

**AN ECONOMETRIC MULTI-DIMENSIONAL CHOICE MODEL OF ACTIVITY-
TRAVEL BEHAVIOR**

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ABSTRACT

Recent evidence suggests that many activity-travel choices are inter-dependent with one another and hence inextricably linked in ways that need to be better understood to help inform the specification of activity-based travel model systems. Model systems in practice often sequentially link a series of choice dimensions into a deeply nested logit model where accessibility variables (logsum terms) from lower nests cascade up through the structure to the higher levels in the model structure. While these model systems are convenient from a practical standpoint, they ignore the potential jointness in choice-making processes and do not effectively and directly capture the effects of spatial land use and built environment characteristics on activity generation. In this paper, a unified model of activity type choice (generation), time of day choice, mode choice, destination choice, and time use allocation (duration) is formulated and estimated on a survey sample data set drawn from the 2000 San Francisco Bay Area Travel Survey (BATS). The model system constitutes a joint multiple discrete continuous extreme value (MDCEV) – multinomial logit (MNL) model, in which all discrete choices, except for destination choice, and the continuous duration dimension are modeled using the MDCEV, and destination choice is modeled as a MNL (with sampling of alternatives) nested and therefore integrated with the MDCEV model component. The parameter estimates of the joint model offer behaviorally intuitive results that support the integrated treatment of these choice dimensions as a choice “bundle”. The potential applicability of the model system is demonstrated through a policy simulation example that shows how changes in travel cost and time variables lead to changes in out-of-home discretionary activity participation.

Keywords: activity type choice, time of day choice, activity duration, mode and destination choice, joint model, simultaneous equations model, integrated model, MDCEV-MNL model

1. INTRODUCTION AND MOTIVATION

Travel demand modeling is characterized by an increasing shift towards activity-based travel demand modeling approaches that explicitly recognize that travel is undertaken to fulfill activity needs and desires dispersed in space and time (Meloni *et al.*, 2004). The focus on activity-based approaches is spurred on by enhanced understanding of activity travel behavior dimensions, increasing concerns of global climate change as well as the recent advances in micro-simulation based computation approaches. The move towards microsimulation-based approaches facilitates the disaggregate representation of behavioral agents and their interactions, while simultaneously incorporating the ability to analyze policy impacts and address equity concerns at the level of the individual traveler or any sub-market segment of interest (Miller and Roorda, 2003).

The major objective of the activity based micro-simulation approaches is to strive to mimic and replicate activity-travel processes of individuals. These choice processes include such dimensions as activity type choice, time of day choice, trip chaining or linking choice, joint versus solo activity engagement choice, destination choice, mode choice, activity sequencing decisions, and activity time allocation (duration) decisions. Many of these choice processes are discrete in nature (*e.g.*, activity type choice, time of day period choice, mode and destination choices), while others are continuous (*e.g.*, activity duration). The structure of the inter-dependencies across these choice variables assumed by the analyst has important implications for activity-based model specifications.

Given the large number of choice variables considered in the behavioral process, it is not surprising that many approaches have opted for a sequential framework in which activity-travel choices are modeled sequentially. These approaches often resort to the adoption of deeply nested logit models (Ben-Akiva and Lerman, 1985) where one choice process is nested within another choice process and so on, forming a long chain of inter-connected nests to complete the representation of the behavioral process (Bowman, 1995; Bowman and Bradley, 2006; PB Consult, 2005). As it is virtually impossible to estimate such long chains of nested logit models simultaneously (*i.e.*, in one single step), components of the nested logit model are usually estimated one step (or maybe two steps) at a time and the logsum from one level is carried up to the next higher level, resulting in a sequential estimation and model application approach. Although there are other behavioral model systems that attempt to move away from such deeply nested logit specifications, such as those based on computational process modeling and heuristic approaches (for example, see Arentze and Timmermans, 2005), the fact remains that most current activity-based model systems break down the behavioral decision process so that one is modeling only one or two choice processes at any step in the model system. It may be argued that some choice processes are best modeled sequentially; for example, a longer-term choice of work or residential location is likely to precede a shorter-term choice of time of departure for a discretionary trip. On the other hand, there are a host of choices, such as destination choice, mode choice, activity type choice, activity duration choice, and activity accompaniment choice that one would expect to be short-term choices made contemporaneously. Although a sequential treatment of such contemporaneous choice mechanisms is convenient from a practical model estimation and application standpoint, it is unclear whether such model systems truly replicate behavioral processes.

On the other hand, resorting to a simultaneous equations modeling framework for will allow the analyst to incorporate the complex inter-dependencies that often characterize activity-travel choice processes. However, the simultaneous equations approach results in a substantial increase in computational complexity, particularly when the number of choice dimensions being

modeled becomes greater than two. In fact, one could argue that current practice has adopted the sequential framework in the activity-based modeling realm because of the estimation challenges and computational complexity associated with specifying, identifying, and estimating simultaneous equations model systems that represent joint choice processes in which individuals and households are making a “package” of activity-travel choices as a “bundle”. In other words, it is conceivable that individual agents are making choices regarding the type of activity to pursue, the mode and destination, and the time allocation to the activity in one swoop, thus motivating the adoption of a “joint” choice model specification in which unobserved factors unknown to the analyst may be simultaneously impacting multiple dimensions of interest (Jara-Diaz *et al.*, 2007). The current paper contributes to the literature on modeling activity travel choice processes simultaneously.

The growing interest in the ability to model multiple choice dimensions simultaneously, where the endogeneity of many choice variables is explicitly recognized in the activity-travel behavior modeling arena, motivates this paper. Specifically, this paper presents a joint model system of five choice dimensions:

- Activity type choice
- Activity time of day choice (treated as discrete time intervals)
- Mode choice
- Destination choice
- Activity duration (continuous choice dimension)

These five dimensions are of particular interest to policy makers to devise strategies that influence travel behavior. For instance, to devise a policy to reduce vehicle emissions, it is necessary for any modeling tool to provide information on activity flexibility (activity type and time-of-day), travel mode, activity location and distance (destination), and vehicle soak times (activity duration). These five choice dimensions are of critical interest to any activity-based model system regardless of the model design that might be adopted. Thus, this paper aims to specify and estimate a comprehensive econometric model system that jointly models these five choice dimensions in a holistic unifying utility-maximization framework. The model system explicitly includes consideration of built environment attributes including level of service variables and spatial land use characteristics to capture the potential impacts of such variables on the activity generation process, a key area that warrants additional research. Such a model specification provides the ability to examine induced and suppressed demand effects in response to changes in system capacity and level of service.

The modeling methodology adopted in this paper builds on previous work by the authors and constitutes a joint multiple discrete continuous extreme value model and multinomial logit model system (Bhat, 2005, Bhat *et al.*, 2006, Bhat, 2008). The multiple discrete continuous extreme value (MDCEV) model component is used to jointly analyze activity type choice, activity time of day choice, mode choice, and activity duration. Specifically, the MDCEV model is used to represent activity participation (discrete choice) and time use (continuous choice) for different types of activities at different time periods of the day by different travel modes. The activity location choice is modeled using a multinomial logit (MNL) model nested within the MDCEV framework. The model system is estimated for a survey sample drawn from the 2000 San Francisco Bay Area Travel Survey (BATS), a comprehensive database that includes detailed household and personal socio-economic, demographic, and activity-travel information together with a host of secondary transportation level-of-service and land use variables.

The next section presents the modeling methodology in detail. This is followed by a description of the dataset and survey sample. The fourth and fifth sections present model estimation and policy simulation results, while the sixth and final section offers concluding remarks.

2. MODELING METHODOLOGY

This section presents the modeling methodology for the joint MDCEV-MNL model structure. First, the utility structure is presented, second, the econometric model specification is presented, and finally the procedure for sampling of location choice alternatives is discussed. An intuitive behavioral interpretation of the model structure is offered as well.

2.1 Utility Structure

Consider the following utility specification for the integrated analysis of individuals' activity time-use, timing, mode choice, and location choice decisions:

$$U(\mathbf{x}) = \{\psi_1 \ln x_1\} + \left\{ \gamma_2 \psi_2 \ln \left(\frac{x_2}{\gamma_2} + 1 \right) \right\} + \sum_{ptm=3}^{62} \left\{ \gamma_{ptm} \psi_{ptm} \ln \left(\frac{x_{ptm}}{\gamma_{ptm}} + 1 \right) \right\} \quad (1)$$

In the above equation, the first term $\psi_1 \ln x_1$ corresponds to the utility contribution of the total daily time invested (x_1) in all maintenance activities, and the second term corresponds to the utility contribution of the total daily time invested (x_2) in all in-home (IH) discretionary activities. The next set of terms correspond to the utility contribution due to the time investment (x_{ptm}) in out-of-home (OH) discretionary activity episode types (indexed by ptm), with each activity episode type defined by its purpose (p), timing (t), and mode of travel (m). In the current empirical context considered in this paper, there are five OH discretionary activity purposes (volunteering, socializing, recreation, meals, and shopping), six time periods (3am-7am or early morning, 7am-9am or morning, 9am-12noon or late morning, 12noon-4pm or afternoon, 4pm-7pm or evening, and 7pm-3am or night), and two modes of travel (auto, and non-auto), yielding 60 different types of OH discretionary activity episodes (or ptm combinations). Thus, there are a total of 62 MDCEV choice alternatives in that one or more of these alternatives may be chosen by an individual through the course of a day.¹ For each of these alternatives, the ψ terms (ψ_1, ψ_2 , and ψ_{ptm}) are the baseline utility parameters that control the discrete choice of the alternative. For all alternatives except the first alternative, the γ terms (γ_2 and γ_{ptm}) allow for corner solutions (*i.e.*, the possibility of not choosing the alternative) as well as satiation effects (*i.e.*, diminishing marginal utility with increasing time investment).² There is no γ term

¹ Without loss of generality, all individuals can be assumed to participate in maintenance activities. On the other hand, an individual can participate in none, or one, or more of IH discretionary and 5 OH discretionary activity purposes (p) identified above. If (s)he chooses to participate in OH discretionary activities, (s)he can do so during one or more of the 6 time periods (t), and access the activities using one or more of the 2 travel modes (m). Thus, there is multiple discreteness in the choices across the activity purpose, activity timing, and travel mode dimensions.

² To distinguish the satiation along OH discretionary activity purpose, activity timing, and travel mode dimensions (and to facilitate estimation), γ_{ptm} ($ptm = 3, 4, \dots, 62$) is parameterized as $\gamma_{ptm} = \gamma_p \times \gamma_t \times \gamma_m$, where $\gamma_p, \gamma_t, \gamma_m$, are the estimated dimension-specific satiation parameters.

corresponding to the first alternative (maintenance activity) as it is always chosen by all individuals.

Finally, let each of the 60 OH discretionary activity episode types (ptm) be defined (by its purpose-timing-mode (ptm) combination) such that an individual participates in no more than one episode of that type in a day. Consequently, if an individual chooses to undertake an activity episode type (ptm), it has to be at only one of the several destination alternatives (l) available to her/him.

Let the index for the activity destination (or location) be l , and let N_{ptm} be the set of destinations available for an activity episode type (ptm). Further, for each activity episode type (ptm), let ψ_{ptm} be defined as follows (Bhat *et al.*, 2006):

$$\psi_{ptm} = \exp\left(\sum_{l \in N_{ptm}} \delta_{lptm} W_{lptm}\right), \quad (2)$$

where, W_{lptm} is the utility perceived by the individual for undertaking the OH discretionary activity episode of purpose p , during time period t , by traveling on mode m to location l , and δ_{lptm} is a dummy variable taking a value of 1 if the l^{th} location is chosen for that activity episode such that $\sum_{l \in N_{ptm}} (\delta_{lptm}) = 1$ (*i.e.*, only one location is chosen).

With the above definition of ψ_{ptm} and other terms described earlier, the individual is assumed to maximize the utility function $U(\mathbf{x})$ in Equation (1) subject to $x_1 + x_2 + \sum_{ptm} x_{ptm} = X$; $x_1 > 0$, $x_2 \geq 0$, $x_{ptm} \geq 0 \forall ptm = 3, 4, \dots, 62$. Since the individual maximizes $U(\mathbf{x})$ and can choose only one location for each activity episode ptm type, the functional form of $U(\mathbf{x})$ implies that the individual will consider the location that provides the maximum utility for each activity episode ptm type in the process of maximizing $U(\mathbf{x})$ (see Bhat *et al.*, 2009). That is,

$$\sum_{l \in N_{ptm}} \delta_{lptm} W_{lptm} = \max_{l \in N_{ptm}} W_{lptm}, \text{ or } \psi_{ptm} = \exp\left(\max_{l \in N_{ptm}} W_{lptm}\right) \text{ Thus, the individual's utility maximizing}$$

problem can be written as:

$$U(\mathbf{x}) = \{\psi_1 \ln x_1\} + \left\{ \gamma_2 \psi_2 \ln \left(\frac{x_2}{\gamma_2} + 1 \right) \right\} + \sum_{ptm} \left\{ \gamma_{ptm} \exp\left(\max_{l \in N_{ptm}} W_{lptm}\right) \ln \left(\frac{x_{ptm}}{\gamma_{ptm}} + 1 \right) \right\} \quad (3)$$

subject to $x_1 + x_2 + \sum_{ptm} x_{ptm} = X$; $x_1 > 0$, $x_2 \geq 0$, $x_{ptm} \geq 0 \forall ptm$.

The analyst can solve for the optimal values of x_1, x_2 , and x_{ptm} by forming the Lagrangian and applying the Kuhn-Tucker (KT) conditions. Specifically, the following KT conditions can be formed (see Bhat, 2008):

$$H_2 = H_1 \text{ if } x_2 > 0 \quad (4)$$

$$H_2 < H_1 \text{ if } x_2 = 0$$

$$H_{ptm} = H_1 \text{ if } x_{ptm} > 0$$

$$H_{ptm} < H_1 \quad \text{if } x_{ptm} = 0$$

where,

$$H_1 = \ln(\psi_1) - \ln(x_1),$$

$$H_2 = \ln(\psi_2) - \ln\left(\frac{x_2}{\gamma_2} + 1\right), \text{ and}$$

$$H_{ptm} = \max_{l \in N_{ptm}} W_{lptm} - \ln\left(\frac{x_{ptm}}{\gamma_{ptm}} + 1\right)$$

2.2 Econometric Structure

To complete the model specification, let $\psi_1 = \exp(\beta'z_1 + \varepsilon_1)$ and $\psi_2 = \exp(\beta'z_2 + \varepsilon_2)$, where $\beta'z_1$ and $\beta'z_2$ are the observed baseline utility components of maintenance and IH discretionary activities, respectively, and ε_1 and ε_2 are the corresponding unobserved components assumed to be independent and identically Gumbel distributed. Further, to define ψ_{ptm} , we expand W_{lptm} as:

$$W_{lptm} = \beta'z_{ptm} + \phi'w_{lptm} + \eta_{lptm} \quad (5)$$

where, $\beta'z_{ptm}$ is the observed baseline utility corresponding to the activity purpose, timing, and mode of the OH discretionary activity episode ptm , $\phi'w_{lptm}$ is the observed utility corresponding to the potential location l for the activity episode, and η_{lptm} is the unobserved utility component associated with the location l of activity episode ptm . Similar to ε_1 and ε_2 , the η_{lptm} terms are assumed to be independent and identically distributed (across different activity episode ptm types) Gumbel terms. Within each activity episode ptm type, however, all of the error terms may share common unobserved attributes (specific to the activity episode ptm type) generating correlations among the η_{lptm} terms across all potential locations for the activity episode. Thus, for each activity episode ptm type, the following distribution of error terms may be used:

$$F(\eta_{1ptm}, \eta_{2ptm}, \dots, \eta_{Lptm}) = \exp\left\{-\left[e^{-\eta_{1ptm}/\theta_{ptm}} + e^{-\eta_{2ptm}/\theta_{ptm}} + \dots + e^{-\eta_{Lptm}/\theta_{ptm}}\right]^{\theta_{ptm}}\right\} \quad (6)$$

where the θ_{ptm} is the dissimilarity parameter indicating the level of correlation among the η_{lptm} terms across all the potential locations for the activity episode ptm combination. Given this error distribution, using the properties of Gumbel distribution, H_{ptm} in Equation (4) can be expressed as:

$$\begin{aligned} H_{ptm} &= \max_{l \in N_{ptm}} \left\{ \beta'z_{ptm} + \phi'w_{lptm} + \eta_{lptm} \right\} - \ln\left(\frac{x_{ptm}}{\gamma_{ptm}} + 1\right) \\ &= \beta'z_{ptm} + \theta_{ptm} \ln \sum_{l \in N_{ptm}} \exp\left(\frac{\phi'w_{lptm}}{\theta_{ptm}}\right) + \zeta_{ptm} - \ln\left(\frac{x_{ptm}}{\gamma_{ptm}} + 1\right) \end{aligned} \quad (7)$$

where, ζ_{ptm} is a standard independent and identically distributed (across ptm) Gumbel error term.

In this equation, $\ln \sum_{l \in N_k} \exp\left(\frac{\phi' w_{lk}}{\theta_k}\right)$ constitutes the logsum term.

Next, following the MDCEV model derivations (see Bhat, 2008), the probability that the individual chooses the first Q out of K ($=62$) activity purpose-timing-mode alternatives (this may include maintenance as well as the IH discretionary activities without any timing and mode distinctions) for time investments $x_1^*, x_2^*, \dots, x_Q^*$ may be written as:

$$P(x_1^*, x_2^*, \dots, x_Q^*, 0, 0, \dots, 0) = \left[\prod_{k=1}^Q r_k \right] \left[\sum_{k=1}^Q \frac{1}{r_k} \right] \left[\frac{\prod_{k=1}^Q e^{V_k}}{\left(\sum_{h=1}^K e^{V_h} \right)^Q} \right] (Q-1)!, \quad (8)$$

where³

$$r_1 = \left(\frac{1}{x_1^*} \right) \text{ and } r_k = \left(\frac{1}{x_k^* + \gamma_k} \right) \forall k > 1$$

$$V_1 = \beta' z_1 - \ln(x_1),$$

$$V_2 = \beta' z_2 - \ln\left(\frac{x_2}{\gamma_2} + 1\right), \text{ and}$$

$$V_k = \beta' z_k + \theta_k \ln \sum_{l \in N_k} \left(\frac{\phi' w_{lk}}{\theta_k} \right) - \ln\left(\frac{x_k}{\gamma_k} + 1\right); \forall k > 2$$

The conditional probability that location l will be chosen for an activity episode purpose-timing-mode (ptm) combination k , given that $x_k^* > 0$, is given by:

$$P(l | x_k^* > 0; l \in N_k) = P[\phi' w_{lk} + \eta_{lk} > \phi' w_{l'k} + \eta_{l'k} \forall l' \neq l] \quad (9)$$

Based on the multivariate Gumbel distribution function for the η_{lk} (or η_{lptm}) terms ($l = 1, 2, \dots, L$) from Equation (6), the above probability expression can be computed using the following standard multinomial logit formula:

$$P(l | x_k^* > 0; l \in N_k) = \frac{\exp\left(\frac{\phi' w_{lk}}{\theta_k}\right)}{\sum_{l' \in N_k} \exp\left(\frac{\phi' w_{l'k}}{\theta_k}\right)} \quad (10)$$

³ Note that the notation for the subscripts of the choice alternatives has been changed to k ($=1, 2, \dots, 62$) from $1, 2, ptm$ ($=3, 4, \dots, 62$) for convenience.

Next, the unconditional probability that the individual spends x_1^* amount of time in daily maintenance activities, x_2^* amount of time in daily IH-discretionary activities, x_3^* amount of time in OH discretionary activity episode purpose-timing-mode (*ptm*) combination 3 (*i.e.*, $k=3$) at location a , x_4^* amount of time in OH discretionary activity episode purpose-timing-mode (*ptm*) combination 4 (*i.e.*, $k=4$) at location b , ... and so on, may be written as:

$$\begin{aligned} & P(x_1^*, x_2^*, x_3^* \text{ at } a, x_4^* \text{ at } b, \dots, x_Q^* \text{ at } q, 0, 0, 0, \dots, 0) \\ & = P(x_1^*, x_2^*, \dots, x_Q^*, 0, 0, \dots, 0) \times P(a | x_3^* > 0) \times P(b | x_4^* > 0) \dots P(q | x_Q^* > 0) \end{aligned} \quad (11)$$

2.3 Sampling of Location Choice Alternatives

A practical issue with the proposed MDCEV-MNL model (as also with the deeply nested logit approach) is that, since there can be a large number of location choice alternatives at the single discrete choice level (and since multiple single discrete choice models may be invoked), the model estimation can be highly computation intensive. To reduce the computation time, the analyst can include only a smaller sample of the location choice alternatives (with the chosen alternative in the sample) during estimation. According to McFadden (1978), random sampling of alternatives will not compromise the consistency of the location choice model parameters as long as a simple multinomial logit modeling framework is maintained for the location choice as in Equation (10).⁴ However, sampling the location choice alternatives warrants a correction to

the log-sum term $\ln \sum_{l \in N_k} \exp\left(\frac{\phi' w_{lk}}{\theta_k}\right)$ used in the MDCEV component of the joint model (see

Equation 7). This is because, in this term, the sum of exponentials of the utilities (scaled by the

dissimilarity parameter) of all the location choice alternatives $\sum_{l \in N_k} \exp\left(\frac{\phi' w_{lk}}{\theta_k}\right)$ is not equal to the

sum of exponentials of the utilities of a sample of those alternatives. This is corrected by incorporating a scaling factor (π_k) that is equal to the total number of available location choice alternatives divided by the number of sampled alternatives. Since location choice alternatives are sampled randomly, and since the random sample varies across individuals and activity purpose-timing-mode (*ptm*) combinations, this scaling factor should help approximate the logsum term reasonably well. That is:

$$\ln \left(\pi_k \sum_{l \in \text{a random sample of } N_k} \exp\left(\frac{\phi' w_{lk}}{\theta_k}\right) \right) \approx \ln \sum_{l \in N_k} \exp\left(\frac{\phi' w_{lk}}{\theta_k}\right) \quad (12)$$

⁴ The reader will note here that Equation (10) is derived from a nested extreme value error term distribution as in Equation (6). However, since this distribution assumes the same scale parameter for all location choice alternatives associated with the activity episode *ptm* type, the location choice parameters will be consistent. In essence, as long as the error distributions do not allow different scale parameters across the location choice alternatives associated with an activity episode *ptm* type (*i.e.*, to accommodate spatial correlations, *etc.*) and no random coefficients are estimated in the location choice model, one can use a random sample of location choice alternatives to consistently estimate the model parameters. See Bierlaire *et al.* (2008) for more details on sampling related issues with multi-dimensional choice models.

In this study, 30 location choice alternatives are randomly sampled from 1099 potential locations yielding, $\pi_k = 36.63$.

2.4 An Intuitive Behavioral Interpretation

The probability expression in Equation (11) is a combination of MDCEV and single discrete choice probabilities. Specifically, for each OH discretionary activity episode purpose-timing-mode (*ptm*) combination chosen by an individual, a single discrete choice model of location choice is invoked. The parameters ϕ and θ_k appear in both the MDCEV probability expression (Equation 8) as well as the standard discrete choice probability expression for the choice of activity location (Equation 10) to create jointness between the multiple discrete-continuous and single discrete choices. Further, the logsum term (see Equation 7) appearing in the MDCEV probability expression carries the accessibility of destinations (or potential locations) from the single discrete location choice model to the MDCEV model of time investment by activity purpose, timing, and travel mode. Thus, Equation (11) represents a unified and comprehensive model of activity-travel program generation that incorporates the influence of accessibility measures on activity time-use, timing, and mode choices.

The proposed two-level MDCEV-MNL model is an attractive alternative to the deeply nested logit modeling approach available in the literature, where accessibility measures have to propagate up to the activity generation level through multiple levels of a deeply nested logit model. Further, the MDCEV-MNL model provides a seamless way of incorporating time-use (and the impact of accessibility on time-use) into the framework. Specifically, the modeling framework explicitly accommodates the concept that individual's activity time-use (*i.e.*, time allocation) decisions are important and influential components of their activity-travel decision-making (Bhat and Koppelman, 1999). On the other hand, the deeply nested logit approach does not explicitly incorporate activity time-allocation choices into the analysis framework in a straight forward manner. Another appealing feature is that the model recognizes the simultaneity of the activity time-use, timing, mode choice, and location choice decisions within a unified utility maximization framework.

3. DATA DESCRIPTION

The data set used in this paper is derived from the 2000 San Francisco Bay Area Travel Survey (BATS), designed and administered by MORPACE International Inc. for the Bay Area Metropolitan Transportation Commission (MTC). The data includes information on: (1) Individual and household socio-demographics for over 15,000 households in the Bay Area, and (2) All activity episodes (including activity type, start and end times of the activity, geo-referenced location of activity participation, and mode of travel to the activity) undertaken by the individuals in all surveyed households for a two-day period.

The travel survey records were augmented extensively with several secondary data items, including land-use characteristics, transportation network level-of-service data, and Census population and housing data. In addition, geo-referenced data on businesses, bicycle facilities, highways and local roads were used to derive spatial variables characterizing the activity-travel environment (ATE) in and around the household locations of the individuals in the data set. Details regarding the data preparation and augmentation processes can be found in Guo and Bhat (2004) and Pinjari *et al.* (2009).

As mentioned in the previous section, the activity choice dimensions modeled in this paper include activity type choice, activity time of day choice, travel mode choice, activity

location (destination) choice, and activity time use allocation (duration)⁵. The MDCEV model component alternatives are formed as combinations of activity type, time of day, and travel mode while the duration of each activity episode constitutes the continuous dependent variable. Finally, the MNL module accommodates the activity location or destination choice. There are: (a) a maintenance activity type, (b) an in-home discretionary activity type, and (c) five out-of-home discretionary activity types, six time periods, and two travel modes, yielding a total of 62 possible MDCEV choice alternatives ($2 + 5 \times 6 \times 2 = 62$). It is to be noted that the activity timing and travel mode analysis is limited to the five out-of-home discretionary activity types.

In order to control for fundamental differences between workers and non-workers in their activity engagement patterns and choice processes, and in the interest of brevity, the analysis in this paper was restricted to the sample of 5,360 non-working individuals (includes employed individuals not reporting to work on the survey day) aged 16 years or above. Descriptive statistics for this sample of individuals are presented in Table 1. All 5,360 individuals participate in in-home maintenance for an average duration of nearly 11 hours. Forty percent engage in in-home discretionary activities for an average duration of about 5.5 hours. Note that the average durations are computed over those who actually participate in the activity type. A little over one-half of the sample participated in OH discretionary activities, for an average duration of about 2.5 hours. It is found that the automobile mode is the preferred and dominant mode of travel accounting for nearly 90 percent of all out-of-home discretionary activity engagement. Non-maintenance shopping shows a relatively high participation rate, but lower time allocation (regardless of mode), while activities such as meals, socializing, and recreation show lower participation rates but higher time allocation. Across the top of the table (in the grey shaded row), it is seen that only a very small percent of individuals participate in OH discretionary activities in the early morning, and the percentage steadily rises into the afternoon, and then shows a decline towards the night hours. Activities undertaken in the morning and early morning, however, show the longest average durations relative to those in the afternoon and evening, potentially indicating the effect of time constraints that might get tighter towards the latter half of the day. Overall, this table shows the interplay among the dimensions of activity-travel participation that merit a unified approach towards modeling these behavioral characteristics.

4. EMPIRICAL ANALYSIS

4.1 Model Specification and Estimation Results

Model estimation was performed using Gauss code written specifically to estimate the joint MDCEV-MNL model system. Although it would have been ideal to estimate a separate destination choice model for each of the 60 OH discretionary activity purpose-timing-mode (*ptm*) combination categories, for this initial effort, a single MNL location choice model was estimated for all discretionary activity *ptm* categories. However, extending the estimation process to incorporate 60 MNL models of destination choice is straightforward by specifying dimension-specific model coefficients; the model specification here is one in which all destination choice model coefficients are restricted to be identical across all activity purpose categories, timing categories, and mode categories. Several variables were included in the model specification including household and personal socio-economic and demographic variables,

⁵ In the current study, individual time budget required in the MDCEV model is specified as (24 hours – individual's sleep activity duration).

contextual variables such as day of week and season of the year, and a host of spatial variables characterizing the activity-travel environment (ATE) around the household locations, not to mention several transportation network level of service variables. The spatial ATE variables included density measures, activity opportunity and accessibility measures, and population and housing data for the neighborhood (traffic analysis zone). The ATE measures were considered at the level of the traffic analysis zone and at finer spatial resolutions, including within 0.25 mile, 1 mile, and 5 mile radii buffers of the household location (see Guo and Bhat, 2004 and Pinjari *et al.*, 2009 for complete details).

In the current research effort, a comparison was made between the joint MDCEV-MNL model that integrates destination choice with activity choices and an independent MDCEV-MNL model that does not incorporate the log-sum parameters in the MDCEV component. The goodness of fit of the two models were compared using the Bayesian Information Criterion (BIC), which is given by the expression $-2 \times \ln(L) + \text{number of parameters} \times \ln(Q)$, where $\ln(L)$ is the log-likelihood value at convergence and Q is the number of observations. The model that results in the lower BIC value is the preferred model. The BIC value for the MDCEV-MNL model (with 103 model parameters) is 150514.2, which is considerably lower than that for the independent MDCEV-MNL model (152334.2 with 102 model parameters). Thus, the BIC suggests that the simultaneous MDCEV-MNL model of integrated activity choices and destination choice provides a superior statistical fit than the independent MDCEV-MNL model that ignores endogeneity arising from the presence of common unobserved attributes that simultaneously influence multiple choice dimensions.

The discussion in this paper is limited to the results of the joint MDCEV-MNL model. The MDCEV component is specified (and the results are presented) in such a way that the effect of each variable is first identified separately along the activity purpose, activity timing and travel mode dimensions. Subsequently, any interaction effects of the variable over and above the uni-dimensional effects are identified. A blank entry corresponding to the effect of a variable indicates no significant effect of the variable on the integrated choice process. Further, the effects of variables on the baseline utilities have been constrained to be equal if coefficient equality could not be rejected based on statistical tests. Finally, t-statistics are presented in parentheses. The final specification of the MDCEV component of the model is presented in Tables 2. In the interest of brevity, and considering the large number of alternatives (62), tables showing estimates of baseline preference constants and satiation parameters are not furnished here.

Overall, the model results show indications as expected. Larger household sizes are associated with greater levels of participation in maintenance activities (in and out of home), while single persons are more prone to out-of-home socializing and recreation in the evening. The presence of very young kids motivates activity engagement in the prime period of the day as opposed to early mornings and late nights, although those with school age children are more restricted to pre- and post-school hours. The number of working adults contributes negatively to activity engagement in the middle of the day, presumably due to work constraints. Lower income individuals are more prone to in-home discretionary activities, while higher income individuals are prone to undertake out-of-home activities, consistent with expectations. Higher levels of car ownership contribute negatively to in-home activity participation and non-auto mode use.

Females are more likely to engage in volunteering and maintenance activities, particularly in the midday period, confirming the role of gender differences in activity engagement. Younger individuals are likely to socialize in the evening and night, while older individuals (65+ years) are more likely to volunteer and not undertake night activities. Those

who are licensed to drive have a greater propensity for out-of-home activities, while the reverse is true for those physically disabled. Employed individuals engage less in maintenance activities and in-home discretionary activities, even on days that they do not work (this analysis was limited to non-working days for all 5,360 individuals, whether they are employed or not). Fridays are associated with greater out-of-home discretionary activity participation, and night time activities. On rainy days, it is less likely that individuals will eat out using non-auto modes. Population density contributes positively to out-of-home meals, shopping by non-auto mode, possibly because such areas are better served by transit and have better walk and bicycle access to destinations. Overall, the findings are consistent with expectations and consistent with those found earlier by Pinjari and Bhat (2010).

The estimation results for the destination choice model are presented in Table 3. The destination choice model component was estimated with 30 randomly sampled choice alternatives for each location choice decision. The effects of transportation network level of service, built environment, and demographic interaction terms were represented in the final model specification. Auto travel times and costs decrease the utility associated with choosing a destination for any activity type. The presence of bicycle lanes, total employment, the size of the zone, and zonal household income positively impact destination choice for discretionary activities while retail and service employment, increasing fraction of land devoted to residential uses in the zone, and accessibility to passive and natural recreation contribute negatively to destination choice for the activity categories considered in this paper. The long list of interaction terms demonstrates how household and personal socio-economic and demographic characteristics play a key role in influencing destination choice for discretionary activities undertaken outside home. In the interest of brevity, a detailed explanation is not provided here, but suffice to say that all of the interaction terms included in the model specification are highly significant and indicate that household socio-economic and demographic characteristics serve to moderate or enhance the likelihood of choosing a certain type of destination for activity engagement. For example, females are more prone to choosing destinations with high density of eat-out centers, as are older people and higher income individuals. Those with kids and in larger households are less prone to choose zones with high household density as destinations, presumably because they prefer more open space and suburban locations to accommodate family activities.

The logsum parameters (θ_{ptm}) estimated for each activity purpose, timing, and travel mode combination were not statistically different from unity. In the final model estimation, all logsum parameters were restricted equal to one. This implies the absence of common unobserved factors across all location choice alternatives specific to an activity type, timing, and mode combination.

Although the log-sum parameter estimates do not indicate significant correlation among unobserved factors across the destination choice alternatives, the MDCEV-MNL model is formulated such that the expected maximum utility values from the MNL alternatives appear in the utility functions of the MDCEV alternatives through the log-sum variables. This enables the upper-level choices (*i.e.*, the activity type, duration, timing, and mode choices) to be sensitive to level-of-service and land-use attributes, and helps capture the impacts of policies on different dimensions of activity-travel behavior.

4.2 Policy Simulation

The major objective of this paper was to develop a unified model of activity-travel and location choices and time use that would allow one to examine the influence of level of service measures and activity-travel environment (ATE) attributes on these choice dimensions in an integrated manner. To demonstrate the capabilities of the model system presented in this paper, the model was used to examine the impacts of the following scenarios on activity and time use behavior:

- Doubling travel cost across all time periods
- Doubling travel cost during peak periods
- Doubling travel cost for auto mode
- Doubling travel time across all time periods
- Doubling travel time during peak periods
- Doubling travel time by auto mode

Logsum variables computed using the activity destination choice MNL model were used as explanatory variables in the MDCEV model to predict individual's participation in and time allocation to activities by activity purpose, timing, and mode. For each policy scenario, logsum variables were computed for all 60 OH discretionary activity purpose, timing, and mode combinations (for use in the base case prediction), and then updated for the specific timing or travel mode categories for which the policy applied (for the policy case prediction). The prediction using MDCEV was carried out for all individuals in the sample using 1000 replications of the error term draws for each individual. Additional details about the forecasting procedure using the MDCEV model are provided in Pinjari and Bhat (2009).

The forecasts under alternative scenarios are presented in Table 4. Specifically, the influence of each policy is reported as an aggregate percent change in the amount of time invested in maintenance activities, in-home discretionary activities, and out-of-home discretionary activities by purpose, time of day, and mode (relative to the base case).

In general, the results provide indications along expected lines. Increases in travel cost lead to reduced out-of-home activity engagement and slight increases in in-home activity engagement. Increases in travel cost during the peak period impact volunteer, eat-meal, and recreation activities more than others, and reduce peak period activity engagement while increasing off-peak activity engagement. Increases in auto travel costs and times reduce the use of auto mode for activity engagement and contribute to enhanced mode shares for non-auto modes. In general, travel time increases appear to have larger impacts than travel costs, suggesting that individuals are more time-sensitive when making activity-travel choices. In terms of the modal impact, it appears that all day travel cost or time increases have a greater impact than a time-specific peak-period travel cost or time increase. It appears that individuals are more likely to respond to price and time signals that cover an entire day as opposed to those that are narrower in the time band of influence. Overall, the policy simulation results clearly show that the model is effective in capturing the responses of individuals to system changes in a unifying framework.

5. CONCLUSIONS

This study aims to present a comprehensive unified model system of activity-travel choices that is consistent with microeconomic utility maximization theory of behavior. The activity-travel choice dimensions analyzed in this paper include activity type choice, time of day choice, mode choice, destination choice, and activity time allocation or duration. All discrete choices, except

for activity destination choice, and the continuous choice dimension of activity duration are modeled simultaneously using the multiple discrete continuous extreme value (MDCEV) model form while the destination choice is modeled using a classic multinomial logit model (MNL) component. The model components are tied together within a utility maximization-consistent framework using logsum variables that reflect the accessibility of destinations for each activity type, timing, and mode combination. Model estimation results and the policy simulation analysis showed that the joint model system has merit, offers behaviorally intuitive interpretation, and offers a goodness of fit statistically superior to that offered by an independent model system that treats various choice dimensions separately and sequentially. The model specifications included built environment and transportation network level of service attributes demonstrating the impact of these variables on activity-travel dimensions. The model system is presented for a non-worker sample drawn from the 2000 San Francisco Bay Area Travel Survey (BATS). The efficacy of the model system presented in the current paper is demonstrated through a host of policy scenarios. These policy scenario evaluations clearly indicate how changes in activity location specific attributes and level-of-service attributes influence activity participation decisions. One of the key empirical findings of this analysis is that the built environment and transportation network level of service attributes of the destinations significantly impact activity time use allocation, an aspect that is often overlooked in the literature.

The model form adopted in this paper has key implications for activity-travel demand model development. It appears that the findings reported here support the notion that individuals make several contemporaneous activity-travel choices jointly as a “bundle”, calling for the simultaneous modeling of various choice dimensions in a unifying framework. Activity-travel model systems that purport to simulate the behavior of agents along the time axis may benefit from the adoption of model forms that are able to simultaneously predict multiple choice dimensions as a “bundle”. Ignoring to do so may yield erroneous policy scenario predictions.

The current study may be enhanced further by estimating dimension-specific (*i.e.*, activity purpose-, timing-, and mode-specific) coefficients for transportation network level of service measures and activity-travel environment attributes in the location choice models. In addition, one needs to note that the policy forecasts provided by the MDCEV model are potentially restrictive in that the total time allocation (budget constraint) is assumed constant across all policy scenarios (there is simply a reallocation of time across activity categories, but maintaining total time expenditure for all activity categories considered constant). Overcoming this limitation is another direction for future research.

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REFERENCES

- Arentze, T.A., and H.J.P. Timmermans. (2005) Albatross Version 2: A Learning-Based Transportation Oriented Simulation System. European Institute of Retailing and Services Studies, Eindhoven, The Netherlands.
- Ben-Akiva, M., and Lerman, S. R. (1985) *Discrete Choice Analysis: Theory and Application to Travel Demand*, Cambridge, Massachusetts: MIT Press.
- Bhat, C.R. (2005) A Multiple Discrete-Continuous Extreme Value Model: Formulation and Application to Discretionary Time-Use Decisions. *Transportation Research Part B*, 39(8), 679-707.
- Bhat, C.R. (2008) The multiple discrete-continuous extreme value (MDCEV) model: role of utility function parameters, identification considerations, and model extensions. *Transportation Research Part B*, 42(3), 274-303.
- Bhat, C.R., and F.S. Koppelman (1999) A retrospective and prospective survey of time-use research. *Transportation* 26(2), 119-139.
- Bhat, C.R., S. Sen, and N. Eluru (2009) The Impact of Demographics, Built Environment Attributes, Vehicle Characteristics, and Gasoline Prices on Household Vehicle Holdings and Use. *Transportation Research Part B*, 43(1), 1-18.
- Bhat, C.R., S. Srinivasan, and S. Sen (2006) A Joint Model for the Perfect and Imperfect Substitute Goods Case: Application to Activity Time-Use Decisions. *Transportation Research Part B*, Vol. 40, No. 10, 827-850.
- Bierlaire, M., D. Bolduc, and D. McFadden (2008) The Estimation of Generalized Extreme Value Models from Choice-based Samples. *Transportation Research Part B*, 42(4), 381-394.
- Bowman, J. (1995) Activity Based Disaggregate Travel Demand Model System with Daily Activity Schedules. MS Thesis in Transportation, Massachusetts Institute of Technology.
- Bowman, J.L., and M. A. Bradley (2006) Upward Integration of Hierarchical Activity-based Models. Working paper.
<http://www.jbowman.net/papers/20060117%20Bowman%20and%20Bradley.pdf>
- Guo, J.Y., and C.R. Bhat (2004) Modifiable areal units: problem or perception in modeling of residential location choice? *Transportation Research Record* 1898, 138-147.
- Jara-Diaz, S.R., M. Munizaga, P. Greeven, and R. Guerra (2007) The unified expanded goods-activities-travel model: theory and results. Paper presented at the 11th World Conference on Transport Research, Berkeley, June 24-28.
- McFadden, D. (1978) Modelling the choice of residential location. In A. Karlquist (ed.) *Spatial Interaction Theory and Residential Location*, North-Holland, Amsterdam, pp. 75-96.
- Meloni, I., L. Guala, and A. Loddo (2004) Time allocation to discretionary in home, out of home activities and to trips. *Transportation*, 31(1), 69-96.
- Miller, E.J. and M.J. Roorda (2003) A prototype model of activity scheduling. *Transportation Research Record* 1831, 114-121.
- PB Consult (2005) The MORPC Travel Demand Model: Validation and Final Report. The Mid-Ohio Regional Planning Commission, Columbus, Ohio.
- Pinjari, A.R., and C.R. Bhat (2009) An Efficient Forecasting Procedure for Kuhn-Tucker Consumer Demand Model Systems: Application to Residential Energy Consumption Analysis. Technical paper, Department of Civil & Environmental Engineering, University of South Florida.

Pinjari, A.R., and C.R. Bhat (2010) A Multiple Discrete-Continuous Nested Extreme Value (MDCNEV) Model: Formulation and Application to Non-Worker Activity Time-Use and Timing Behavior on Weekdays. *Transportation Research Part B*, 44(4), 562-583.

Pinjari, A.R., C.R. Bhat, and D.A. Hensher (2009) Residential Self-Selection Effects in an Activity Time-use Behavior Model. *Transportation Research Part B*, 43(7), pp. 729-748.

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Table 1 Descriptive Statistics of Activity Participation and Time-Use by Activity Purpose, Activity Timing and Travel Mode^a

| | | ACTIVITY TIMING | | | | | |
|---|---|--------------------------------------|---------------------------|----------------------------|---------------------------|---------------------------|---------------------------|
| | | Early Morning (3am-7am) | Morning (7am-9am) | Late Morning (9am-12pm) | Afternoon (12pm-4pm) | Evening (4pm-7pm) | Night (7pm-3am) |
| ACTIVITY PURPOSE and TRAVEL MODE | Number (%) of non-workers participating, and mean duration of participation among those participating | 63 (2.3%) ^b 140 min | 382 (13.9%) 169 min | 1131 (41.1%) 121 min | 1257 (45.7%) 97 min | 720 (26.2%) 103 min | 371 (13.5%) 111 min |
| Maintenance | 5360 (100%) 651 min | -- | -- | -- | -- | -- | -- |
| IH Discretionary | 2133 (39.8%) 341 min | -- | -- | -- | -- | -- | -- |
| OH Discretionary | 2752 (51.3%) 163 min | -- | -- | -- | -- | -- | -- |
| OH Discretionary Auto mode | 2473 (89.9%) 158 min | | | | | | |
| Volunteering | 396 (14.4%) ^c 149 min | 4 (1.0%) ^d | 81 (20.5%) | 137 (34.6%) | 89 (22.5%) | 72 (18.2%) | 63 (15.9%) |
| Socializing | 508 (18.5%) 128 min | 6 (1.2%) | 20 (3.9%) | 125 (24.6%) | 159 (31.3%) | 97 (19.1%) | 77 (15.2%) |
| Meals | 809 (29.4%) 115 min | 13 (1.6%) | 90 (11.1%) | 206 (25.5%) | 270 (33.4%) | 223 (27.6%) | 84 (10.4%) |
| Non-Maintenance Shopping | 1092 (39.7%) 60 min | 4 (0.4%) | 46 (4.2%) | 372 (34.1%) | 571 (52.3%) | 175 (16.0%) | 53 (4.9%) |
| Recreation | 738 (26.8%) 145 min | 33 (4.5 %) | 116 (15.7%) | 256 (34.7%) | 200 (27.1%) | 115 (15.6%) | 88 (11.9%) |
| OH Discretionary Non Auto mode | 432 (15.7%) 134 min | | | | | | |
| Volunteering | 37 (1.3%) 170 min | 2 (5.4%) | 9 (24.3%) | 10 (27.0%) | 8 (21.6%) | 3 (8.1%) | 6 (16.2%) |
| Socializing | 72 (2.6%) 140 min | 0 (0.0%) | 3 (4.2%) | 19 (4.2%) | 27 (37.5%) | 21 (29.2%) | 4 (5.6%) |
| Meals | 135 (4.9%) 119 min | 1 (0.7%) | 9 (6.7%) | 35 (25.9%) | 54 (40.0%) | 25 (18.5%) | 18 (13.3%) |
| Non-Maintenance Shopping | 132 (4.8%) 59 min | 0 (0.0%) | 4 (3.0%) | 50 (37.9%) | 62 (47.0%) | 12 (9.1%) | 6 (4.5%) |
| Recreation | 131 (4.8%) 136 min | 1 (0.8%) | 14 (10.7%) | 52 (39.7%) | 33 (25.2%) | 32 (24.4%) | 6 (4.6%) |

^a The reader will note here that the average time investments reported in this table are for only those who participated in the corresponding activity purpose or for those who participated in OH discretionary activities during the corresponding time period. Also, the activity participation percentages across all activity purposes (or across all time periods, or modes) may sum to more than 100% because of multiple discreteness (*i.e.*, participation in multiple activity purposes and/or during multiple time periods and/or travel by multiple modes over a day). For example, a non-worker can undertake both OH recreation and OH meal activities on a day.

^b Percentages in this row are out of the 2752 non-workers who participated in at least one OH discretionary activity during the day.

^c Percentages in this column, from this row onward, are out of the 2473 non-workers who traveled by auto mode for at least one OH discretionary activity during the day.

^d Percentages from this row and column onward (within this block of rows) are based on total number of non-workers participating in row activity purpose $[(4/396) \times 100 = 1.0\%]$.

Table 2 The MDCEV Model Results: Baseline Parameter Estimates

| | Household (HH) Socio-demographics | | | | | | | | |
|--|--|------------------|----------------------------|------------------------------|-------------------------------|---|------------------------|------------------------|---------------------|
| | HH size | Single member HH | Kids of age <5 yrs present | Kids of age 5-15 yrs present | Number of kids of age <15 yrs | # of adults in HH who worked on the day | HH annual income < 45k | HH annual income >100k | # of vehicles in HH |
| <u>'Activity Purpose' Dimension</u> | | | | | | | | | |
| IH and OH Maintenance | 0.071 (3.74) | - | - | - | - | - | - | - | - |
| IH Discretionary | - | - | - | - | - | - | 0.168 (2.92) | - | -0.061 (-1.89) |
| OH Volunteering | - | - | - | - | - | - | - | - | - |
| OH Socializing | - | 0.420 (3.73) | - | - | - | - | - | 0.169 (3.61) | - |
| OH Recreation | - | - | - | - | - | - | - | 0.169 (3.61) | - |
| OH Meals | - | - | - | - | - | - | - | 0.169 (3.61) | - |
| OH Non-Maintenance Shopping | - | - | - | - | - | - | - | 0.169 (3.61) | - |
| <u>'Activity Timing' Dimension</u> | | | | | | | | | |
| Early Morning | - | - | - | - | - | - | - | - | - |
| Morning | - | - | 0.125 (1.77) | 0.297 (2.10) | - | - | - | - | - |
| Late Morning | - | - | 0.125 (1.77) | - | - | -0.170 (-4.43) | - | - | - |
| Afternoon | - | - | 0.125 (1.77) | - | - | -0.170 (-4.43) | - | - | - |
| Evening | - | - | 0.125 (1.77) | 0.428 (3.88) | - | - | - | - | - |
| Night | - | - | - | - | - | - | - | - | - |
| <u>'Travel Mode' Dimension</u> | | | | | | | | | |
| Auto mode | - | - | - | - | - | - | - | - | - |
| Non-auto mode | - | - | - | - | - | - | - | - | -1.190 (-31.90) |
| <u>Interactions</u> | | | | | | | | | |
| OH Recreation – Evening | - | 0.363 (3.53) | - | - | - | - | - | - | - |
| OH Recreation – Non-auto | - | - | - | - | - | - | - | 0.463 (2.11) | - |
| OH Meals - Non-auto | - | - | - | - | 0.154 (1.17) | - | - | - | - |
| OH Meals - Non-auto - Evening | - | - | - | - | -0.535 (-1.36) | - | - | - | - |

Table 2 (Continued) The MDCEV Model Results: Baseline Parameter Estimates

| | Individual Socio-demographics | | | | | | Contextual | | | ATE attributes | | | |
|--|-------------------------------|-----------------|-------------------|-------------------|---------------------|--------------------|-----------------|-------------------|-------------------|-------------------|--------------------|--------------------------|---------------------|
| | Female | Age < 30 yrs | Age > 65 yrs | Licensed to drive | Physically disabled | Employed | Friday | Fall | Rain | Retail employment | Population density | Total employment density | Density of highways |
| <u>'Activity Purpose' Dimension</u> | | | | | | | | | | | | | |
| IH and OH Maintenance | 0.315 (7.29) | - | - | - | - | -0.173 (-3.59) | - | - | - | - | - | - | - |
| IH Discretionary | - | - | - | - | - | -0.1263 (-1.98) | - | -0.105 (-1.98) | - | - | - | - | - |
| OH Volunteering | 0.350 (3.46) | - | 0.617 (6.51) | 0.743 (9.46) | -0.249 (-3.09) | - | - | - | - | - | - | - | - |
| OH Socializing | - | 0.467 (2.70) | - | 0.743 (9.46) | -0.249 (-3.09) | - | 0.242 (4.31) | - | - | - | - | - | - |
| OH Recreation | - | - | - | 0.743 (9.46) | -0.249 (-3.09) | - | 0.357 (4.14) | - | - | - | - | - | - |
| OH Meals | - | - | - | 0.743 (9.46) | -0.249 (-3.09) | - | 0.242 (4.31) | - | - | - | - | - | - |
| OH Non-Maintenance Shopping | - | - | - | 0.743 (9.46) | -0.249 (-3.09) | - | 0.242 (4.31) | - | - | - | - | - | - |
| <u>'Activity Timing' Dimension</u> | | | | | | | | | | | | | |
| Early Morning | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Morning | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Late Morning | 0.286 (5.10) | - | - | - | - | - | - | - | - | - | - | - | - |
| Afternoon | 0.286 (5.10) | - | - | - | - | - | - | - | - | - | - | - | - |
| Evening | - | 0.308 (1.85) | - | - | - | - | - | - | - | - | - | - | - |
| Night | - | 0.739 (4.78) | -0.482 (-3.70) | - | - | - | 0.404 (3.23) | - | - | - | - | - | - |
| <u>'Travel Mode' Dimension</u> | | | | | | | | | | | | | |
| Auto mode | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Non-auto mode | -0.220 (-2.92) | - | - | - | - | - | - | - | - | - | - | - | - |
| <u>'Interactions'</u> | | | | | | | | | | | | | |
| OH Non-Maintenance Shopping – Afternoon | - | - | - | - | - | - | - | - | - | -0.001 (-2.59) | - | - | - |
| OH activity Non-auto - Afternoon (except shopping) | - | - | - | - | - | 0.369 (1.91) | - | - | - | - | - | - | - |
| OH Meals - Non-auto | - | - | - | - | - | - | - | - | -0.263 (-0.85) | - | - | - | - |
| OH Meals, shopping -Non-auto | - | - | - | - | - | - | - | - | - | 0.016 (5.43) | - | - | - |
| OH Recreation - Non-auto | - | - | - | - | - | - | - | - | - | - | 0.006 (0.75) | - | - |
| OH Social, meals - Non-auto | - | - | - | - | - | - | - | - | - | - | - | -0.069 (-0.88) | - |

Table 3 MNL Component (Location Choice) Model Estimation Results

| Variable | Coefficient | t-stat |
|---|--------------------|---------------|
| LOS Measures | | |
| Auto peak travel time (in minutes) | -0.012 | -11.82 |
| Auto peak travel cost (in dollars) | -0.056 | -2.59 |
| ATE Attributes | | |
| Density of bicycle lanes | 0.129 | 7.75 |
| Retail employment | -0.005 | -5.70 |
| Service employment | -0.005 | -4.47 |
| Logarithm of Total employment | 0.405 | 29.06 |
| Fraction of residential land-use | -2.272 | -41.69 |
| Logarithm of zonal area | 0.056 | 5.44 |
| Mean zonal household income | 0.007 | 9.19 |
| Accessibility to passive and natural recreation | -0.364 | -2.92 |
| <u>Interaction with socio-demographics</u> | | |
| Density of bicycle lanes * age/100 | -0.110 | -4.84 |
| Density of bicycle lanes * Continuous income x 10 ⁻⁵ | 0.042 | 5.46 |
| Density of bicycle lanes * household vehicles | 0.025 | 4.94 |
| Density of eat-out centers * female | 0.003 | 3.26 |
| Density of eat-out centers * Continuous income x 10 ⁻⁵ | 0.010 | 13.31 |
| Density of eat-out centers * age/100 | 0.027 | 32.64 |
| Density of eat-out centers * household size | 0.014 | 28.96 |
| Density of eat-out centers * Own household | 0.002 | 2.17 |
| Logarithm of household population * age/100 | 0.102 | 6.42 |
| Logarithm of household population * household vehicles | 0.011 | 3.32 |
| Household density * No. of kids < 15yrs | -0.006 | -1.32 |
| Household density * household size | -0.001 | -0.36 |
| Household density * household vehicles | 0.009 | 3.41 |
| Accessibility to employment * household size | -0.003 | -6.25 |
| Accessibility to employment * Own household | 0.008 | 15.38 |

Table 4 Policy Simulation Results

| Alternatives | Activity Purpose | | | | | | | Activity Timing | | | | | | Travel Mode | |
|--|------------------|------------------|--------------|-----------|----------|-------------|---------------|-----------------|---------|--------------|-----------|---------|-------|-------------|----------|
| | Maintenance | IH Discretionary | OH Volunteer | OH Social | OH Meals | OH Shopping | OH Recreation | Early Morning | Morning | Late Morning | Afternoon | Evening | Night | Auto | Non-auto |
| Travel cost measure increased by 100% for all time periods | 0.01 | 0.02 | -0.99 | -1.00 | -0.84 | -0.91 | -0.93 | -0.92 | -0.90 | -0.92 | -0.96 | -0.92 | -0.87 | -1.00 | -0.75 |
| Travel cost measure increased by 100% for peak periods | 0.00 | 0.00 | -0.58 | -0.05 | -0.46 | 0.07 | -0.29 | 1.34 | -3.89 | 1.30 | 1.26 | -3.93 | 1.34 | -0.30 | -0.19 |
| Travel cost measure increased by 100% for auto mode | 0.01 | 0.01 | -1.16 | -1.21 | -0.27 | -0.31 | -0.83 | -0.77 | -0.75 | -0.69 | -0.64 | -0.68 | -0.76 | -2.10 | 2.48 |
| Travel time measure increased by 100% for all time periods | 0.04 | 0.06 | -3.36 | -3.40 | -2.86 | -3.09 | -3.18 | -3.11 | -3.07 | -3.13 | -3.26 | -3.13 | -2.95 | -3.39 | -2.57 |
| Travel time measure increased by 100% for peak periods | 0.01 | 0.02 | -1.88 | -0.15 | -1.53 | 0.22 | -0.95 | 4.41 | -12.70 | 4.22 | 4.12 | -12.83 | 4.37 | -0.99 | -0.64 |
| Travel time measure increased by 100% for auto mode | 0.03 | 0.04 | -3.85 | -3.99 | -0.95 | -1.05 | -2.73 | -2.54 | -2.51 | -2.30 | -2.12 | -2.27 | -2.54 | -7.03 | 8.34 |