Multimodal Trip Distribution: Structure and Application

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A multimodal trip distribution function estimated and validated for the metropolitan Washington, D.C., region is presented. In addition a methodology for measuring accessibility, which is used as a measure of effectiveness for networks, using the impedance curves in the distribution model is described. This methodology is applied at the strategic planning level to alternative high-occupancy vehicle alignments to select alignments for further study and right-of-way preservation.

One of the components of travel demand models is the estimation of the rate of decay with distance (or time) from an origin: the greater the separation between an origin and destination the lower the propensity to make the trip. Because time is the key indicator of separation in the utility of a trip maker and travel time and trip quality vary by mode, the decay function is expected to be different for different modes. Not only do travel speeds vary by mode but the choice of mode also partly influences locational decisions and individual willingness to make trips of certain lengths. For instance households wanting to use transit (heavy rail in particular) are more likely to locate along major transit facilities. However, conventionally, trip distribution functions are estimated for automobile trips only and are applied to trips by all modes. The main justification for this procedure is that more than 80 percent of all trips are made by privately owned vehicles, and specific treatment of transit and other modes is not expected to improve model performance significantly. However, with the emerging concern with the environment in recent years and the response of managing travel demand, local and state planning jurisdictions are grappling with a need to evaluate the feasibility of introducing high-occupancy vehicle (HOV) and transit facilities. It therefore becomes important to explicitly account for different distribution characteristics of modes other than single-occupancy vehicles (SOVs). This research hopes to fill this gap by estimating a multimodal trip distribution function for the metropolitan Washington, D.C., region. In addition an application of the model to the evaluation of multimodal networks is described.

Use is made of afternoon peak period transportation planning models developed by the Montgomery County Planning Department (MCPD) over the past few years (*1–4*). Key elements of the model structure include segmentation of trip purposes by direction, which permits accounting for chained trips, peak hour factoring as a function of congestion between origin and destination, the multimodal gravity model for trip distribution described here, and the feedback of travel time outputs from assignment into distribution to ensure travel time consistency through the model chain. Travel time feedback, along with multimodal distribution, will help capture the impact of induced demand—the construction of significant transportation facilities will alter demand patterns over time, even with no change in land-use activity. The impact of transportation on land-use activities is not modeled but is considered exogenous to the model in planning application.

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TRIP DISTRIBUTION

Model Structures

Over the years modelers have used several different formulations of trip distribution. The first was the Fratar or growth model. This structure extrapolated a base year trip table to the future on the basis of growth, but it took no account of changing spatial accessibility because of increased supply or changes in travel patterns and congestion. The next models developed were the gravity model and the intervening opportunities model. Evaluation of several model forms in the 1960s concluded that "the gravity model and intervening opportunity model proved of about equal reliability and utility in simulating the 1948 and 1955 trip distribution for Washington, D.C." (*5*). The Fratar model was shown to have weakness in areas experiencing land-use changes. Because comparisons between the models showed that either could be calibrated equally well to match the observed conditions, because of computational ease, gravity models became more widely spread than intervening opportunities models. Some theoretical problems with the intervening opportunities model were discussed by Whitaker and West (*6*) concerning its inability to account for all trips generated in a zone, which makes it more difficult to calibrate, although techniques for dealing with the limitations have been developed by Ruiter (*7*).

With the development of logit and other discrete choice techniques, new, demographically disaggregate approaches to travel demand were attempted (*8*). By including variables other than travel time in determining the probability of making a trip, it is expected to make a better prediction of travel behavior. The logit model and gravity model have been shown by Wilson (*9*) to be of essentially the same form as the model used in statistical mechanics, as an entropy maximization model. The applications of these models differ in concept in that the gravity model uses impedance by travel time, perhaps stratified by socioeconomic variables, in determining the probability of trip making, whereas a discrete choice approach brings those variables inside the utility or impedance function. Discrete choice models require more information for estimations and more computational time.

Ben-Akiva and Lerman (*10*) have developed combination destination choice and mode choice models using a logit formulation for work and non-work trips. Because of computational intensity, these formulations tended to aggregate traffic zones into larger districts or rings in estimation. In current application some models, including, for instance, the transportation planning model used in Portland, Oreg., use a logit formulation for destination choice (*11*). Research by Allen (*12*) used utilities from a logit-based mode choice model in determining composite impedance for trip distribution. However, that approach, using mode choice log-sums, implies that destination choice depends on the same variables as mode choice. The approach taken in this paper uses mode choice probabilities as a weighting factor and develops a specific impedance function or *f*-curve for each mode for work and non-work trip purposes.

Feedback of Congested Travel Times

One of the key drawbacks to the application of many early models was the inability to take account of congested travel time on the road network in determining the probability of making a trip between two locations. Although Wohl (*13*) noted as early as 1963 research into the feedback mechanism or the "interdependencies among assigned or distributed volume, travel time (or travel 'resistance') and route or system capacity," this work has yet to be widely adopted with rigorous tests of convergence or with a so-called equilibrium or combined solution (*14*). Haney (*15*) suggests that internal assumptions about travel time used to develop demand should be consistent with the output travel times of the route assignment of that demand. Although small methodological inconsistencies are necessarily a problem for estimating base year conditions, forecasting becomes even more tenuous without an understanding of the feedback between supply and demand. Initially heuristic methods were developed by Irwin and Von Cube [as quoted in Florian et al. (*16*)] and others, and later formal mathematical programming techniques were established by Evans (*17*). In the model used in this paper, congested travel times from route assignment are fed back into demand estimation, and the new demand is reassigned to the congested network until convergence (*1*).

A key point in analyzing feedback is the finding in earlier research by the authors that commuting times have remained stable over the past 30 years in the Washington, D.C., metropolitan region, despite significant changes in household incomes, land-use patterns, family structures, and labor force participation (*18*). The commuting time of 28.8 min found in the 1988 Household Travel Survey is almost identical to the Bureau of the Census journey to work time of 29.5 min. Moreover, over the past 20 years even non-work travel times have remained fairly stable, generally between 19 and 20 min for home to non-work trips and 18 min for non-home-based non-work trips.

The stabilities of travel times and distribution curves over the past three decades give a good basis for the application of trip distribution models for relatively long-term forecasting. This is not to suggest that there exists a constant travel budget. According to travel budget hypothesis, commuters in different situations would exhibit very similar travel behaviors and make all budget allocation adjustments on non-travel times (*19*). Prendergast and Williams (*20*) contradict the constant travel budget hypothesis by stating that consumers will substitute among budget components in response to relative price and income changes. However, in spite of the importance given to road pricing in the transportation literature, out-of-pocket transportation costs have remained fairly low. The fact that other factors, including the typical 5-day-a-week commute to work, have not changed significantly suggests a comparatively strong basis on which to estimate a trip distribution model to develop synthetic trip tables for transportation forecasting. Even though commuting times have remained relatively stable, they vary significantly by mode; typically, automobile trips are shorter than transit trips.

Data

The data source for the estimation of the trip distribution model consists of detailed person travel surveys conducted by the Metropolitan Washington Council of Governments for 1968 and 1987–1988 (*21,22*). The 1968 survey consists of a sample of about 20,000 households making 135,000 trips, whereas the 1987–1988 sample involved 8,000 households and 55,000 trips. Each household was assigned a specific 24-hr travel day, and information was collected on all trips made by members of that household on that day. A trip was defined as one-way travel from one address to another. The locations of both ends of the trip were reported along with the time of departure and arrival. Trip duration was obtained by subtracting the time of departure from the time of arrival. These data also report trip purpose at both origin and destination ends, making it possible to identify work trips by accounting for trip chaining (which is defined as travel to a non-work location on the way between home and work).

Three primary travel modes are defined in the two surveys, transit, automobile, and walking. Travel by automobile is further divided by number of persons per vehicle, in which Auto-1 is a driver with no passengers, Auto-2 is a trip in a car with a driver and one passenger, and Auto-3 is a trip in a car with a driver and two or more passengers. Transit includes both rail (Metrorail and commuter rail) and bus. The 1988 survey also provides information on the mode of access to Metrorail, which includes walk to rail or walk to bus to rail (WCT), automobile driver or park and ride (ADT), and automobile passenger or kiss and ride (APT).

Seven trip purposes are defined in this application: home to work (H2W), work to home (W2H), home to other (H2O), other to home (O2H), other to work (O2W), work to other (W2O), and other to other (O2O). For estimation these were grouped into three categories, work, non-work, and chained work. Because chained work trips (W2O) were observed to have a very similar distribution to work to home (W2H), these purposes were consolidated for the estimation of trip impedance. The approach adopted here is different from that undertaken in earlier studies, which only differentiate between home-based and non-home-based trips. By segmenting trips by direction, a better understanding of asymmetric travel patterns, such as linked trips, is possible.

Estimation

Many conventional trip distribution models are stratified by income or automobile ownership, which serves as a surrogate for income. Although in concept stratification for income (or any number of other demographic variables) is desirable, this model was not stratified because income is not available from the 1988 survey and automobile ownership is approaching one car per licensed driver in the region. Thus, the number of transit-dependent (zero-automobile) households who make work trips was extremely small in the sample, and with the stratification by mode, it was too small on which to estimate separate models.

The 1988 Household Travel Survey was used to determine the number of trips by a 5-min time band for each mode and purpose. Using ordinary least squares regression, impedance functions were estimated for application in the gravity model, with the dependent variable being the number of trips per unit area in each 5-min time band. Travel time and mathematical transforms of travel time serve as independent variables. In model estimation the average density of opportunities available in each 5-min time band is assumed to be uniform. In model application the opportunities available (in trips) is multiplied against the impedance function. The number of opportunities is estimated by assuming 5-min radius circular time contours: the first circle (0–5 min) has an area of 25π min squared, the second circle (5–10 min) has an area of $100\pi - 25\pi = 75\pi$ min squared, and so on. A more rigorous methodology could use a geographical information system to estimate the number of opportunities in true travel time contours around each zone. However, for an aggregate analysis this is unlikely to provide a significantly different result for model parameters. The parameters (a, b, c, d) are shown in Table 1 for work trips and Table 2 for non-work trips. Table 3 solves the work trip equations for a variety of travel times. The impedance function uses the following equations:

$$f(C_{ijm}) = e^{(a \cdot t + b \cdot t^{0.5} + c \cdot t^{2} + d)} \quad (1)$$

where $f(C_{ijm})$ is the impedance function for travel time t and a, b, c, and d are the calibration coefficients shown in Tables 1 and 2.

The multimodal impedance function (f_{ij}) is thus expressed as follows:

$$f_{ij} = \sum_{m=1}^{M} P_{ijm} \cdot f(C_{ijm}) \quad (2)$$

subject to

$$\sum_{m=1}^{M} (P_{ijm}) = 1 \quad (3)$$

where

P_{ijm} = probability of using mode m on a trip from i to j (from mode choice model),
C_{ijm} = travel time from i to j using mode m, and
$f(C_{ijm})$ = friction (impedance) function (negative exponential) described in Tables 1 and 2.

In the application of Equation 2 the probabilities from the mode choice model are multiplied by the modal impedance on an origin-destination basis and are summed to obtain composite impedance. A doubly constrained gravity model is used. In that model the impedance matrix for work trips is balanced against each of the production and attraction (origin and destination) vectors to obtain the trip table for work trip purposes (this process is repeated for chained work trips and each non-work trip purpose). These all-mode trip tables are multiplied by the mode choice probabilities to obtain vehicle trips by class (SOV, HOV) and transit person trip tables (walk access, automobile access), which are then assigned. In the feedback procedures described in an earlier paper (*1*), vehicle trips are assigned for a single iteration, producing new origin-destination travel times. The new times are used to update modal probabilities and then impedance matrices. This process is continued, with the new demand assigned to the congested network until convergence.

Validation

The travel time (C_{ij}), multimodal impedance functions (f_{ij}), and then demand to be assigned (T_{ij}) are updated after each iteration of route assignment to ensure consistency between input and output travel times. Because of the travel time feedback method used, the model produces trips, aggregated to 5-min time bands, that appear similar to the observed data, as shown in Figure 1.

The Friedman nonparametric method was used to test the hypothesis that the three travel time distributions—model output, observed 1988, and observed 1968—have been drawn from the same population. A chi-square of 6.3 results (with a 0.042 significance). We fail to reject the hypothesis at the conventional 95 percent confidence level, which implies that there is not enough statistical evidence to suggest that the three distribution curves are different.

On a specific origin-to-destination basis, trip distribution faces a more rigorous test than the comparison with 5-min cohorts. Although travel times can be easily matched when feedback is used along with balancing procedures, area-to-area flows may depend on other factors. These other socioeconomic factors are not directly considered in the distribution model, but are partially captured in

TABLE 1 Multimodal Spatial Trip Distribution Impedance Function (Work Trips).

MODES: VARIABLE:	Auto Drive to Transit	Auto Pass. to Transit	Walk to Transit	Auto-1	Auto-2	Auto-3+	Walk
TIME	0.05	-0.11	-0.08	-0.08	-0.07	-0.06	-0.14
	(2.3)	(-3.8)	(-7.9)	(-17.2)	(-16.4)	(-10.6)	(-11.6)
TIME^0.5	-	0.642	0.265	-	-	-	-
	-	(2.1)	(2.3)	-	-	-	-
TIME^2.0	-0.0011	-	-	-	-	-	-
	(-4.6)	-	-	-	-	-	-
CONSTANT	-2.92	-2.90	-1.91	-0.97	-1.03	-1.31	-0.58
r-squared	0.87	0.88	0.98	0.94	0.94	0.87	0.94

(T-statistic in parentheses)

TABLE 2 Multimodal Spatial Trip Distribution Impedance Function (Non-Work Trips)

MODE: VARIABLE:	Auto-1	Auto-2+	Transit	Walk
TIME	-0.16	-0.16	-0.07	-0.19
	(-6.7)	(-8.4)	(-15.3)	(-11.1)
TIME^2.0	0.000663	0.000758	-	-
	(2.7)	(3.7)	-	-
CONSTANT	-0.39	-0.36	-1.32	-0.19
r-squared	0.95	0.96	0.93	0.95

(T-statistic in parentheses)

mode choice, which does affect the model. It is possible to replicate area-to-area flows by using adjustment factors; however, the stabilities of these adjustment (or *K*) factors over time have not been established. Nevertheless, adjusting the model to match the observed data would seem a better assumption than not making any adjustment. Therefore, in model application, factors are developed that adjust base year trip tables to observed base year origin-destination flows, as developed by gradient reduction methods (*23*).

A second source of error is inaccuracies in the estimates of impedance matrices for the various modes; thus, the balancing procedures will provide a best-fit match of the origin-destination travel times, but those times may not be accurate. Although observed peak-hour travel times are available for the road network for select links, these data do not provide uniform coverage. The link volume delay functions were estimated to match observed congested travel times. Transit routes were specified to match reported headways and schedules. Walk times were estimated assuming 3 mi/hr on a straight-line, euclidean distance. A third factor, travel cost, was also not accounted for in the distribution model, because cost is highly correlated with time.

It would appear that the largest source of error or uncertainty between the applied model and the Household Travel Survey is the apparent tendency of survey respondents to round travel times. Most respondents rounded to the nearest 5-min, but a large number rounded to the nearest 15 min. For instance, a trip maker may actually leave at 5:02 and arrive home at 5:23, a trip of 21 min, but may report leaving at 5:00 and arriving at 5:30, a trip of 30 min, almost a 50 percent rounding error. It is hoped, but not possible to verify, that those rounding up are canceled by those rounding down. This tendency to round was more pronounced in 1968 than in 1988, but it is less apparent in the cumulative distribution curve shown in Figure 1 than it would be in a probability distribution curve.

APPLICATION

The application described in this paper presents a methodology for evaluating long-term additions to the transportation network used by different modes using the trip distribution functions estimated in the previous section. The method for evaluation is based on measures of accessibility by the several modes. The use of accessibility to test the relative impacts of different networks is in contrast to evaluating traffic volumes or total travel times on each of the alternatives.

This work is undertaken as part of the development of the Transitway HOV Vehicle Network Plan for Montgomery County, Md. The model output will facilitate decisions related to reserving transportation rights-of-way within the county and make recommendations for prioritizing the construction of facilities in the proposed transportation alignments. This plan will amend and supplement the county's current Master Plan of Highways. Because

TABLE 3 Evaluation of Impedance Functions (Work Trips)

MODES: / TIME	Auto Drive to Transit	Auto Pass. to Transit	Walk to Transit	Auto-1	Auto-2	Auto-3+	Walk
0	0.054	0.055	0.148	0.380	0.357	0.270	0.560
5	0.067	0.135	0.182	0.257	0.247	0.202	0.277
10	0.080	0.144	0.159	0.174	0.170	0.151	0.137
15	0.089	0.133	0.130	0.118	0.118	0.113	0.068
20	0.095	0.114	0.104	0.080	0.081	0.085	0.033
25	0.096	0.094	0.081	0.054	0.056	0.063	0.016
30	0.092	0.075	0.063	0.037	0.039	0.047	0.008
35	0.083	0.058	0.048	0.025	0.027	0.035	0.004
40	0.072	0.044	0.036	0.017	0.018	0.027	0.002
45	0.058	0.033	0.027	0.011	0.013	0.020	0.001
50	0.045	0.024	0.021	0.008	0.009	0.015	0.000
55	0.033	0.018	0.015	0.005	0.006	0.011	0.000
60	0.023	0.013	0.011	0.004	0.004	0.008	0.000
65	0.015	0.009	0.008	0.002	0.003	0.006	0.000
70	0.010	0.007	0.006	0.002	0.002	0.005	0.000
75	0.006	0.005	0.005	0.001	0.001	0.003	0.000
80	0.003	0.003	0.003	0.001	0.001	0.003	0.000
85	0.002	0.002	0.002	0.001	0.001	0.002	0.000
90	0.001	0.002	0.002	0.000	0.000	0.001	0.000

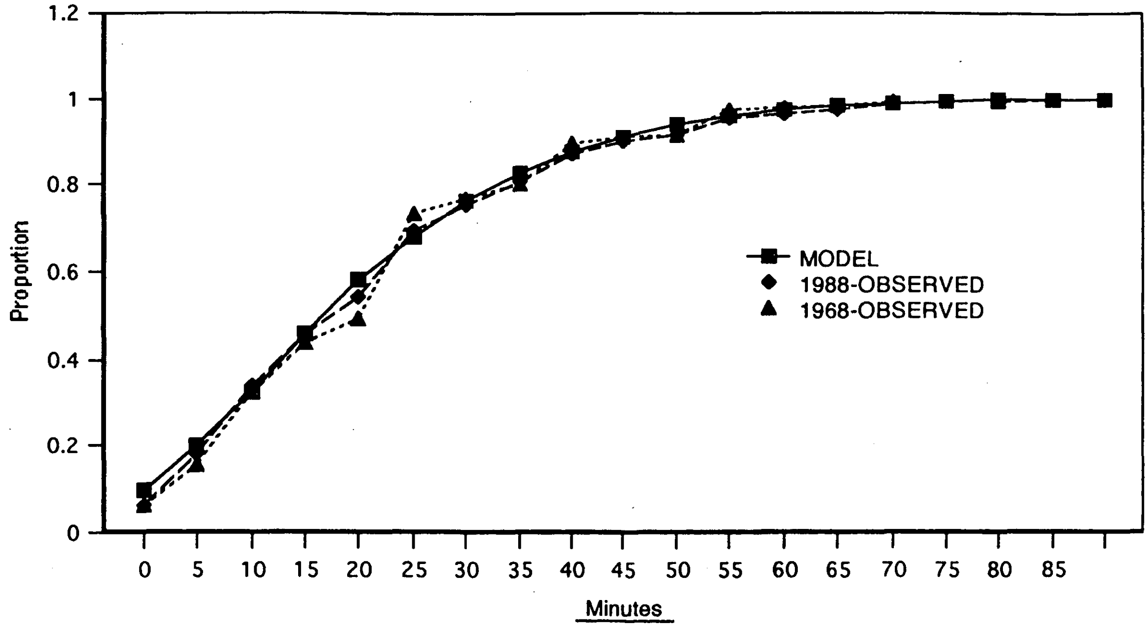

FIGURE 1 Work trip travel time distribution: afternoon peak period, automobile modes, metropolitan Washington, D.C.

combinations of more than 18 alignments are being evaluated simultaneously and up to three modes are possible on each alignment, this is the most ambitious undertaking of its kind that the county has attempted.

The objective of this study, as described in the *Transitway HOV Network Plan Issues Report* (*24*), is to increase the mobility of Montgomery County residents and workers. Mobility is used here to mean the access to jobs by households. As noted above experience over the past 30 years in metropolitan Washington, D.C., shows that individuals will maintain an average separation between home and work of about 30 min. In the long term it is doubtful whether a significant network improvement in a congested urban environment will actually reduce travel times. Downs' Iron Law of Congestion states that network improvements enable individuals to make longer trips, enable travelers who are not in the peak now to switch to the peak, and induce additional travelers to that facility (*25*). However, network additions can improve accessibility or the availability of destinations. If within the same travel time additional destinations or opportunities can be reached, then an improvement to mobility has been made. This study was thus directed to evaluating the accessibility of alternative network alignments.

Earlier research has reported that "the network design problem is an NP-hard problem that defies efficient solution techniques" (*26*). The problem gets especially acute when testing for 18 alignments and three modes in a model of the entire Baltimore-Washington, D.C. region, with a 16,000-link network. To the authors' knowledge no procedure that attempts to evaluate the impact of network alignments and prioritize networks on the basis of accessibility has been used. The solution methodology proposed in this paper does not guarantee the optimal solution, but it lays the groundwork for quantifying the impacts of each alignment on a consistent basis, particularly in an attempt to rank the benefit-cost ratio of the alignments.

The problem is broken into two components. The first is to develop a criterion for evaluating a network as a whole. The second is to determine what a particular facility contributes to that network.

Evaluating Networks

Extensive research has been undertaken in the field of the network design problem. An excellent summary is provided by Magnanti and Wong (*27*). The essence of the discrete network design models, they suggest, is "to choose those arcs (e.g., roadways or railbeds) to include, or add to, a transportation network accounting for the effects that the design decision will have on the operating characteristics of the transportation system." To evaluate the benefits of alternatives, a consistent measure of effectiveness is needed.

Conventionally, the objective function of the network design problem is to minimize user costs (e.g., travel time) and system costs (e.g., construction) subject to a variety of constraints, such as facility capacity. This conventional approach does not successfully account for elastic demand in which travel time may not be minimized by an additional facility. Adding a facility may result in an increase in travel along that facility such that link travel time declines only marginally, and system travel time (as measured in vehicle hours of travel, for instance) may increase.

Consumer surplus has been suggested as a measure of user benefits in the economic evaluation of transportation alternatives (*28*). Consumer surplus is defined in economic terms as the difference between the amounts people would willingly pay at the margin for various amounts of a specific good and the amount they do pay at market prices, or as the area above the demand curve and below the price line (*29*). However, in reviewing evaluation methods, Hutchinson (*30*) notes that "it seems clear that the real economic good of interest to an urban community at the level of strategic planning is the broad accessibility properties of a region." For that reason a similar approach that does not depend on trips but that depends only on the easier-to-predict and fixed estimated activity at the trip ends is accessibility. Hanson (*31*) states: "Personal accessibility is usually measured by counting the number of activity sites (also called 'opportunities') available at a given distance from the person's home and 'discounting' that number by the intervening distance." Here opportunities are defined as the number of jobs in a zone, whereas discounting is achieved by a function of the travel time (the trip distribution impedance curves estimated in the previous section) to those jobs obtained from a transportation model. Because the model is applied to the p.m. peak period, employment is in the origin traffic zone here.

The accessibility equation used is

$$A_{jm} = \sum_{i=1}^{I} [f(C_{ijm}) \cdot \mathrm{EMP}_i] \tag{4}$$

where

A_{jm} = accessibility index for residential zone j by mode m,
$f(C_{ijm})$ = friction factor between zones i and j by mode m, and
EMP_i = employment in zone i.

This process is performed as well for accessibility to homes from workplaces. To evaluate the entire network, the accessibility index for each zone is averaged, weighted by the number of households in the zone. This evaluation is important because the benefits to the system are paramount. The equation for this is

$$B^1_m = \sum_{j=1}^{J} (A_{jm} \cdot \mathrm{HH}_j) / \sum_{j=1}^{J} (\mathrm{HH}_j) \tag{5}$$

where

B^1_m = benefit of network 1 by mode m,
= countywide weighted average of accessibility indexes, and
HH_j = households in destination zone j.

Achieving a multimodal or composite benefit is important. Adding a facility should be expected in general to improve accessibility for each mode because congestion will decline, helping any mode that uses the road network (SOV, HOV, bus). There are situations in which this will not occur; Braess's paradox is one example in which adding a link can result in worse conditions overall (*32*). Accessibility in systems with elastic demand and traffic-sensitive intersection control will not necessarily improve with an added facility. Improving accessibility in one corridor may increase demand in that corridor, worsening conditions in both perpendicular corridors (east-west congestion will worsen if more traffic signal green time is given to north-south movements as an example) and in somewhat parallel corridors (increased demand from one origin owing to travel time savings on one set of links increases travel times for other origins sharing unimproved links with the first origin).

The composite work trip benefit is considered here as a simple summation of the mode-specific benefits (Equation 6):

$$B^1_w = \sum_{m=1}^{M} B^1_{wm} \tag{6}$$

where B^1_w is the composite (multimodal) benefit for work trips (average accessibility index) and B^1_{wm} is the benefit for mode m for work trips.

Parenthetically, an extension to this model would consider accessibility for all activities (trip purposes) pursued in the course of a day. Some research has investigated non-work accessibility (*33*). A general formulation of an accessibility index might weight work accessibility by work trip frequency or time spent at work and non-work activities by their frequency or duration. Non-work could further be separated into more detailed activity patterns (shop, school, etc.). Such a generalized composite accessibility score may take the following form:

$$B^1_T = \sum_{p=1}^{P} F_p B^1_p \tag{7}$$

where F_p is the frequency or duration of purpose p (work, school, etc.) and B^1_p is the composite (multimodal) benefit for purpose p.

Evaluating Individual Facilities

A means for estimating the contribution of each alignment to the system needs to be developed, which avoids the large combination of possible alternatives. Here, the measure of effectiveness of the alignment is considered by evaluating two networks. The first network has all possible alignments; the second network has all alignments except that under consideration. By considering all possible alignments, the benefit of the doubt is given to the alignment under test. For instance, in an HOV scenario HOV time savings on other facilities may increase the utility on the facility under test. The following equation is used to obtain the benefit from the facility under test:

$$B = B^2 - B^1 \tag{8}$$

where B^2 is benefit (average accessibility) from the full network and B^1 is the benefit from the test network.

For the first round of analysis an alignment that was not viable (a benefit-cost ratio below a certain threshold) after considering the benefits of all other proposed complementary alignments to the network probably could be eliminated from further analysis. Later rounds of analysis may add alignments to a base network rather than subtract alignments from a complete network to determine the recommended sequencing of network additions.

It is difficult, however, to translate change in accessibility into monetary terms. At this point in the analysis we are not directly estimating dollar costs, but evaluation requires that we have some surrogate for cost. In this study we propose to use distance (mileage) as that surrogate. A benefit per mile will enable a direct comparison of the suitability of the alignments of the same mode. Each alignment will be ranked by its benefit-cost (accessibility-mileage) ratio, in which the benefit is the improvement in accessibility and the cost is mileage.

Results

This section presents some results of an application of the methods discussed above to evaluate a number of HOV alignment alternatives. This application uses the year 2010 as a forecast horizon, with land use forecasts and anticipated networks consistent for that time period (*34*). Of the 18 alignments considered in the full study, 8 were considered feasible for possible HOV treatment. They were tested as described earlier, some as adding lanes and some as converting lanes from a baseline assumption. They are described in brief as follows.

- Improvements to links that currently exist:
  1. I-495 (Capital Beltway) from I-270 East Spur to I-95, add one lane in each direction;
  2. I-495 from American Legion Bridge to I-270 West Spur, add one lane in each direction;
  3. I-95 from I-495 to I-695 (Baltimore Beltway), add one lane in each direction.
- Changes in operation for links that currently exist:
  4. US-29 from I-495 to MD-650, convert one lane in each direction, and from MD-650 to I-70, add one lane in each direction;
  5. Clara Barton Parkway from Canal Street to I-495, convert two lanes in peak direction.
- Changes in assumed operation for links that are planned:
  6. Inter-County Connector (ICC), from I-370 to I-95, convert one lane in each direction;
  7. M-83 from ICC to I-270, convert one lane in each direction; and
  8. MD-27 from I-270 to MD-80, add one lane in each direction.

As can be seen from Table 4, the improvements that had the highest benefit to Montgomery County residents and employers per mile in terms of added accessibility were adding two lanes to the Capital Beltway (I-495) within the county. This facility is heavily congested, running at levels of service E and F during the peak period. Adding to I-95, which is less congested and just outside of the county, had less accessibility impact for county residents and workers, as might be expected. From a regional perspective it has a higher accessibility, suggesting that benefits to a locality may differ somewhat from those to the region.

The conversion of lanes from general purpose to HOV use has run into some controversy, most recently on the Dulles Toll Road in Virginia. Two of the conversions described here are real, in that they would convert existing pavement to HOV use. The others are only conversions in the modeling sense because the facility has not yet been constructed. One lane of a facility, which was assumed as HOV-2 only in the full network, was converted to general purpose in the test network.

Of the real conversions, the highest benefit was associated with the Clara Barton Parkway, which is an existing limited-access facility between downtown Washington, D.C., and the Capital Beltway running parallel to the Potomac River. Accessibility increased by conversion from general purpose to HOV-2+ lanes. In addition, travel speeds increased, whereas the person throughput remained about the same (the number of vehicles on the facility was halved).

Projects 1, 2, and 3 were recommended to the state for further study, whereas Alignment 6 is currently under intensive study. Alignments 5 and 8 are being pursued as part of this study. Alignment 7 worked better as an SOV addition, although it closely paralleled an already planned HOV lane, and so it was dropped. Similarly, Alignment 4 parallels Alignment 3, and so it was not pursued for automobile HOV treatment.

TABLE 4 Multimodal Accessibility Benefit by HOV Alignment

	Access to Jobs	Access to Houses
Full-Network	119900	66000
1) I-495 East Leg	3510 362/mile	3040 313/mile
2) I-495 West Leg	5390 1172/mile	4140 900/mile
3) I-95	1530 67/mile	810 35/mile
4) U.S. 29	-60 -2.5/mile	620 25/mile
5) Clara Barton Pkwy.	2625 208/mile	-130 -18/mile
6) ICC	280 15/mile	910 48/mile
7) M-83	880 107/mile	1730 210/mile
8) MD 27	2808 208/mile	2492 184/mile

CONCLUSION

The trip distribution impedance functions were developed for each of seven modes and work and non-work purposes in a transportation planning model. A method for combining these mode-specific functions into a single composite impedance function by using mode shares as weights was implemented. The multimodal trip distribution impedance functions were tested in a transportation planning model with feedback between different components to produce consistent results. This method has the advantage that it accounts for changes in transportation supply better than does a conventional gravity model that uses only automobile impedance. Because transportation planning more and more must deal with additions of multiple modes, models need to account for all of these choices.

A method for evaluating networks using multiple modes was developed in this paper to support transportation planning and decision making. The benefits are defined as the accessibility between homes and jobs provided by the network given a fixed land-use pattern. Accessibility is measured as the sum of the area under the trip distribution impedance curve (or *f*-curve). Costs are approximated as distance in this preliminary planning model. The use of multimodal distribution with travel time feedback is necessary to estimate accessibility by automobile, a major component in total accessibility.

The relationships described in this paper have a number of implications for transportation planners. An increase in supply will generally result in an increase in transportation accessibility and therefore in realized demand. This relationship is a variation on Say's Law, developed in the late 1700s, which states that "supply creates its own demand" (*35*). Thus, the widespread usage of fixed demand or travel time between locations in various transportation planning applications will, of itself, miss a key factor in new facility utilization, induced demand. An example of this induced demand can be seen with the introduction of Metrorail in metropolitan Washington, D.C. A new service constructed between 1968 and the present resulted in a doubling of transit work trip mode shares from 5 to 10 percent. The individuals choosing transit did so because on the particular trips they make, rail transit is preferable to other modes. In addition, because of the transit service, these individuals and the firms or government agencies for which they work locate to take advantage of this new transportation supply. Because Washington, D.C., has a high proportion of federal employment, the locational decision on the part of work sites was not made on a strictly economic basis, which can be seen in Washington's higher than average home-to-work trip travel time, 29.5 min, second only to New York City's (D. Levinson and A. Kumar, Accessibility, Propensity, and Mobility, working paper, 1993). Nevertheless, use of only automobile-travel times in the demand estimation or measurement of accessibility would misstate the patterns of transit demand, because transit trips tend to be longer in duration than automobile trips. The spatial interaction decision happens all of the time on a smaller scale with various changes in supply and the demand of other trip makers as measured through congested travel time.

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REFERENCES

1. Levinson, D. M., and A. Kumar. *Integrating Feedback into the Transportation Planning Model: Structure and Application.* In *Transportation Research Record 1413,* TRB, National Research Council, Washington, D.C., 1992, pp. 70–77.
2. Levinson, D. M., and A. Kumar. *Specifying, Estimating and Validating a New Trip Generation Structure: A Case Study of Montgomery County, Maryland.* In *Transportation Research Record 1413,* TRB, National Research Council, Washington, D.C., 1992, pp. 107–113.
3. *TRAVEL 2 Technical Documentation.* Montgomery County Planning Department, Silver Spring, Md., 1993.
4. Levinson, D. M. *An Integrated Transportation Planning Model.* Master's thesis. University of Maryland, College Park, 1992.
5. Heanue, K. E., and C. E. Pyers. *A Comparative Evaluation of Trip Distribution Procedures.* In *Highway Research Record 114,* HRB, National Research Council, Washington, D.C., 1966, pp. 20–50.
6. Whitaker, R., and K. West. *The Interviewing Opportunities Model: A Theoretical Consideration.* In *Highway Research Record 250,* HRB, National Research Council, Washington, D.C., 1968, pp. 1–7.
7. Ruiter, E. *Improvements in Understanding, Calibrating, and Applying the Opportunity Model.* In *Highway Research Record 165,* HRB, National Research Council, Washington, D.C., 1967, pp. 1–21.
8. Ben-Akiva, M., and S. Lerman. *Discrete Choice Analysis.* MIT Press, Cambridge, Mass., 1985.
9. Wilson, A. G. *A Statistical Theory of Spatial Distribution Models. Transportation Research,* Vol. 1, pp. 253–269, 1967.
10. Ben-Akiva, M., and S. Lerman. *Discrete Choice Analysis,* MIT Press, Cambridge, Mass., 1985.
11. *Report to Federal Transit Administration on Transit Modeling.* Metropolitan Planning Organization, Portland, Oreg.
12. Allen, B. *Trip Distribution Using Composite Impedance.* In *Transportation Research Record 944,* TRB, National Research Council, Washington, D.C., 1984, pp. 118–127.
13. Wohl, M. *Demand, Cost, Price and Capacity Relationships Applied to Travel Forecasting.* In *Highway Research Record 38,* HRB, National Research Council Washington, D.C., 1963, pp. 40–54.
14. Boyce, D., M. Lupa, and Y. F. Zhang. *Introducing "Feedback" into the Four-Step Travel Forecasting Procedure vs. the Equilibrium Solution of a Combined Model.* Presented at 73rd Annual Meeting of the Transportation Research Board, Washington, D.C., 1994.
15. Haney, D. *Consistency in Transportation Demand and Evaluation Models.* In *Highway Research Record 392,* HRB, National Research Council, Washington, D.C., 1972, pp. 13–25.
16. Florian, M., S. Nguyen, and J. Ferland. *On the Combined Distribution Assignment of Traffic. Transportation Science,* Vol. 9, 1975, pp. 43–53.
17. Evans, S. P. *Derivation and Analysis of Some Models for Combining Trip Distribution and Assignment. Transportation Research,* Vol. 10, 1976, pp. 37–57.
18. Levinson, D., and A. Kumar. *The Rational Locator: Why Travel Times Have Remained Stable. Journal of the American Planning Association,* Summer 1994.
19. Tanner, J. C. *Expenditure of Time and Money on Travel. Transportation Research A,* Vol. 15A, No. 1, 1981, pp. 25–38.
20. Prendergast, L. S., and R. D. Williams. *Individual Travel Time Budgets. Transportation Research A,* Vol. 15A, No. 1, 1981, pp. 39–46.
21. *1968 Household Survey Computer Tapes.* Metropolitan Washington Council of Governments, Washington, D.C., 1968.
22. *1988 Household Survey Computer Tapes.* Metropolitan Washington Council of Governments, Washington, D.C., 1988.
23. Spiess, H. *A Gradient Approach for the O-D Matrix Adjustment Problem.* Center for Transportation Research Paper 692. University of Montreal, Montreal, Quebec, Canada, 1990.
24. *Transitway HOV Network Plan Issues Report.* Montgomery County Planning Department, Silver Spring, Md. 1993.
25. Downs, A. *Stuck in Traffic.* Brookings Institution, Washington, D.C., 1992.
26. Chan, Y., S. Shen, and N. Mahaba. *Transportation-Network Design Problem: Application of a Hierarchical Search Algorithm.* In *Transportation Research Record 1251,* TRB, National, Research Council, Washington, D.C., 1989.
27. Magnanti, T. L., and R. T. Wong. *Network Design and Transportation Planning: Models and Algorithms. Transportation Science,* Vol. 18, No. 1, Feb. 1984.
28. Neuberger, H. *User Benefit in the Evaluation of Transport and Land Use Plans. Journal of Transport Economics and Policy,* Vol. 5, 1971, pp. 52–75.
29. Byrns, R., and G. Stone. *Microeconomics.* Scott Foresman and Company, Glenview, Ill., 1984, p. 164.
30. Hutchinson, B. G. *Principles of Urban Transport Systems Planning.* Scripta Book Company, Washington, D.C., 1974. p. 275.
31. Hanson, S. *The Geography of Urban Transportation.* The Guilford Press, New York, 1986, p. 5.
32. Murchland, J. D. 'Braess' Paradox of Traffic Flow. *Transportation Research,* Vol. 4, 1970, pp. 391–394.
33. Handy, S. *Regional Versus Local Accessibility: Implications for Non-Work Travel.* Presented at 72nd Annual Meeting of the Transportation Research Board, Washington, D.C., 1993.
34. *Cooperative Forecast Round IV,* Metropolitan Washington Council of Governments, Washington, D.C., 1988.
35. Say, J. B. *Treatise on Political Economy.* 1803.

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