the capital investment increases, incremental cost savings generally decrease. The highest cost alternative, the western extension of the nonstop busway from Halsted Street to Pulaski Road, achieves little bus operating and capital cost savings over a nonstop busway terminating at Halsted Street because the western extension is only suitable for use by the peak-period Archer Avenue expressway bus lines. The three lower cost investments that can be used by all Archer Avenue bus lines show more regular benefits with increased investment.

CONCLUSIONS

The corridor model developed at the University of Pennsylvania was designed to aid transportation planners in the short-range or implementation planning stage of the planning process for improvements in major transportation corridors. The model therefore considers as alternatives not only the construction of new facilities but also pricing options for public and private transportation. The linear program treats these alternatives parametrically, by using time and cost variables, and can consider a wide range of design and operation policies. The technique helps to overcome one of the major weaknesses of traditional transportation planning—the limited number of plans that can be considered by the traditional model system because of time and money requirements.

The application also indicates that the corridor model is substantially operational. Although the mathematical formulation used in this paper is considerably simplified, it is clear that the general mathematical programming approach has advantages in transportation planning that is subregional in character and less detailed than route location planning. The present linear program form is only a starting point, however, for the development of suitable methods to fill that gap.

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Comparing Modes in Urban Transportation

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Modal comparisons are defined as those studies in which an analyst compares urban transport modes with each other in a generalized framework, attempting to assess relative advantages and disadvantages of modes under a variety of conditions. This paper establishes a link between comparative analyses of transport modes and urban planning processes and generates a basis both for a normative theory of modal comparisons and for a critique of existing works in this field.

An ongoing debate in the field of urban transportation planning revolves around comparative advantages and disadvantages of various transportation modes. It often takes the form of polemics, such as bus versus rail. Considering the variety of conflicting positions and the potential impact of the conflict on policies and investment decisions, a methodological study of this debate is long overdue. The main purpose of this paper, which is a summary of a larger report (1), is to establish a link between comparative analyses of transportation modes and urban planning processes and thus generate a basis both for a normative theory of modal comparisons and for a critique of existing works in this field.

A transportation mode is initially defined as a particular combination of transportation-related structures, vehicles, and strategies of operation. Within the broad setting of urban transportation planning, modes are usually compared in the following specific contexts:

1. When a planner deliberates which modes to include as components of alternative plans for a given urban area (this context will be called a site-specific design of alternatives);
2. When a decision-making body evaluates a set of alternative transportation plans for a given urban area (this activity is expected to end up with a decision or at least a recommendation and will be called site-specific evaluation); and
3. When an analyst compares modes with each other in a general fashion, attempting to determine conditions under which a particular mode is in some sense better than others or to arrive at rankings of several modes under a variety of conditions (studies of this type, which will be called modal comparisons, are usually not site specific although they sometimes make use of data from a single site).

It is customary to analyze decision processes by breaking them down into activities such as clarification of goals, design of alternatives, evaluation, and action. Such activities take place both in the site-specific, urban planning context and in the context of modal comparison; in fact, alternatives considered in these two contexts are similar. Both exercises involve evaluations using similar criteria, and both end with expressions of preference. Nevertheless, they differ in scale and in depth and should not be confused with each other. They also serve different purposes, by answering similar questions from different questioners. Perhaps the most significant difference between them is that modal comparisons arrive at expressions of preference for transportation modes through a technical process and site-specific evaluations arrive at these preferences through a political process.

Modes are what transport plans are made of. The site-specific planner faces numerous possible combinations of transportation structures, vehicles, and operational strategies and, because of time and money limitations, can consider only a few of these combinations in depth. The task will be made easier if he or she is provided with modal descriptions that enable the planner to screen many alternatives quickly and select the few that are promising in a specific context. Comparisons, or descriptions that bring out similarities and differences between the things compared, are well suited for this purpose.

Although the site-specific planner cannot evaluate all modes, somebody must. The design of alternatives for a modal comparison should therefore be based on a structured, exhaustive classification of modes. No single exercise can be expected to compare all, or even many, modes, but it should sample the set of modes in a systematic manner.

Alternatives in transportation planning are evaluated on the basis of their service characteristics, costs, and external (nontransport) effects. There are many ways to select and organize this type of information, including making judgments about which parameters to include, exclude, stress, or deemphasize; choosing between aggregate measures or distributions; and exercising a preference for quantitative or qualitative information. If evaluation criteria used in modal comparisons are to be useful, they should broadly correspond to criteria used in the site-specific decision process.

Evaluation criteria in urban transportation planning have changed substantially in the past 20 years in both theory and practice, reflecting changes in planners' perceptions of what constitutes the transportation problem. Until the mid-1960s, the prevalent view of urban transportation was that of a closed, functional system designed to achieve narrow but precise objectives. Then, as a result of the revolt against freeways and the general