INTEGRATION OF AN ACTIVITY-BASED MODEL SYSTEM

AND A RESIDENTIAL LOCATION MODEL

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ABSTRACT

We present an integrated discrete choice model system of a household's residential location choice and its members' activity and travel schedules. A daily schedule consists of tours, characterized by destinations, times of day and travel modes. The activity and travel models supply the residential model with an accessibility measure for each household member, namely the expected maximum utility among available daily activity schedules, conditioned by the chosen pattern of tours and, for workers, the workplace. A nested logit model system is estimated and applied for Boston. It does not fit the data quite as well as a work-trip based comparison model, but its predictions capture additional effects attributable to the more comprehensive accessibility measure.

INTRODUCTION

This paper continues a line of research and development in the area of discrete choice residential and travel demand models, with the aim of improved forecasts of urban land use and travel. In an early application to residential demand, Lerman (1976) developed a logit model of a household's joint choice of residential location, housing type, auto ownership and mode to work. This model was enhanced empirically (Ben-Akiva, Lerman, Damm et al., 1980; Weisbrod, Lerman and Ben-Akiva, 1980) and theoretically (Ben-Akiva and de Palma, 1986) to represent the process as a two-stage dynamic process involving transaction costs. The model was subsequently developed as part of a forecasting system for The Dutch Ministry of Transport (Clarke, de Jong and Ryan, 1991) but has not been used operationally.

The importance of accessibility in explaining the residential choice is well known (see, for example, Gunn, 1994). Lerman (1976) included forms of travel time and cost for the work commute. Ben-Akiva and Lerman (1977) proposed the use of expected maximum utility from travel demand models as a superior measure of accessibility. But they also noted the inadequacy of the measure if it comes from a trip based travel demand model which fails to capture the interdependence of an individual's trip decisions across trips in a tour, and across tours in the daily schedule.

Others have used representations of accessibility to explain residential location that are similar to those of this line of research. For example, over a period of 15 years Anas (1981; 1984; 1994; 1995) has developed an evolving unified model of land use and transport which now includes the household's joint selection of residence; work location, commute mode and route of the household head; and shopping trip frequencies by destination, route and mode. Its measures of accessibility are the travel time and cost for the modeled trips.

An activity based travel demand model system has recently been developed which represents an individual's choice of a daily activity schedule (Ben-Akiva and Bowman, 1995). By integrating this system with a residential choice model we are now able to test the Ben-Akiva and Lerman (1977) suggestion of a more broadly defined accessibility measure. In the next section we present the ideas behind the integrated model system with the residential accessibility measure derived from the daily activity schedule. This is followed by a case study that uses data from the Boston metropolitan area, in which we estimate parameters of the system, called the activity based model, and compare it with a residential choice model that uses a trip based accessibility measure.

THEORETICAL BASIS OF THE MODEL

The framework of residential, activity and travel decisions

Fig. 1 provides a framework for considering residential, activity and travel decisions (Ben-Akiva, Bowman and Gopinath, 1996; Ben-Akiva and Lerman, 1985).

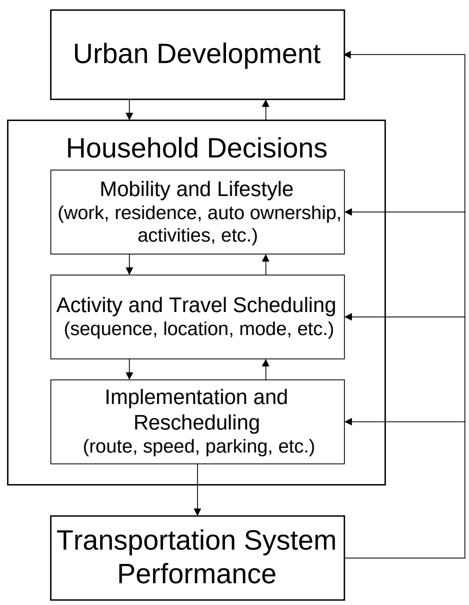

Fig. 1: Activity and travel decision framework. Many household decisions, occurring over a broad range of timeframes, interact with each other and with the urban development process and transportation system performance.

Urban development decisions influence the opportunities available to households and individuals. Real estate developers provide the locational opportunities for firm and individual location decisions. Through their location and production decisions, firms determine job locations.

Individual and household choices occur over a broad range of timeframes. Mobility and lifestyle decisions, such as residential location, employment, automobile ownership and activity participation, occur at irregular and infrequent intervals, in a timeframe of years. Activity and travel scheduling occurs at more frequent and regular intervals such as days and weeks. It involves selection of activities, assignment to household members, sequencing, and the selection of locations, times and methods of travel. Rescheduling occurs in the shortest timeframe, within the day, as activities are carried out, in response to information which prompts changes to the planned activity and travel schedule.

Urban development directly influences the decisions of individuals and households, who in turn affect the performance of the transportation system, in terms of travel volumes, speeds, congestion and environmental impact. At the same time transportation system performance affects the urban development and individual decisions.

Residential location and activity based accessibility

The residential decision is made by individuals and households. The outcome may be conditioned by the workplace decision or vice versa. It may, if it is a household decision, be conditioned by one member's workplace choice, and condition a second member's workplace choice. We consider here only the case of a household residential decision conditioned by the workplace decisions of its members.

In general, a household may consider each member's accessibility when it makes a residential choice, giving more weight to some members than to others. For example, accessibility of primary workers in a family may carry more weight than that of adult children, aging parents or nonworkers. Traditional gender roles may influence the consideration of accessibility among married couples. Also, the effect of members' accessibility may interact in the household decision. For example, for a working couple the effect of proximity to both workplaces may be greater than the separate effects of proximity to each workplace.

Although the residential choice is a household decision, household members also conduct activities individually. Therefore, we define accessibility at the individual level. We first define an activity schedule as a particular set of activities undertaken in a particular time-space path We next assume that (1) an individual can establish preferences over the set of activity schedules available at a given residential location, (2) the preferences can be represented by a set of utility functions which, from the analyst's standpoint, are random variables, and (3) the individual maximizes utility. We then define accessibility as the expected value of the individual's maximum utility among the activity schedules available, given a residential location.

This definition of accessibility has three important features. First, it allows one residential location to have greater accessibility for one person than for another person when the two have different characteristics. For instance, a residential location in a small town near schools and shops may be quite accessible for a fulltime parent, but very inaccessible for a single professional who works and socializes in the urban center. Second, by measuring preferences among available activity schedules, this definition takes the view that accessibility depends primarily on activity opportunities. Finally, by considering activity schedules instead of trips, the measure accommodates individuals' desires to participate in a variety of activities, the combination of activities via trip chaining and the satisfaction of activity needs without travel. The second and third features are exemplified by a residential location with poor travel connections to employment centers, but near shops and recreational opportunities, which is considered quite accessible by a telecommuting professional.

Model structure

We can implement the accessibility measure defined above in an integrated discrete choice model system of a household's residential choice and its members' conditional activity scheduling decisions. In Fig. 2 the activity schedule model, given a residential location, provides the expected utility to each household member. Each member's expected maximum utility (i.e., accessibility) enters the utility function in the model of household residential choice.

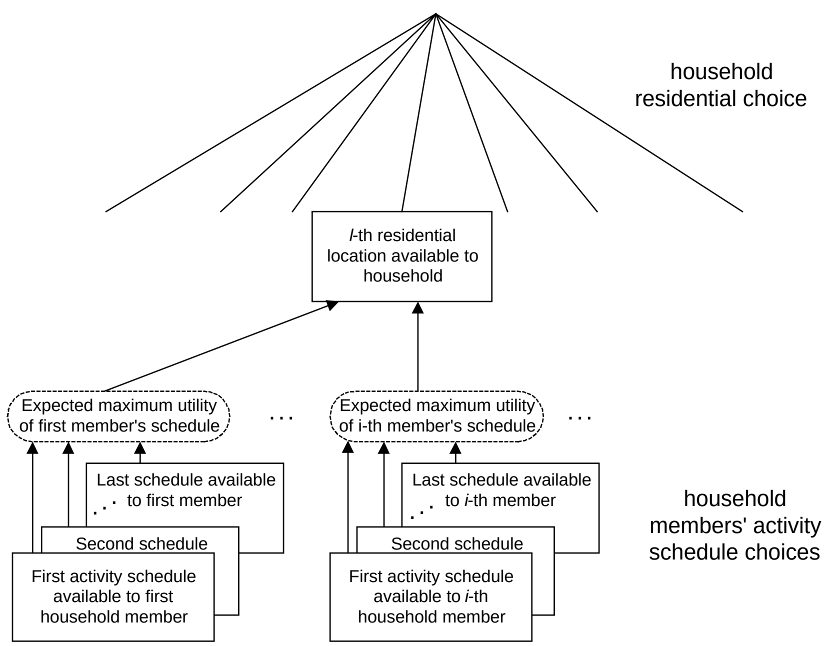

Fig. 2: Accessibility in the residential choice. For a household, the utility of each residential location alternative is affected by the accessibility it gives the household members, that is, the expected utility arising from their available activity schedules

Consider a discrete choice model of residential location choice specified as a multinomial logit (MNL) or nested logit (NL), where the utility of each residential location is specified as

$$U_l = V_l + \varepsilon_l \, , \qquad (1)$$

where U_l is the utility of residential location *l* for a given household, V_l is its systematic component and ε_l is its random component. In the MNL model ε_l is Gumbel distributed, independently and identically across locations, and the probability that location *l* will be chosen by the household is

$$p(l) = \frac{\exp(\mu V_l)}{\sum_{l' \in L} \exp(\mu V_{l'})}, \qquad (2)$$

where μ is the scale parameter and *L* is the set of available residential locations. If the utility function is linear in the unknown parameters and there are no interactive effects of accessibility across household members, then the systematic portion of the utility can be written as

$$V_l = \beta' X_l + \sum_{i \in I} \alpha_i V_{i|l}, \qquad (3)$$

where X_l is a vector of location *l* attributes interacted with household characteristics; $V_{i|l}$ is the expected maximum utility among all activity schedules available to individual *i*, given residential location *l*; *I* is the set of individual members of the household; and α and β are vectors of coefficients.

Consider a conditional activity schedule choice model with the utility of each schedule alternative specified as

$$U_{si|l} = V_{si|l} + \varepsilon_{si|l}, \qquad (4)$$

where $U_{si|l}$ is the utility of schedule alternative *s* for household member *i* located at *l*, $V_{si|l}$ is its systematic component, and $\varepsilon_{si|l}$ is its random component, distributed IID Gumbel with scale parameter $\tilde{\mu}$. Then the probability that *i* chooses activity schedule *s* from the set *S* of schedules available to *i*, given residential location *l*, is

$$p_i(s \mid l) = \frac{\exp(\tilde{\mu} V_{si|l})}{\sum_{s' \in S} \exp(\tilde{\mu} V_{s'i|l})}. \qquad (5)$$

The log of the denominator is the expected value of the maximum utility among schedules available to *i* given *l*. That is, it is the accessibility measure we use as a variable in (3). Specifically,

$$\frac{1}{\tilde{\mu}} \ln \sum_{s \in S} \exp(\tilde{\mu} V_{si|l}) + \gamma / \tilde{\mu} = E(\max_{s \in S} U_{si|l}) = V_{i|l}, \qquad (6)$$

where γ is Euler's constant (~ 0.577). The constant term $\gamma / \tilde{\mu}$ can be ignored.

Together, equations (1) through (6) comprise the integrated model system of household residential location and members' activity schedule choices.

The daily activity schedule

A daily activity schedule model provides the accessibility measures of equation 6 to the integrated system. This model was presented in an earlier paper (Ben-Akiva and Bowman, 1995) so we give only a summary here. Demand for activity and travel is viewed as a choice among all possible combinations of activity and travel in the course of a weekday. Scheduling is treated as an individual decision, with household interactions represented only implicitly, through the specification of household characteristics in the utility functions. The model uses a daily timeframe because of the day's primary importance in regulating activity and travel behavior. Although it could be argued that accessibility for the residential choice should be measured over a longer period, so that it includes activity demands which vary from day to day according to a broader activity program, the daily schedule matches our definition of accessibility more closely than existing trip based measures.

As shown in Fig. 3, the daily activity schedule consists of a set of tours tied together by an overarching daily activity pattern. The daily activity pattern is characterized by (1) the purpose of the primary activity, (2) the type of tour for the day's primary activity, including the number, purpose and sequence of activity stops, and (3) the number and purpose of secondary tours. Each tour includes the choices of activity destinations, and the mode and timing of associated travel. Tour decisions are conditioned by the choice of daily activity pattern, and the utility of a particular pattern depends on the expected utility of its component tours. This representation incorporates the trade-offs people make when scheduling their activities, such as the choice to combine activities into a single tour or spread them among multiple tours.

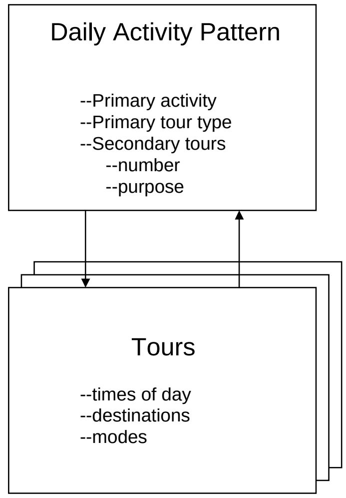

Fig. 3: The Daily Activity Schedule. An individual's multidimensional choice of a day's activities and travel consists of tours interrelated in a daily activity pattern.

Fig. 4 illustrates the model architecture using a hypothetical observation of one individual's travel diary. The itinerary shows that this person departed for work at 7:30 A.M., traveling by transit from home in traffic zone A to work in zone B. At noon they walked out for lunch and personal business, returning to work for the afternoon. At 4:40 P.M. they returned home from work, again by transit. That evening at 7:00 P.M. they drove to the mall in traffic zone C for shopping, and drove home later that evening.

Itinerary

7:30 AM	Travel by transit from home in zone A to work in zone B.
noon	Walk for lunch and personal business, returning to work
4:40 PM	Return home by transit.
7:00 PM	Drive to mall in zone C for shopping, returning home

Daily Activity Schedule

Daily Activity Pattern

Primary activity	work
Primary tour type	home-work-other-work-home
Number and purpose of secondary tours	1 tour, purpose 'other'

Primary Tour

Primary	destination	zone B
	mode	transit
	timing	AM peak
		PM peak
Secondary	destination	zone B
	mode	walk
	timing	midday
		midday

Secondary Tour

Primary	destination	zone C
	mode	auto
	timing	evening
		evening

Fig. 4: Modeled components of the daily activity schedule. This hypothetical itinerary, collected in a 24 hour travel diary survey, is translated into the modeled components of the daily activity schedule.

Fig. 4 also depicts how the proposed model represents this choice. In the daily activity pattern, the primary activity is work; the primary tour type is the sequence "home-work-other-work-home", reflecting the purpose and sequence of the activity stops in the tour; and one secondary tour is undertaken, with a purpose of "other" (i.e., other than work or school). In the tour schedule, the work destination is zone B, the mode of the primary activity is transit, and travel to and from the activity occurs during the A.M. and P.M. peak periods; the destination, mode and timing of the secondary activity of the primary tour are zone B, walk, and midday; and finally, the destination, mode and timing of the secondary tour are zone C, auto, and evening.

CASE STUDY

Data

We demonstrate the model system using a 1991 24-hour household travel diary survey from the Boston metropolitan area, supplemented by land use and transportation system attributes.

A few statistics from the survey reveal the complexity and variety in activity and travel schedules. Fig. 5 shows that a substantial percentage of people stay home for the entire day, and 40% take 2 or more tours away from home. The patterns vary dramatically across the population. For example, adults in households with small children are much more likely to take 2 or more tours. Among these, the patterns of males and females differ substantially. Females are more likely to stay home all day and to take 3 or more tours.

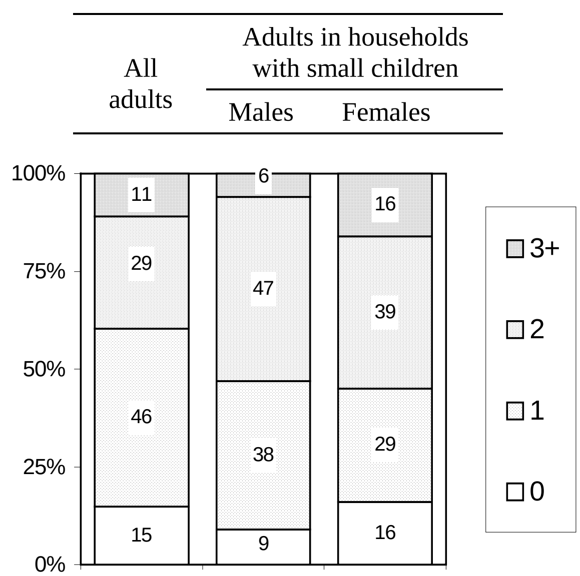

Fig. 5: Number of tours in the daily activity pattern among all adults, males with small children and females with small children (Boston, 1991). 15% of adults stayed home all day; adults in households with small children were more likely to take 2 or more tours, and females with small children were more likely than males to stay home or take at least 3 tours away from home.

In Fig. 6 we see that 25% of the workers conduct activities away from the workplace sometime during the workday, another 39% stop for other activities on the way to or from work and only 36% make a simple round trip to work without conducting other activities during the work tour. Here again, the patterns vary within the population.

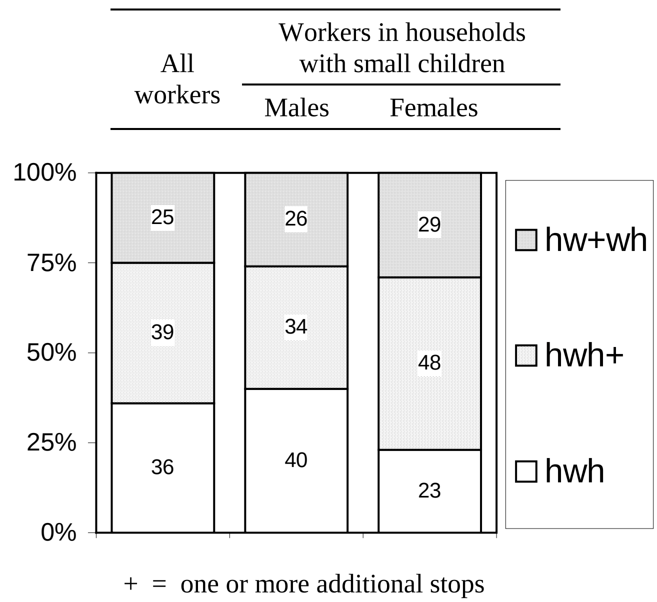

Fig. 6: Complexity of the work commute tour among all workers, males with small children and females with small children (Boston, 1991). 25% of workers traveled for activities away from the workplace during the workday (hw+wh), 39% stopped for activities on the way to or from work (hwh+) and 36% went directly to work and back home again (hwh). The distributions are different for males and females with small children.

Because of the variety of activity and travel patterns, the majority of travel time is devoted to activities other than the work commute. Of the 9100 travel hours reported in the travel survey, the work commute requires only 24%, whereas travel for activities chained with the commute, non-work primary tours and secondary tours require 15%, 43% and 17%, respectively. This reveals the weakness of the usual work-trip based accessibility measure. Such a measure properly represents accessibility only for the group of individuals who make a single work tour without stopping for other activities during the tour. This group represents a small percentage of the population. The remaining people are involved in a substantial amount of activities and related travel that the usual measure ignores.

Fig. 7 reveals that mode choice differs between primary and secondary tours. Use of transit almost disappears for secondary tours. There are also substantial drops in drive alone and increases in shared ride and walk alternatives.

Mode	**Primary Tours**	**Secondary Tours**
Drive alone	56%	41%
Shared ride	15	30
Walk	13	26
Transit with walk access	10	2
Transit with auto access	4	0
Bicycle	1	1
Total	100	100

Fig. 7: Modes of travel on primary and secondary tours (Boston, 1991). On secondary tours, use of transit almost disappears and drive alone drops, while shared ride and walk increase substantially.

For the purposes of the case study certain households are removed from the data set . These include households which made trips outside the metropolitan area or used travel modes excluded from our analysis, and those for whom important data are missing or inconsistent. Individuals born after 1974 are also excluded.

Fig. 8 lists the number of observations used in the estimation of each dimension of the model system.

Dimension	**Number of observations**
Residential choice	1259 households
Daily activity pattern	5232 persons
Primary tour time of day	4546 tours
Primary tour mode and destination	3830 tours
Secondary tour time of day	2873 tours
Secondary tour mode and destination	2068 tours

Fig. 8: Number of observations used in the estimation of the model system

Fig. 9 shows the number of households in the residential choice model sample, in several categories.

Variable name and description	**Number of households**
with one adult*, a worker	422
with two or more adults*, one worker	175
with two or more working adults	436
with one adult*, a nonworker	146
with two or more adults*, all nonworkers	80
Homeowners	746
Renters	513
in single unit detached housing	562
in other housing	697
families with children under 16	248
families without children under 16	469
nonfamilies	542

* excluding adult children and aging parents

Fig. 9: Counts of the households in the residential choice model sample, classified by number of adults and workers, tenure, housing type and family status. Dashed lines separate classifications, each with rows summing to the total of 1259 households.

Fig. 10 provides descriptive statistics of the 787 geographic zones of the Boston metropolitan area used as the alternative set for the residential location and activity destination models. The figure shows information relevant to the residential choice.

Variable name and description	Min	Mean	Max
Violent crime rate. Number of violent crimes reported in 1993 per person living in town during the 1990 census. Violent crimes include murder, rape, robbery and aggravated assault.	0	.009	.022
School standardized test scores. Average of 12 standardized (MEAP) test scores in 1990 for student's residing in the zone's town. Each score is averaged across the students in the town, and then the 12 averages are averaged.	1086	1271	1518
Housing value per bedroom. Median value divided by the mean number of bedrooms, of owner occupied units in the zone, in US $1K units.	6.9	63.2	286.5
Culture and recreation expenditure. The town's average annual per capita expenditure on culture and recreation, in US $1 units	3.2	32.7	83.8
Residential tax. The town's annual residential tax per household, in US $1 units	193	495	1636
Residential density excluding 3 densest zones, in thousands per square kilometer	.3	8.9	172.3

Fig. 10: Descriptive statistics of the 787 zones in the Boston metropolitan area

Daily activity schedule model

The models in the daily activity schedule system are ordered in a conditional hierarchy, shown in Fig. 11, with primary tour models conditioned by the choice of a daily activity pattern, and secondary tour models conditioned by the primary tour choices. Except for the time of day models, the system is linked as a sequentially estimated nested logit system, with conditional models supplying expected maximum utility, or logsum variables, to the higher level models.

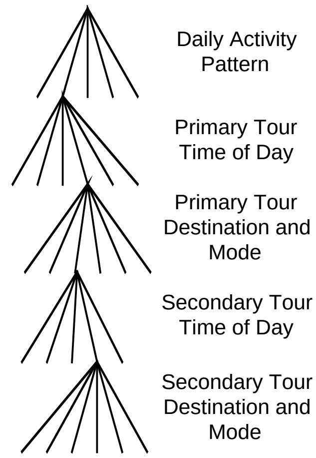

Fig. 11: Daily Activity Schedule hierarchy. In this nested logit system, models on lower tiers are conditioned by decisions in higher tiers. Except for time of day models, lower tier models also supply expected maximum utility to higher tier models.

Fig. 12 and Fig. 13 describe all dimensions of the decision as it is modeled in the case study, and Fig. 14 shows how the case study model would represent the Fig. 4 example itinerary.

Decision Dimension	Alternative	Proportion in Sample	Description
Primary activity	home	.165	at home all day
	work	.412	the daily activity pattern includes at least 1 work activity
	school	.057	the daily activity pattern includes no work activities and at least 1 school activity
	other	.366	the daily activity pattern includes no work or school activities
Primary tour type	HWH	.196	simple tour from home to work and back
	HWH+	.249	work tour with at least 1 additional stop for another activity
	HW+WH	.173	work tour with a work-based subtour, and any number of additional stops
	HWHWH	.011	work tour with an intermediate stop at home
	HWHWH+	.014	work tour with an intermediate stop at home, plus 1 or more additional stops
	HSH	.032	simple tour from home to school and back
	HSH+	.030	school tour with at least 1 additional stop for another activity
	HOH	.123	simple tour with purpose other than work or school
	HOH+	.128	tour with purpose other than work or school, with at least 1 additional stop for another activity
Number and purpose of secondary tours	0	.617	no secondary tours
	1,C	.092	one secondary tour, with a purpose (ie the primary activity of the tour) which is time constrained (work, work related, school, banking/personal business)
	1,U	.188	one secondary tour with a purpose which is not time constrained (social, recreational, eat out, shopping)
	2+,C	.023	two or more secondary tours, all time constrained
	2+,CU	.055	two or more secondary tours, 1 or more time constrained and 1 or more not time constrained
	2+,U	.024	two or more secondary tours, none time constrained

Fig. 12: Dimensions of the Daily Activity Pattern. The choice of a daily activity pattern involves the selection of one alternative from each of the decision dimensions, such as work in a tour with a work-based subtour (HW+WH) and conduct an additional time-constrained secondary tour (1,C).

Decision Dimension	Alternative	Proportion in Sample		Description
		Prim	Sec	
Departure time from home to activity	A.M. peak	.61	.14	6:30 AM to 9:29 AM
	midday	.24	.30	9:30 AM to 3:59 PM
	P.M. peak	.05	.31	4:00 PM to 6:59 PM
	other	.10	.25	7:00 PM to 6:29 AM
Departure time from activity to home	A.M. peak	.02	.08	6:30 AM to 9:29 AM
	midday	.40	.30	9:30 AM to 3:59 PM
	P.M. peak	.44	.21	4:00 PM to 6:59 PM
	other	.14	.41	7:00 PM to 6:29 AM
Destination				zone of the tour's primary activity location
Mode				the principal mode used on the tour
	Auto, drive alone	.56	.41	Drive alone is the principal mode used on the journey to or the journey from the tour's primary activity location.
	Auto, shared ride	.15	.30	Shared ride is the principal mode used for both the journey to and the journey from the tour's primary activity location.
	Transit, with auto	.04	.00	Transit is the principal mode of the tour, and the journey to or the journey from the tour's primary activity location includes both transit and auto.
	Transit, with walk	.10	.02	Transit is the principal mode of the tour, and neither the journey to nor the journey from the tour's primary activity location includes drive alone or auto access to transit.
	Walk	.13	.26	Walk is the exclusive mode used on the journey to or the journey from the tour's primary activity location, and the other journey does not include bicycle or drive alone.
	Bicycle	.01	.01	Bicycle is the principal mode on the journey to or the journey from the tour's primary activity location, and the other journey is not principally by drive alone.

Fig. 13: Dimensions of the tour decisions. For each tour in the daily activity pattern, one alternative must be chosen from each of the decision dimensions, such as depart from home during A.M. peak, depart from activity during the P.M. peak, travel by transit with walk access, and conduct activity in some specific zone of the metropolitan area.

Itinerary

7:30 AM	Travel by transit from home in zone A to work in zone B.
Noon	Walk for lunch and personal business, returning to work
4:40 PM	Return home by transit.
7:00 PM	Drive to mall in zone C for shopping, returning home

Daily Activity Schedule

Daily Activity Pattern		
Primary activity		work
Primary tour type		HW+WH
Number and purpose of secondary tours		1,U
Primary Tour		
Primary	destination	zone B
	Mode	Transit, with walk
	Timing	AM peak
		PM peak
Secondary Tour		
Primary	destination	zone C
	Mode	Auto, drive alone
	Timing	other
		other

Fig. 14: Hypothetical travel diary example as modeled in the case study.

The implemented model is simpler than the design presented earlier, and would be improved by (1) including a more detailed representation of alternatives with at-home activities, (2) including a more detailed categorization of primary tour types which would identify the sequence of all activities modeled in the primary tour, and (3) explicitly modeling the secondary activity on primary tours. Such enhancements would yield a more refined list of schedule alternatives, possibly improving the model’s ability to distinguish accessibility among residential locations.

Fig. 15 lists the utility function explanatory variables for each dimension of the daily activity schedule model, showing that the traditional measures of travel time and cost enter the utility functions of the primary and secondary tour mode and destination choice models. Model estimation results are presented in Ben-Akiva and Bowman (1995).

Model component	**Explanatory variables**
Daily Activity Pattern	alternative specific constants socioeconomic variables expected maximum utility of primary tour
Primary tour	
timing	alternative specific constants alternative specific constants for some daily activity pattern types
mode and destination	alternative specific constants cost and cost/income in-vehicle time and out-of-vehicle time distance (non-motorized modes) autos per driver alternative specific constants for some daily activity pattern types and market segments expected maximum utility from the secondary tours
Secondary tour	
timing	alternative specific constants alternative specific constants for some daily activity pattern types
mode and destination	alternative specific constants cost/income in-vehicle time and out-of-vehicle time distance (non-motorized modes) autos per driver household income alternative specific constants for some daily activity pattern types and market segments constants for modes and destinations that match primary tour mode or destination

Fig. 15: Explanatory variables in the utility functions of the daily activity schedule model components. The traditional measures of travel time and cost enter the utility functions of the primary and secondary tour mode and destination choice models (Ben-Akiva and Bowman, 1995).

Residential Location Model

The residential location aggregate alternatives are defined by 787 traffic analysis zones. The model is conditioned by the household's choice of tenure (rent vs. own) and building structure (detached single unit vs. other), which impact the quantity and price of housing stock available to the household in each zone.

Estimation of the residential utility function parameters in this case requires three bias correction procedures. All three involve adding terms to the utility functions of the alternatives. These terms are not true components of the model's utility functions, but enable consistent estimation of the model parameters using standard maximum likelihood estimation software for logit models[1]. First, geographic (endogenous) stratification of the sample requires a zone specific term equal to the natural log of the ratio of the zone's sample proportion to its proportion in the population. Second, because of the large number of alternatives, the parameters are estimated with a sample of 8 alternatives, drawn by stratified importance sampling, for each household. The sample includes three central area zones of the same income category as the household (high or low), three outlying zones of the same income category, and two zones of the other income category. By sampling high probability zones more heavily, importance sampling increases the amount of information in the sample, but it requires a term in the utility function consisting of the natural log of the inverse of the sampling rate. Third, the aggregation of alternatives requires a term representing the size of the aggregate alternative. For this we use the natural log of the occupied housing stock, by tenure and type, taken from the 1990 U.S. census. The methodology used for estimation, including all three adjustment procedures, is described in Ben-Akiva and Lerman (1985).

The model is specified with linear (in the unknown parameters) utility functions. Accessibility variables are included in the household's utility function for up to two adults, with first priority given to workers, second to males and third to birth order, excluding adult children and aging parents. Separate parameters are included for workers and nonworkers. Models that distinguish accessibility by gender were rejected because of sign problems arising from data collinearity.

In all cases, the expected utility used as the accessibility variable is conditioned upon the choice of daily activity pattern (i.e., primary activity, primary tour type, and number and purpose of secondary tours). Measures unconditioned by the daily activity pattern were rejected because coefficient estimates well in excess of 1 indicated a large variance in the daily pattern utility relative to the residential location utility. This result statistically invalidates the anticipated nested logit model hierarchy in which the daily activity pattern is conditioned on the residential choice. Instead the result suggests a hierarchy which conditions residential location on the daily pattern and conditions the details of the activity schedule (i.e., tour destinations, modes and times of day) on the residential location. This may be caused by our lack of information to explain the daily activity pattern choice. On the other hand the result may indicate that the daily pattern reflects a longer term lifestyle decision, one that should be integrated at the long-term level with other mobility and lifestyle choice models.

Worker expected utility measures are also conditioned by workplace choice. Such measures provide substantially more information than those that are unconditioned. This may indicate that in the daily schedule model, the daily work destination choice should be conditional on a long term workplace decision. With the existing model, the expected utility of the worker's daily activity schedule carries no information about the regular workplace. This result also reflects the strong correlation between the residential location and workplace choices.

Taking the above results into consideration, the residential utility of equation (3) is implemented for households with one worker and at least one nonworker as

$$V_l = \beta' X_l + \alpha_w V_{w|lp_w d_w t_w} + \alpha_n V_{n|lp_n t_n}, \qquad (7)$$

where α_w is the weight given to the worker's accessibility, estimated as .6561 (Fig. 16 line 3); $V_{w|lp_w d_w t_w}$ is the expected maximum utility among all activity schedules available to the worker *w*, given residential location *l* and *w*'s daily activity pattern p_w, work destination d_w and work tour timing t_w ; α_n is the weight given to the nonworker's accessibility, estimated as -.2456 (Fig. 16 line 4); and $V_{n|lp_n t_n}$ is the expected maximum utility among all activity schedules available to the nonworker *n*, given residential location *l*, and *n*'s daily activity pattern p_n and primary tour timing t_n . The activity schedule accessibility measure (c.f. equation (6)) is implemented for the worker in this household as

$$
\begin{aligned}
V_{w|lp_w d_w t_w} &= \frac{1}{\tilde{\mu}} \ln \sum_{m \in M_{w|lp_w d_w t_w}} \exp(\tilde{\mu} V_{mw|lp_w d_w t_w}) \\
V_{mw|lp_w d_w t_w} &= \tilde{V}_{mw|lp_w d_w t_w} + V'_{mw|lp_w d_w t_w} \qquad (8)\\
V'_{mw|lp_w d_w t_w} &= \sum_{j=1}^{J_w} \{\ln \sum_{m^s d^s \in MD_{jw|lp_w d_w t_w m t_w^s}} \exp(V_{m^s d^s jw|lp_w d_w t_w m t_w^s})\},
\end{aligned}
$$

where $\tilde{\mu}$ is the scale parameter and $V_{mw|lp_w d_w t_w}$ is the systematic component of *w*'s primary tour mode and destination utility; $M_{w|lp_w d_w t_w}$ is the set of modes *m* available to *w* for the work tour; $V'_{mw|lp_w d_w t_w}$ is the component of $V_{mw|lp_w d_w t_w}$ attributable to the expected maximum utility of associated secondary tours and $\tilde{V}_{mw|lp_w d_w t_w}$ is the other component; $V_{m^s d^s jw|lp_w d_w t_w m t_w^s}$ is the systematic component of the utility of a particular secondary mode and destination alternative $m^s d^s$ for the *j*th of J_w secondary tours in *w*'s daily pattern, taken from the set $MD_{jw|lp_w d_w t_w m t_w^s}$ of alternatives available to *w* for the *j*th secondary tour, given the primary mode *m* and *w*'s secondary tour timing t_w^s ; and the scale of secondary tour mode and destination utility is normalized to 1.

	Variable name and description	Activity based model system (activity-based accessibility measure) Coefficient estimate (col. 1)	Activity based model Standard error (col. 2)	Trip based model (customary impedance measure) Coefficient estimate (col. 3)	Trip based model Standard error (col. 4)
Accessibility variables used in the activity based system					
1	**expected utility of the daily activity schedule**, given the daily activity pattern and work location, households with one adult, a worker	.7112	.050		
2	sum of expected utility of 2 workers' daily activity schedules, given their daily activity patterns and workplaces, households with 2+ working adults	.5011	.033		
3	expected utility of 1 worker's daily activity schedule, given the daily activity pattern and work location, households with 2+ adults and only 1 worker	.6561	.071		
4	expected utility of 1 non-worker's daily activity schedule, given the daily activity pattern, households with 2+ adults and only 1 worker	-.2456	.085		
5	expected utility of the daily activity schedule, given the daily activity pattern, households with one adult, a non-worker	.1687	.079		
6	sum of expected utility of 2 non-workers' daily activity schedules, given their daily activity patterns, households with 2+ adults and no workers	.03957	.055		
Variables used in both models					
7	(the town's **violent crime rate**, in annual crimes per resident)*(the household's annual per capita income, in $1K US units)	-.1123	.18	-.2975	.19
8	**Residential density** in 1000's of people per sq km, for households with children under 16	-.03292	.010	-.03315	.010
9	a transformation of **estimated annual income remaining** after housing expenses, in $1,000 US units: (ln($I$+1) if I>0, and I if I<=0, where I is income minus .1*zonal median owner occupied housing value for owners, and I is income minus 12*zonal median monthly rent for renters. Thus the unit effect of income diminishes as remaining income increases above zero)	.07864	.022	.08072	.022
Accessibility variables used in the trip based system					
10	**composite round-trip impedance for the journey to work**, in minutes: $((\text{auto travel time})^{-1}+(\text{transit in-vehicle-time} + 2.5*\text{transit out-of-vehicletime})^{-1.28})^{-1}$, households with one adult, a worker			-.0495	.0035
11	sum of composite impedance for 2 workers' journeys to work, households with 2+ working adults			-.03057	.0021
12	composite impedance for 1 worker's journey to work, households with 2+ adults and only 1 worker			-.03971	.0043
13	**Size correction term**: natural logarithm of the number of housing units of the household's chosen tenure and structure in the zone	1.115	.054	1.083	.054
Summary statistics	Number of observations	1259		1259	
	$L(0)$	-2531		-2531	
	$L(\hat{\beta})$	-1355		-1335	
	ρ^2	.4645		.4725	

Fig. 16: Estimation results of the activity based residential location model and a trip based model. Variables 1 through 9 and their col. 1 coefficients enter the activity based model's residential location utility functions. Variables 7 through 12, with col. 3 coefficients, are for the trip based model. For a household with one worker, one nonworker and children under 16, the activity based model's utility functions include variables 3,4,7,8 and 9 for each residential alternative, and the trip based model's utility functions include variables 7,8,9 and 12. Variable 13, the size correction term that accounts for different sizes of the aggregate alternatives (i.e., zones), enters the utility functions of both models. The statistical fit of the trip based model is slightly better than that of the activity based model

Fig. 16 presents detailed descriptions of all the variables and parameter estimates of the residential choice model. Variables 1 through 6 are the accessibility variables for various member and household types. Parameter estimates for worker variables (rows 1-3) are all large and significantly positive, indicating a strong influence of worker accessibility on the household's residential choice. In contrast, the parameter for the nonworker in a one-worker household (row 4) is smaller and bears the wrong sign. This may reflect less importance to the household of nonworker accessibility relative to the worker's accessibility, as well as positive collinearity between these two variables. In nonworking households, the parameter of single nonworkers is significantly positive but smaller than those of workers, while that of two nonworkers is not significantly larger than zero.

In addition to the accessibility measures, we include (rows 7-9) an estimate of the violent crime rate, residential density for households with children, and the income remaining after housing expenses (following Lerman (1976) and Anas (1995)). The income remaining variable is a function of housing prices, which are determined in the housing market, and may be viewed as endogenous. However, in this disaggregate model of residential choice we consider the household to be a price taker with insignificant effect on the market price. We are therefore able to treat price as exogenous. Other variables which were considered but dropped from the specification include school educational performance, proximity to industrial acreage, town's expenditure on culture and recreation, residential tax rate, and a CBD dummy.

Row 13 shows the parameter estimate of the size correction term described above. The estimate is nearly within two standard errors of 1, the theoretically correct value.

For comparison purposes, Fig. 16 includes estimation results from a similar model in which the expected utility measures are dropped. They are replaced by a work journey impedance variable customarily used by Boston's Central Transportation Planning Staff. The variable is a composite measure of travel time, based on auto and transit travel times. The parameter estimates take the correct negative sign. This trip based model, so named because it measures impedance for a single trip, actually explains slightly more of the variation in the sample data. However, it provides no measure of accessibility for households without workers, and the impedance measure lacks sensitivity to variables -- other than travel time -- which can affect residential choice via the utility of daily activity schedules. For example, this model is not sensitive to the distribution of land use.

Model application

We demonstrate the residential choice model by applying it and the trip based model to the estimation sample, applying them under the conditions of the model estimation (base case) and under a hypothetical forecast scenario. We report summary results for each of 8 subregions of the metropolitan area. The subregions are defined by dividing the region geographically into 4 concentric rings, and subdividing each ring into two subregions based on transit access time. Within each subregion we report results separately for worker and nonworker households.

Fig. 17 reports the fit of the models with observed behavior under the base conditions. Both models yield similar fit, with a tendency to overestimate the center for worker households and underestimate it for nonworker households. This indicates the presence of unspecified geographical factors with different effects for worker and nonworker households, suggesting the need for market specific geographic constants in the model. This lack of fit does not, however, substantially affect the models' predictions, because the predictions measure changes from modeled base conditions.

				Activity based model system (activity based accessibility measure)		Trip based model (customary impedance measure)	
Subregion	**Ring-Transit access**	**Household type**	**Sample frequency**	**Modeled frequency**	**% error**	**Modeled frequency**	**% error**
1	1-better	worker	154	155.1	.7	156.7	1.8
		nonworker	33	28.5	-13.6	25.4	-23.0
		all	187	183.5	-1.9	182.1	-2.7
2	1-worse	worker	194	214.1	10.4	212	9.3
		nonworker	50	37.5	-25.0	34.7	-30.6
		all	244	251.6	3.1	246.7	1.1
3	2-better	worker	119	146.2	22.9	144.5	21.4
		nonworker	20	19.6	-2.0	18.5	-7.5
		all	139	165.8	19.3	163.0	17.3
4	2-worse	worker	105	136.0	29.5	131.5	25.2
		nonworker	33	25.3	-23.2	23.6	-28.5
		all	138	161.3	16.9	155.1	12.4
5	3-better	worker	150	149.0	-.7	148.8	-.8
		nonworker	29	34.8	20.0	34.9	20.3
		all	179	183.7	2.6	183.7	2.6
6	3-worse	worker	132	116.7	-11.6	117.3	-11.1
		nonworker	19	28.3	48.9	29.0	52.6
		all	151	144.9	-4.0	146.3	-3.1
7	4-better	worker	89	57.9	-34.9	64.6	-27.4
		nonworker	18	25.9	43.9	29.6	64.4
		all	107	83.8	-21.7	94.2	-12.0
8	4-worse	worker	90	58.2	-35.3	57.7	-35.9
		nonworker	24	26.2	9.2	30.3	26.3
		all	114	84.4	-26.0	88.0	-22.8

Fig. 17: Fit of activity based model system and trip based model with observed residential choice behavior among members of the estimation sample. Both models yield a similar fit

The forecast scenario involves two major changes in auto and transit service, one in the central area and the other on the fringe. First, extreme congestion and congestion management policy are introduced throughout most of the center (ring 1 and the less transit-accessible portion of ring 2). This is accompanied by a transit improvement project in the less transit accessible portion of the center. Second, a transit improvement project is introduced in the portion of the outlying area (ring 4) served by transit. Conditions remain unchanged in a buffer zone (ring 3) between the inner and outlying areas, in which we can observe effects of changed conditions in the other areas. The scenario thus treats the 8 subregions differently, but the treatment is uniform within each subregion.

Fig. 18 shows two measures of the forecast scenario's impact. Both measures are calculated without system equilibration. That is, the forecasts reflect only the demand response, assuming the attributes of residential locations other than accessibility remain constant. The first measure, reported in columns 1 and 2, summarizes for each subregion the benefit (i.e., change in consumer surplus) of the policy on the portion of the sample living in the subregion at the time of the survey. It allows only for changes in activity and travel choices, given the actual residential location of the sample. It represents a short term benefit and consists entirely of the change in accessibility caused by the transport policy. We convert the change to dollars based on the model's relative values of accessibility and travel cost.

			Average consumer surplus change, given residential location (dollars)		Population change (percentage)	
Subregion	**Ring-Transit access**	**Service level change** household type	**Activity based model (col. 1)**	**Trip based model (col. 2)**	**Activity based model (col. 3)**	**Trip based model (col. 4)**
1	1-better	**downgrade auto**[1]				
		worker	-$2200	-$1200	-49%	-37%
		nonworker	0	0	0	0
		all	-1800	--950	-41	-32
2	1-worse	**downgrade auto**				
		worker	-2400	-1300	-58	-42
		nonworker	0	0	0	0
		all	-1900	-1000	-50	-36
3	2-better	**no change**				
		worker	0	0	56	29
		nonworker	0	0	0	0
		all	0	0	50	26
4	2-worse	**downgrade auto and improve transit**[2]				
		worker	-3000	-1500	-68	-29
		nonworker	0	0	0	0
		all	-2300	-1100	-57	-24
5	3-better	**no change**				
		worker	0	0	56	33
		nonworker	0	0	0	0
		all	0	0	46	26
6	3-worse	**no change**				
		worker	0	0	53	30
		nonworker	0	0	0	0
		all	0	0	42	24
7	4-better	**improve transit**				
		worker	+3	+190	51	63
		nonworker	0	0	0	0
		all	+2	+160	35	43
8	4-worse	**no change**				
		worker	0	0	55	33
		nonworker	0	0	0	0
		all	0	0	38	22

[1]**Downgrade auto** includes increase in-vehicle time by 100% during peak periods and 50% offpeak, $10 peak period toll if travel time exceeds offpeak travel time by 10%, $5 parking surcharge for single-occupant vehicles, $2.50 parking surcharge for HOVs, 5 minute extra parking search time, 5 minute extra parking-related walk time. Parking changes apply to all OD pairs within the subregion, other changes apply to OD pairs if origin is within the subregion.
[2]**Improve transit** includes 50% reduction of transit access time, and 25% reduction of in-vehicle time for all OD pairs with origin in the subregion, and employer sponsored transit incentive for all employees residing in the subregion.

Fig. 18: Predicted changes in consumer surplus and population of each subregion under the forecast scenario. The activity based model is more sensitive than the trip based model to changes in auto service level (e.g., ring 1), and less sensitive to changes in transit service level (e.g., subregion 7). This difference can be attributed to the activity based model's use of expected utility from an entire daily schedule, in contrast to the trip based model's use of a weighted combination of auto and transit commute travel time.

Columns 3 and 4 report the percentage change in the predicted population. To produce it we calculate the residential choice probabilities (equation 2) of each household under the forecast and base scenarios. Then, for each subregion, we sum them and calculate the percentage change.

As expected, both models predict a shift away from the center, where auto service is downgraded, toward areas with either no change or improvements in transit service. The major cause of this shift is the change in auto service. Both measures give evidence of this. Without allowing residential change, subregion 7's consumer surplus barely increases in response to the transit improvement and in subregion 4 the negative effect of downgraded auto service overshadows the transit improvement. When residential change is allowed, subregion 7's population change is similar to subregions with no service level changes, and subregion 4 changes like subregions with only downgraded auto service.

The results also reveal a distinct difference in the performance of the two models. Overall sensitivity to the policy is much greater in the activity based model than in the trip based model. An aggregate measure of overall sensitivity, the size-weighted average of the absolute percentage change in population of the subregions, is 46% in the activity based model and only 29% in the trip based model. The greater overall sensitivity may reflect the broader scope of the activity based model's accessibility measure. In other words, the activity based model is capturing the effect on residential choice of accessibility for activities beyond the work commute.

The activity based model is also more sensitive than the trip based model to changes in auto service level (e.g., ring 1), and less sensitive to changes in transit service level (e.g., subregion 7). In fact, it predicts almost no measurable effect of the transit changes. This can be partially explained by the activity based model's use of expected utility, rather than travel time, as the measure of accessibility. Because of transit's small market share, changes in transit travel time have much less effect on expected utility than corresponding changes in auto travel time. However, some of the sensitivity difference would probably remain even if the trip based model used an expected utility measure. This is because the activity based model captures the preference of nearly all persons, including transit commuters, to use their autos for secondary travel. Thus, a change in auto service affects auto and transit commuters, and a change in transit service affects only a portion of the activities of transit commuters.

Neither model predicts any shifts in nonworker households under the policy, evidenced by zeroes throughout Fig. 18. There can be no change for the trip-based model, because its accessibility measure is only present in worker households. The activity based model, on the other hand, includes accessibility terms for nonworking households. However, the small size of the parameters (lines 5 and 6 of Fig. 16), and the extremely small changes in expected utility induced by the policy change, result in no measurable change in the impact measures. This may indicate the insensitivity of nonworker residential location to accessibility, at least in this sample. It more likely indicates a specification error in the activity based model. For example, nonworkers may, like workers, condition their residential choice upon accessibility for specific activities and destinations. Implementation of an activity based accessibility measure for nonworkers may require the modeling of long term activity commitments.

Model application with a hypothetical forecast scenario provides no actual data with which to evaluate the relative accuracy of the models' predictions. Nevertheless, the above analysis of the contrasts between the results of the two models lends intuitive appeal to the activity based predictions.

CONCLUSION

In this paper we have demonstrated the integration of an activity based travel demand model system and a residential location model. Residential accessibility is measured by the expected maximum utility of household members' daily activity schedules. Although the activity based model includes accessibility for nonworker households, its predictions for these households are insensitive to changes in travel conditions, suggesting misspecification of the model for this subpopulation. The activity based accessibility measure is conditioned by the daily activity pattern, reflecting a lack of information explaining the daily activity pattern choice, and indicating a possible necessity to model the daily pattern decision as a longer term decision. The residential choice model does not fit the data quite as well as a comparison model which uses a more traditional work journey impedance variable. Its predictions, however, capture additional effects attributable to the more comprehensive measure of accessibility.

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FOOTNOTES

[1] All models were estimated and applied using ALOGIT, by Hague Consulting Group, The Hague, Netherlands.