MULTI-MODAL TRIP DISTRIBUTION:

STRUCTURE AND APPLICATION

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ABSTRACT

This paper presents a multimodal trip distribution function estimated and validated for the metropolitan Washington region. 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 HOV alignments to select alignments for further study and Right-of-Way preservation.

INTRODUCTION

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. As 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 applied to trips by all modes. The main justification for this procedure is that more than 80% 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 and transit facilities. It becomes important, therefore to explicitly account for different distribution characteristics of modes other than SOV. This research hopes to fill this gap by estimating a multimodal trip distribution function for the metropolitan Washington region. In addition, an application of the model to the evaluation of multi-modal 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 and origin and destination; the multi-modal 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 multi-modal 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.

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 based on growth, but took no account of changing spatial accessibility due to 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 1960's 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. As comparisons between the models showed that either could be calibrated equally well to match 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 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 (6,7).

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 have a better prediction of travel behavior. The logit model and gravity model have been shown by Wilson to be of essentially the same form as used in statistical mechanics, as an entropy maximization model (9). The application 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, while a discrete choice approach brings those variables inside the utility or impedance function. Discrete choice models require more information to estimate and more computational time.

Ben-Akiva and Lerman have developed combination destination choice and mode choice models using a logit formulation for work and non-work trips (10). 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, Oregon use a logit formulation for destination choice (11). Research by Allen used utilities from a logit based mode choice model in determining composite impedance for trip distribution (12). 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 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” (13), this work has yet to be widely adopted with rigorous tests of convergence, or with a so-called “equilibrium” or “combined” solution (14). Haney suggests internal assumptions about travel time used to develop demand should be consistent with the output travel times of the route assignment of that demand (15). While 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.) and others, and later formal mathematical programming techniques were established by Evans (16,17). In the model used in this paper, congested travel times from route assignment are fed back into demand estimation, and the new demand is re-assigned 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 thirty years in the Washington Metropolitan Region, despite significant changes in household income, land use pattern, family structure, and labor force participation (18). The 1988 Household Survey commuting time of 28.8 minutes is almost identical to Census Journey to Work time of 29.5 minutes. Moreover, over the past twenty years even non-work travel times have remained fairly stable, generally between 19 and 20 minutes for home to non-work trips and at 18 minutes for non-home based non-work trips.

The stability of travel times and distribution curves over the past three decades gives 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 behavior and make all budget allocation adjustment on non-travel times (19). Prenderghast and Williams contradict the constant travel budget hypothesis by stating that consumers will substitute among budget components in response to relative price and income changes (20). However in spite of the importance given to road pricing in the transportation literature, out-of-pocket transportation costs have remained fairly small. The fact that other factors, including the typical five 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 auto trips are shorter than transit.

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 (MWCOG) for 1968 and 1987-88 (21,22). The 1968 survey consists of a sample of about 20,000 households making 135,000 trips while the 1987-88 sample involved 8,000 households and 55,000 trips.

Each household was assigned a specific 24 hour "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 location of both ends of the trip was reported along with the time of departure and arrival. Trip duration was obtained by subtracting time of departure from that of arrival. This 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 walk. Travel by automobile is further divided by number of person per vehicle, where 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), auto driver or "park and ride" (ADT), and auto 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 (W20) was 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 auto ownership, which serves as a surrogate for income. While in concept, stratification for income (or any number of other demographic variables) is desirable, this model was not stratified as income is not available from the 1988 survey and auto ownership is approaching one car per licensed driver in the region. Thus, the number of transit dependent (zero-auto) 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 five minute time band for each mode and purpose. Using Ordinary Least Squares (OLS) regression, impedance functions were estimated for application in the gravity model, with the dependent variable being number of trips per unit area in each five minute 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 five minute time band is assumed uniform. In model application, opportunities available (in trips) is multiplied against the impedance function. The number of opportunities is estimated by assuming five minute radius circular time contours: the first circle (0-5 minutes) has an area of 25π minutes squared, the second circle (5-10 minutes) has an area of $100\pi - 25\pi = 75\pi$ minutes 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:

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

where:

f(Cijm) is the impedance function for travel time t

a,b,c, and d are calibration coefficients shown in Tables 1 and 2

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

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

subject to:

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

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

$f(C_{ijm})$ = friction (impedance) function (negative exponential) described in Tables 1 and 2

In application of equation 2, the probabilities from the mode choice model are multiplied by the modal impedance on an O-D basis and summed to obtain composite impedance. A doubly constrained gravity model is used wherein, 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, auto 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 O-D 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 (Cij), multi-modal impedance functions (fij), and then demand to be assigned (Tij) 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 five minute time- bands which appear similar to the observed data, as shown in Figure 1.

The Friedman non-parametric 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 five minute 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 socio-economic factors are not directly considered in the distribution model, but are partially captured in mode choice, which does affect the model. It is possible to replicate area to area flows by using adjustment factors, however the stability of these adjustment (or K) factors over time has not been established. Nevertheless, adjusting the model to match observed data would seem a better assumption than not making any adjustment. Therefore, in model application, factors are developed which adjust base year trip tables are to "observed" base year O-D flows as developed using 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 the O-D travel times, but those times may not be accurate. While observed peak hour travel times are available for the road network for select links, this data does 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 miles per hour on a straight-line, euclidean distance. A third factor, travel cost, was also not accounted for in the distribution model, as 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 respondent round to the nearest five minutes, but a large number round to the nearest fifteen minutes. For instance, a tripmaker may actually leave at 5:02 and arrive home at 5:23, a trip of 21 minutes, but report leaving at 5:00 and arriving at 5:30, a trip of 30 minutes, almost a 50% 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 1988, but 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 impact 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- High Occupancy Vehicle Network Plan for Montgomery County, Maryland . 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. As combinations of over 18 alignments, and up to three modes possible on each alignment are being evaluated simultaneously, 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 thirty years in Metropolitan Washington shows that individuals will maintain an average separation between home and work of about thirty minutes. 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 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 region, with a 16,000 link network. To the authors knowledge, no procedure has been used which attempts to evaluate the impact of network alignments and prioritize networks on the basis of accessibility. The solution methodology proposed in this paper does not guarantee the optimal solution, but it lays the groundwork to quantify 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." In order to evaluate the benefits of alternatives, a consistent measure of effectiveness (MOE) 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 wherein 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 (VHT) 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 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." (30) For that reason, a similar approach, which does not depend on trips, but only on the easier to predict and fixed estimated activity at the trip ends, is accessibility. Hanson 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" (31). Here opportunities are defined as the number of jobs in a zone, while 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. As the model is applied to the p.m. peak period, employment is in the origin traffic zone here.

The accessibility equation used is:

$$A_{jm} = \sum_{i=1}^{I} [f(C_{ijm})^* EMP_i] \tag{4}$$

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

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 as the benefits to the system are paramount. The equation for this is below:

$$B_m^1 = \sum_{j=1}^{J} [A_{jm} * HH_j] / \sum_{j=1}^{J} [HH_j] \qquad (5)$$

where:

B_m^1 = Benefit of network 1 by mode m

= Countywide weighted average of Accessibility Indices

HH_j = Households in Destination Zone (j)

Achieving a multi-modal, 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 using the road network (SOV, HOV, Bus). There are situations where this will not occur, Braess's paradox is one example where 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 due 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 here considered as a simple summation of the mode specific Benefits (Eq. 7).

$$B_w^1 = \sum_{m=1}^{M} B_{wm}^1 \tag{7}$$

where:

B_w^1= composite (multi-modal) Benefit for work trips (average accessibility index)

B_{wm}^1= 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:

$$B_T^1 = \sum_{p=1}^{P} F_p B_p^1 \tag{9}$$

where

F_p = frequency or duration of purpose "p" (work, school, etc. ...)

B_p^1 = composite (multi-modal) 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.

$$B = B^2 - B^1 \quad (10)$$

where:

B^2 = Benefit (average accessibility) from full network

B^1 = Benefit from test network

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

It is however difficult 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, where 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 High Occupancy Vehicle 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 eighteen alignments considered in the full study, eight were considered feasible for possible HOV treatment. They were tested as described above, some as adding lanes, some as converting lanes from a baseline assumption. They are described in brief below:

Improvements to links which currently exist.

1) I-495 (Capital Beltway) from I-270 East Spur to I-95, add 1 lane in each direction

2) I-495 from American Legion Bridge to I-270 West Spur, add 1 lane in each direction

3) I-95 from I-495 to I-695 (Baltimore Beltway) add 1 lane in each direction

Changes in operation for links which currently exist

4) U.S. 29 from I-495 to MD 650 convert 1 lane in each direction
and from MD 650 to I-70 add 1 lane in each direction

5) Clara Barton Parkway from Canal St. to I-495, convert 2 lanes in peak direction

Changes in assumed operation for links which are planned

6) Inter-County Connector (ICC) , from I-370 to I-95 convert 1 lane in each direction

7) M-83 from ICC to I-270, convert 1 lane in each direction

8) MD 27 from I-270 to MD 80, add 1 lane in each direction

As can be seen from Table 4, the improvements which 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 LOS 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 somewhat differ from those of the region.

The converting of lanes from general purpose to HOV use has of course 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 as 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 Clara Barton Parkway, which is an existing limited access facility between downtown Washington 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 while 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, while 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, while closely paralleling an already planned HOV lane, and so was dropped. Similarly, alignment 4 parallels alignment 3, and so was not pursued for automobile HOV treatment.

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 using mode shares as weights was implemented. The multi-modal trip distribution impedance functions were tested in a transportation planning model with feedback between different components to produce consistent results. This method has the advantages that it better accounts for changes in transportation supply than does a conventional gravity model using only automobile impedance. As transportation planning more and more has to deal with additions of multiple modes, models need to account for all of these choices.

A method for evaluating networks using multiple modes is 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 (or f-) curve. Costs are approximated as distance in this preliminary planning model. The use of multi-modal distribution with travel time feedback is necessary to estimate accessibility by auto, a major component in total accessibility.

The relationships described in this study 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 1700's 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%. 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 has a high proportion of federal employment, the locational decision on the part of worksites 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 minutes, second only to New York City (36). Nevertheless, utilization of only auto travel times in the demand estimation or measurement of accessibility would misstate the patterns of transit demand, as transit trips tend to be longer in duration than auto 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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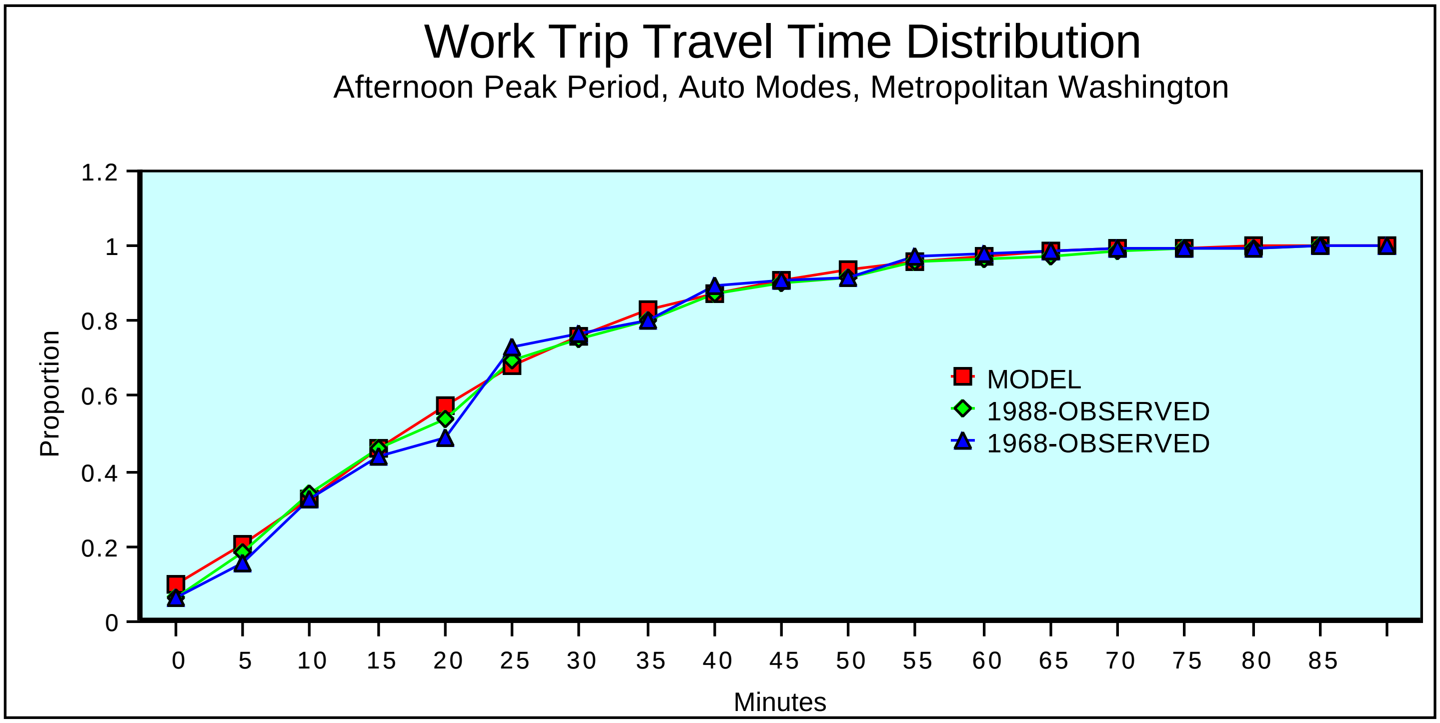
Work Trip Travel Time Distribution
Afternoon Peak Period, Auto Modes, Metropolitan Washington
Proportion
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
Minutes
MODEL
1988-OBSERVED
1968-OBSERVED

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	-0.00106	-	-	-	-	-	-
	(-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-statisitic in parentheses)

TABLE 2:

Multimodal Spatial Trip Distribution Impedance Function

(Non-Work Trips)

VARIABLE: \ MODE:	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-statisitic in parentheses)

TABLE 3: Evaluation of Impedance Functions (Work Trips)

TIME \ MODES:	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
SUM	0.923972	0.968368	1.05257	1.176653	1.153348	1.067499	1.106754

Table 4: Multi-modal Accessibility Benefit by HOV Alignment

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