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An activity-episode generation model that captures interactions between household heads: development and empirical analysis

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Abstract

In this paper, we develop an approach for modeling the daily number of non-work, out-of-home activity episodes for household heads that incorporates in its framework both interactions between such members and activity setting (i.e. independent and joint activities). Trivariate ordered probit models are estimated for the heads of three household types – couple, non-worker; couple, one-worker; and couple, two-worker households – using data from a trip diary survey that was conducted in the Greater Toronto Area (GTA) during 1987. Significant interactions between household heads are found. Moreover, the nature of these interactions is shown to vary by household type implying that decision-making structures and, more generally, household dynamics also vary by household type. In terms of predictive ability, the models incorporating interactions are found to predict more accurately than models excluding interactions. The empirical findings emphasize the importance of incorporating interactions between household members in activity-based forecasting models.

Keywords: Activity analysis; Activity generation; Household; Interactions; Joint activities; Travel behavior; Travel demand; Trivariate ordered probit model

1. Introduction

Since the late 1970s, the rapidly expanding literature subsumed under the activity-based paradigm has increased significantly our understanding of urban travel behavior and provided

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insights into new approaches to replace current models of urban travel demand – namely, the Urban Transportation Modeling System (UTMS). Unlike trip-based approaches, the activity-based paradigm, more commonly known as *activity analysis*, recognizes explicitly that travel is a demand derived from the need to participate in out-of-home activities. In other words, discrete activities or patterns of activities are investigated, not trips. Jones et al. (1990) identify several features of the paradigm including recognition that decision-making occurs in a household context, taking into account interactions among household members. This differs, however, from the reality of activity-based research to date.

With few exceptions, the decision-making unit in both empirical studies and modeling efforts is the individual, not the household. Obviously, this implies that few studies have investigated interactions among household members in terms of their activity-travel behavior. Of those that have, the importance of such interactions is clearly demonstrated. For example, the findings of Kostyniuk and Kitamura (1982) indicate that participation in joint out-of-home activities during the evening is quite common for some couples. Specifically, young couples without children and dual-earner couples in which both husband and wife work on a given day are oriented toward such activities. In a more recent study that employs a structural equations model to capture interactions between male and female household heads in terms of their participation in work, maintenance and discretionary activities, Golob and McNally (1997) find that male work activity governs interactions. Their study shows that an increase in such activity leads to an increase in female maintenance activity and travel and to a decrease in female discretionary activity and travel. Furthermore, the number of young children in the household is related to the substitution of work and maintenance activities between male and female household heads. Finally, Gliebe and Koppelman (2001) estimate a share model of daily time use in two-adult households that distinguishes between independent and joint activity participation. Their findings demonstrate the importance of employment levels and the presence of children on time allocation to such activities.

Despite the paucity of empirical research to date, there is convincing evidence which suggests that interactions among household members can no longer be ignored in the development of behaviorally sound, activity-based forecasting models (e.g. Gliebe and Koppelman, 2001; Golob and McNally, 1997; Kostyniuk and Kitamura, 1982). Moreover, from a pragmatic point of view, such household-level models (i.e. models that capture interactions among household members) are superior to those developed for individuals in that they offer potentially more accurate and reliable forecasts. Two reasons are suggested for this. First, individual-level models are incapable of handling complex responses to travel demand management (TDM) strategies. For example, a person who performs an activity during the evening commute may forgo the activity when working a compressed workweek. This response obviously favors the alternative work-schedule strategy. However, the individual-level model does not consider that this activity may be reassigned to another household member who also undertakes it after work. In this case, the TDM strategy would prove ineffective in reducing travel demand. Second, such models do not account for joint out-of-home activities. This means that predictions of activity-travel behavior are likely to be inaccurate. For example, multiple out-of-home activities may be predicted for household members when, in fact, only one exists.

To date, only Wen and Koppelman's model is developed at the household level, accounting explicitly for interactions among household members (cf. Wen and Koppelman, 1999, 2000). This is surprising given the fact that the household is incorporated conceptually in other activity-based forecasting models (e.g. Kitamura et al., 1996; Stopher et al., 1996). Wen and Koppelman postulate a decision-making process whereby households first generate out-of-home maintenance activities and then assign them to specific members for execution. They incorporate the number of such activity episodes in their modeling framework, which is a necessary prerequisite for forecasting models. Furthermore, they extend the household decision-making process to include the allocation of automobiles to household members, which is defined in terms of the number of activity episodes for which an automobile is available. A three-tier nested logit model is used to implement the modeling framework, which, despite its advances over previous research, still has two shortcomings. First, it is limited to couples that do not engage in out-of-home maintenance activities together, thereby ignoring joint activities. Second, although the nested logit model allows the household decisions to be estimated simultaneously, it does not account for the ordinal nature of the first decision – that is, the number of out-of-home maintenance episodes.

Obviously, as highlighted by the discussion above, there remains a need to incorporate interactions among household members in the development of behaviorally sound, activity-based forecasting models. Our paper presents one such attempt at addressing this issue. Specifically, the daily number of non-work, out-of-home activity episodes is modeled for the heads of three common household types: couple, non-worker, one-worker and two-worker households. To capture interactions between such household members in terms of their participation in independent and joint out-of-home activity episodes, we develop the trivariate ordered probit model. To our knowledge, this is the first attempt to extend Mckelvey and Zavoina's pioneering work on the ordered probit model to account for three ordered decisions whose outcomes are determined by a joint decision-making process (cf. McKelvey and Zavoina, 1975).

Our focus on modeling the daily number of non-work, out-of-home activity episodes for household heads is based on a consensus among researchers that the decision-making process underlying observed activity-travel behavior can be split into two distinct, yet interrelated, components: activity generation and activity scheduling (e.g. Bhat and Koppelman, 1993, 1994; Doherty and Axhausen, 1999; Ettema et al., 1993, 1996; Gärling et al., 1989; Recker et al., 1986a,b; Wen and Koppelman, 1999, 2000). While activity scheduling has been the focus of much research activity in recent years, the same is not true for activity generation. Despite this situation, however, a common assumption underlying the very few studies that have addressed conceptually or empirically the subject of activity generation is that household members generate activities collectively and then assign them to individual members for execution (e.g. Bhat and Koppelman, 1993; Wen and Koppelman, 1999, 2000). Obviously, this process is based on interactions among household members. For this reason, activity generation is a natural starting point for developing behaviorally sound, activity-based forecasting models.

Our approach to modeling activity generation captures interactions between household heads in terms of *all* non-work, out-of-home activity episodes that they participate in on a daily basis. Although our approach does not distinguish between specific activity types, it has several strengths, in addition to capturing interactions, which define its usefulness for practical forecasting purposes. These strengths include explicit recognition of membership identity within a household, explicit recognition of activity setting (i.e. independent and joint activities) and explicit recognition of activity episodes as units of analysis. Three alternatives exist that are also capable of capturing interactions between household heads – namely, nested logit models (e.g. Wen and

Koppelman, 1999, 2000), structural equations models (e.g. Golob and McNally, 1997) and share models (e.g. Gliebe and Koppelman, 2001). Moreover, unlike our approach, these models are capable of distinguishing between activity types. Despite this strength, however, they appear to be of limited value for activity generation because they lack one or more of the strengths identified above with reference to our modeling framework. For example, structural equations models and share models are used to model continuous variables, not ordinal ones. Although our approach to modeling activity generation within households is not necessarily a panacea, it does provide a robust alternative to other methods that are capable of capturing interactions between household heads.

The remainder of this paper is organized as follows. Section 2 presents the modeling framework for the trivariate ordered probit model. Section 3 describes the data and sample used in the empirical analysis. Section 4 presents the empirical findings. The contributions of this study to activity-based research and suggestions for further research are summarized in Section 5.

2. Modeling framework

2.1. Overview

As mentioned, we develop the trivariate ordered probit model to model the daily number of non-work, out-of-home activity episodes for household heads. The strengths of the model, in the present application, are threefold. First, the model accounts for two activity settings: independent and joint activities. These settings are based on the number of household heads participating in activity episodes. In other words, the presence of other household members, such as children, is not used to define the settings. Activities undertaken by one household head are independent activities, whereas those undertaken by both household heads together are joint activities. Second, the model considers both the discrete and *ordinal* nature of the decisions confronting household heads – namely, the *number* of independent and joint out-of-home activity episodes. Finally, the model accounts explicitly for interactions between household heads in terms of their participation in such activities. To our knowledge, this is one of the first attempts to incorporate both activity setting and interactions between household heads in a modeling framework.

A consistent finding in the activity-based literature is that work has a negative impact on participation in non-work, out-of-home activities (e.g. Bhat and Singh, 2000; Golob and McNally, 1997). For this reason, we assume that the nature of interactions between household heads will vary according to the number of heads employed. Thus, models are estimated for the following household types to capture inherent differences in interactions:

1. *couple*, *non-worker households*: married or unmarried, male–female couples with or without children in which neither household head works;
2. *couple*, *one-worker households*: married or unmarried, male–female couples with or without children in which only one household head works; and
3. *couple*, *two-worker households*: married or unmarried, male–female couples with or without children in which both household heads work.

2.2. Trivariate ordered probit model

In the following presentation of the model structure, for each household h, let j represent the number of independent, non-work, out-of-home activity episodes that the male head undertakes during the day ($j = 0, 1, \ldots, J$), let k represent the number of such episodes that the female head participates in ($k = 0, 1, \ldots, K$) and let l represent the daily number of non-work, out-of-home activity episodes that both heads undertake together ($l = 0, 1, \ldots, L$). It should be noted, however, that in the case of couple, one-worker households, j and k refer to working and non-working heads, respectively. The equation system can now be written as:

$$\begin{aligned} y_{1h}^* &= \beta_1 x_{1h} + \varepsilon_{1h}, \quad y_{1h} = j \quad \text{if } \mu_{1,j} < y_{1h}^* \leqslant \mu_{1,j+1}, \\ y_{2h}^* &= \beta_2 x_{2h} + \varepsilon_{2h}, \quad y_{2h} = k \quad \text{if } \mu_{2,k} < y_{2h}^* \leqslant \mu_{2,k+1}, \\ y_{3h}^* &= \beta_3 x_{3h} + \varepsilon_{3h}, \quad y_{3h} = l \quad \text{if } \mu_{3,l} < y_{3h}^* \leqslant \mu_{3,l+1}, \end{aligned} \tag{1}$$

where y_{1h}^*, y_{2h}^* and y_{3h}^* are, respectively, the propensity for the male head of household h to engage in independent, out-of-home activity episodes, the propensity for the female head to engage in such episodes and the propensity for both heads to undertake joint activity episodes. The observed number of independent episodes for the male head is represented by y_{1h} and for the female head, y_{2h}. y_{3h} represents the observed number of joint episodes. The x's are vectors of exogenous variables. The β's are corresponding vectors of parameters that are estimated along with the threshold values (i.e. the μs) for each equation. The random error terms $\varepsilon_{1h}, \varepsilon_{2h}$ and ε_{3h} are assumed to be distributed identically and independently across households in accordance with the standard normal distribution.

Male and female household heads interact to make decisions regarding the choices in (1). From the analyst's point of view, these interactions are both observed and unobserved. For example, the heads of a couple, one-worker household may decide that the working head must leave the only household vehicle at home for use during the day by the non-working head. Such an arrangement would likely reduce the propensity for the working head to participate in independent, non-work, out-of-home activity episodes, while increasing that of the non-working head. In other words, a negative association exists between the two choices. The analyst can easily capture such an interaction by using dummy variables. In reality, however, interactions between household heads will be mostly unobserved. For example, one household head may be actively involved with community organizations in the evening. If the other household head is to participate in non-work, out-of-home activity episodes during this period, he or she must do so independently. This arrangement precludes any joint out-of-home activity episodes. The key to capturing such unobserved interactions between household heads is to correlate the random error terms $\varepsilon_{1h}, \varepsilon_{2h}$ and ε_{3h}. For this, a standard normal trivariate distribution function is specified such that:

$$\phi_3(\cdot) = \phi_3(\varepsilon_{1h}, \varepsilon_{2h}, \varepsilon_{3h}, \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}). \tag{2}$$

Likewise, the corresponding cumulative density function is given as:

$$\Phi_3(\cdot) = \Phi_3(\varepsilon_{1h}, \varepsilon_{2h}, \varepsilon_{3h}, \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}). \tag{3}$$

The ρs represent the correlations between the random error terms.

From (1) and (3), the joint probability that the male and female heads of household h will participate, respectively, in j and k independent, non-work, out-of-home activity episodes, as well as l joint episodes is:

$$\begin{aligned}
P_{hjkl} = {} & \Phi_3\left[(\mu_{1,j+1} - \beta_1 x_{1h}), (\mu_{2,k+1} - \beta_2 x_{2h}), (\mu_{3,l+1} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& - \Phi_3\left[(\mu_{1,j} - \beta_1 x_{1h}), (\mu_{2,k+1} - \beta_2 x_{2h}), (\mu_{3,l+1} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& - \Phi_3\left[(\mu_{1,j+1} - \beta_1 x_{1h}), (\mu_{2,k} - \beta_2 x_{2h}), (\mu_{3,l+1} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& - \Phi_3\left[(\mu_{1,j+1} - \beta_1 x_{1h}), (\mu_{2,k+1} - \beta_2 x_{2h}), (\mu_{3,l} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& - \Phi_3\left[(\mu_{1,j} - \beta_1 x_{1h}), (\mu_{2,k} - \beta_2 x_{2h}), (\mu_{3,l} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& + \Phi_3\left[(\mu_{1,j} - \beta_1 x_{1h}), (\mu_{2,k} - \beta_2 x_{2h}), (\mu_{3,l+1} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& + \Phi_3\left[(\mu_{1,j} - \beta_1 x_{1h}), (\mu_{2,k+1} - \beta_2 x_{2h}), (\mu_{3,l} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right] \\
& + \Phi_3\left[(\mu_{1,j+1} - \beta_1 x_{1h}), (\mu_{2,k} - \beta_2 x_{2h}), (\mu_{3,l} - \beta_3 x_{3h}), \rho_{\varepsilon_1\varepsilon_2}, \rho_{\varepsilon_1\varepsilon_3}, \rho_{\varepsilon_2\varepsilon_3}\right].
\end{aligned} \tag{4}$$

The parameters to be estimated in the trivariate ordered probit model are the $J + K + L - 3$ threshold values $(\mu_{1,0}, \mu_{2,0}, \mu_{3,0}, = -\infty; \mu_{1,1}, \mu_{2,1}, \mu_{3,1}, = 0; \mu_{1,J+1}, \mu_{2,K+1}, \mu_{3,L+1}, = +\infty)$, the βs and the ρs. The parameters are obtained by maximizing the log-likelihood function:

$$L^* = \sum_{h=1}^{H} \sum_{j=0}^{J} \sum_{k=0}^{K} \sum_{l=0}^{L} Z_{hjkl} \log P_{hjkl}, \tag{5}$$

where:

$$Z_{hjkl} = \begin{cases} 1 & \text{if the heads of household } h \text{ participate in } j, k \text{ and } l \text{ activity episodes,} \\ 0 & \text{otherwise.} \end{cases}$$

A program is written in GAUSS™ (Aptech Systems, Maple Valley, WA) for this task.

3. Data and sample

The data for this research are derived from a trip diary survey that was conducted for the Ontario Ministry of Transportation during February and March 1987. The sample of households for this survey was selected from households that responded to a much larger survey conducted in the Greater Toronto Area (GTA) in 1986 – that is, the 1986 Transportation Tomorrow Survey. The trip diary survey used a mail questionnaire to obtain socio-demographic information on each household surveyed, including all members over the age of five. It also collected detailed information concerning the daily travel behavior of such members for a pre-selected weekday. Complete questionnaires were obtained for 1948 households.

Of this total, only 738 households were used in the present study because of a rigorous screening procedure. The original sample was first classified by household type. Any household that did not fit into one of the three types identified for analysis was removed from the sample. Next, for household heads, the number of non-work, out-of-home activity episodes was recorded, by purpose, for each activity setting (i.e. independent and joint activities). The trip diary identified six activity types besides work and home: shopping, drop off/pick up passenger, entertainment/socializing/recreation, personal business, school and other. Households were eliminated from the

Table 1
Observed distributions of the daily number of non-work, out-of-home activity episodes undertaken by household heads

Number of episodes	Couple, non-worker households		Couple, one-worker households		Couple, two-worker households	
	Original sample[a]	Retained sample[b]	Original sample	Retained sample	Original sample	Retained sample
Independent (M/W)[c]						
0	0.5278	0.5500	0.6578	0.6707	0.5635	0.5908
1	0.2500	0.2917	0.2243	0.2329	0.2690	0.2737
2	0.1389	0.1583	0.1027	0.0964	0.0964	0.0921
3	0.0208		0.0000		0.0431	0.0434
4	0.0278		0.0076		0.0102	
5	0.0208		0.0076		0.0127	
6	0.0069				0.0000	
7	0.0000				0.0051	
8	0.0000					
9	0.0000					
10	0.0069					
Independent (F/N)[d]						
0	0.6667	0.7250	0.3878	0.3976	0.5457	0.5610
1	0.2014	0.2000	0.2738	0.2851	0.2437	0.2547
2	0.0833	0.0750	0.1673	0.1687	0.1294	0.1328
3	0.0208		0.0684	0.0723	0.0482	0.0515
4	0.0069		0.0722	0.0763	0.0076	
5	0.0000		0.0152		0.0152	
6	0.0069		0.0114		0.0051	
7	0.0000		0.0000		0.0000	
8	0.0139		0.0000		0.0000	
9			0.0038		0.0051	
Joint						
0	0.7500	0.7917	0.8897	0.8996	0.8832	0.8862
1	0.1181	0.1333	0.0798	0.0843	0.0914	0.0921
2	0.0694	0.0750	0.0228	0.0161	0.0228	0.0217
3	0.0278		0.0000		0.0000	
4	0.0139		0.0038		0.0000	
5	0.0069		0.0038		0.0000	
6	0.0000				0.0000	
7	0.0069				0.0000	
8	0.0000				0.0000	
9	0.0069				0.0025	
Summary statistics						
Number of households (n)	144	120	263	249	394	369
Proportion retained[e]		0.83		0.95		0.94

[a] Sample prior to the removal of ordered-response categories.
[b] Sample retained for analysis (i.e. after removal of ordered-response categories).
[c] Independent activity episodes for males (couple, non-worker and two-worker households) or workers (couple, one-worker households).
[d] Independent activity episodes for females (couple, non-worker and two-worker households) or non-workers (couple, one-worker households).
[e] Proportion of the original sample (i.e. sample prior to the removal of ordered response categories) retained for analysis.

sample if a head went to school on the survey day. The reason for this is that school, like work, is a mandatory activity that imposes constraints on non-work activities. The number of episodes was then totaled, by setting, for the heads of each household. These totals were used to create three distributions for each household type – two pertaining to the number of independent episodes undertaken by each household head and one pertaining to the number of joint episodes (see Table 1). Our rule of thumb was to eliminate ordered response categories containing few, if any, observations. This decision was made to ensure an adequate number of observations for analysis. For two of the household types, the remaining categories contained approximately 95% of the original observations (see Table 1). In total, 63 households of all three types were removed from the sample. Upon completion of the screening procedure, the sample consisted of 120 couple, non-worker households, 249 couple, one-worker households and 369 couple, two-worker households. Observed distributions of the daily number of non-work, out-of-home activity episodes for the heads of households retained in the sample are shown in Table 1.

4. Empirical findings

4.1. Model specification and variable selection

To ascertain whether or not household heads determine jointly the number of independent and joint, non-work, out-of-home activity episodes that they undertake on a daily basis, two models were specified for each of the above household types. The first specification, which we denote as a joint model, captured any unobserved interactions between household heads by correlating the error terms in (1). For the second specification, these error terms were left uncorrelated by setting the ρs in (4) to zero, which implies that the daily number of non-work, out-of-home activity episodes for each equation in (1) is determined independently. This specification is appropriately denoted as an independent model. For each household type, the two models were compared using the following likelihood ratio test statistic:

$$-2[L_I^*(\beta) - L_J^*(\beta)], \tag{6}$$

which is χ^2 distributed with three degrees of freedom. $L_J^*(\beta)$ and $L_I^*(\beta)$ are, respectively, the log-likelihood values from the joint and independent model specifications.

The choice of independent variables for potential inclusion in the models estimated was guided by the findings from previous activity-based research and intuitive arguments regarding the effects of variables designed to capture interactions between household heads. The variables included in the final model specifications are found in Table 2, along with their definitions. The first group of variables measures socio-demographic characteristics of households and their heads, whereas the second group is defined only for those heads that work.

An important finding of our research concerns the definition and inclusion of interaction terms in the models. Obviously, these terms increase model fit. However, the reason they are included in the analysis is because they improve the theoretical validity of the models with respect to activity-episode generation. This point is demonstrated by the following example. One of the variables included in the final specifications estimated for couple, non-worker households is *licensed and*

Table 2
Independent variables used in the empirical analysis

Variable	Definition
Socio-demographic characteristics	
Age	Age of household head in years $\times 10^{-1}$
Children $\leqslant 5$ years present	1 if household contains children $\leqslant 5$ years old; 0 otherwise
Children $\geqslant 6$ years, $\leqslant 10$ years present	1 if household contains children $\geqslant 6$ years old and $\leqslant 10$ years old; 0 otherwise
Children $\geqslant 6$ years, $\leqslant 15$ years present	1 if household contains children $\geqslant 6$ years old and $\leqslant 15$ years old; 0 otherwise
Household income	Annual household income in dollars $\times 10^{-4}$
Licensed and vehicle present	1 if female head of couple, non-worker household is licensed and the household has a vehicle; 0 otherwise
Licensed, one-vehicle household and vehicle unavailable while worker is at work	1 if non-working head of couple, one-worker household is licensed and the only household vehicle is unavailable for use while the working head is at work; 0 otherwise
Licensed, one-vehicle household and vehicle available while worker is at work	1 if non-working head of couple, one-worker household is licensed and the only household vehicle is available for use while the working head is at work; 0 otherwise
Licensed and multiple-vehicle household	1 if non-working head of couple, one-worker household is licensed and the household has more than one vehicle; 0 otherwise
Male licensed, female licensed and vehicle present	1 if both heads of couple, non-worker household are licensed and the household has a vehicle; 0 otherwise
Only male licensed and vehicle present	1 if only male head of couple, non-worker household is licensed and the household has a vehicle; 0 otherwise
Only worker licensed and vehicle present	1 if only working head of couple, one-worker household is licensed and the household has a vehicle; 0 otherwise
Reside in Metropolitan Toronto	1 if household lives in Metropolitan Toronto; 0 otherwise
Work characteristics	
Household heads commute together	1 if heads of couple, two-worker household commute to work together in a household vehicle; 0 otherwise
Multiple-vehicle household and drive alone to work	1 if household has more than one vehicle and household head drives alone to work; 0 otherwise
One-vehicle household and drive alone to work	1 if household has only one vehicle and household head drives alone to work; 0 otherwise
Same work schedule as female	1 if male head of couple, two-worker household has same work schedule as female head; 0 otherwise
Transit to work	1 if household head takes public transit to work; 0 otherwise
Work duration	Work duration of household head in minutes $\times 10^{-2}$

vehicle present – an interaction term that captures the mobility constraints of female heads. This variable was derived from earlier findings concerning two other variables: one defined to indicate the possession of a driver's license (i.e. *license*) and the other, the presence of a vehicle in the household (i.e. *vehicle*). Specifically, we found that both variables were significant, but not when included together in the models. The inclusion of only one of the two variables, however, would lead to theoretically inconsistent models. For example, if only *license* was included in the final specifications, a licensed female head living in a household without a vehicle would have the same propensity to undertake independent, non-work, out-of-home activity episodes as one that is licensed and lives in a household with a vehicle. By including the interaction term *licensed and vehicle present* in the models, this theoretical inconsistency was overcome. Similar arguments can be made regarding the other interaction terms found in Table 2.

Two additional items are of note concerning the variables included in the final model specifications. First, we tested for both linear and nonlinear relationships between age and activity-episode generation. In all instances, linear relationships were found. Second, several of the variables are outcomes from decisions (e.g. *transit to work*). Such variables are included in the analysis because the modeling framework does not allow for the simultaneous estimation of such choices along with those concerning the number of non-work, out-of-home activity episodes to be undertaken independently and jointly by household heads. The variables do, however, play important roles in establishing conditions that influence daily activity-episode generation. For this reason, exclusion of such variables would lead to a partial and perhaps incorrect understanding of the process. On a more practical note, when developing an activity-based forecasting system, it can be assumed that such decisions precede activity-episode generation. In this case, inclusion of the variables establishes a conditional relationship between models.

4.2. Couple, non-worker households

Table 3 presents the results for both specifications estimated for the heads of couple, non-worker households. A visual comparison of the models indicates that their respective parameter estimates differ very little. In fact, the independent and joint models estimated for both couple, one-worker and couple, two-worker households exhibit this same characteristic. For this reason, the independent model results for these households are not included in this paper. However, as part of the summary statistics shown in Table 4, we do include the likelihood ratio test statistic given in (6) for each household type.

For couple non-worker households, a value of 14.6 for this statistic rejects the null hypothesis that all the correlation coefficients are zero. In other words, the daily number of independent and joint, non-work, out-of-home activity episodes is determined jointly by household heads. However, as shown in Table 3, only two of the three correlation coefficients are significant. The error terms for the number of independent episodes undertaken by male and female heads are positively correlated. This indicates a positive unobserved interaction between household heads. On the other hand, the error terms for the number of joint episodes and the number of independent episodes undertaken by female heads are negatively correlated. This suggests a substitution effect between the two activity settings – that is, unobserved interactions that increase the propensity for female heads to participate in independent activity episodes decrease the propensity for household heads to undertake joint episodes. Incorporating unobserved interactions between male and female heads in the modeling framework improves considerably the overall goodness-of-fit of the model, which is computed as follows:

$$\rho^2 = 1 - \frac{L^*(\beta)}{L^*(c)}, \tag{7}$$

where $L^*(\beta)$ is the value of the log-likelihood function at its maximum – that is, when it includes independent variables – and $L^*(c)$ is the value of the log-likelihood function when it includes only

Table 3
Joint and independent model results estimated for couple, non-worker households

Variable	Joint model		Independent model	
	Coefficient	t-statistic	Coefficient	t-statistic
Independent activity episodes for males				
Constant term	2.9620	6.785	3.3673	4.309
Socio-demographic characteristics				
Children $\geqslant 6$ years, $\leqslant 15$ years present	−1.9097	−2.657	−2.3232	−2.854
Age	−0.4458	−7.356	−0.5019	−4.463
Threshold values				
One and two activity episodes	0.9663	6.785	0.9764	6.738
Independent activity episodes for females				
Constant term	−0.7535	−4.774	−0.7948	−4.034
Socio-demographic characteristics				
Licensed and vehicle present	0.3849	1.698	0.4583	1.760
Threshold values				
One and two activity episodes	0.8807	5.355	0.8702	5.326
Joint activity episodes				
Constant term	−1.3408	−4.474	−1.4037	−4.607
Socio-demographic characteristics				
Male licensed, female licensed and vehicle present	0.6052	1.675	0.6967	1.914
Only male licensed and vehicle present	0.7584	2.113	0.8311	2.277
Threshold values				
One and two activity episodes	0.6615	4.316	0.6615	4.314
Correlation coefficients				
Male and female	0.4356	3.657		
Female and joint	−0.3208	−2.023		
Male and joint	−0.0504	−0.333		
Summary statistics				
n	120		120	
$L^*(0)$	−395.5		−395.5	
$L^*(c)$	−285.2		−285.2	
$L^*(\beta)$	−264.5		−271.8	
$-2[L^*(c) - L^*(\beta)]$	41.4		26.8	
ρ^2	0.0726		0.0470	

constant terms and threshold values (i.e. the μs). The value of ρ^2 is 0.073 for the joint model, which is considerably higher than a value of 0.047 for the independent model.

As shown in Table 3, three variables are found to influence significantly the propensities for male and female heads to participate in independent, non-work, out-of-home activity episodes. For male heads, age has a negative impact on the number of such episodes, as does the presence of children between the ages of six and 15. The latter finding suggests that male heads spend more time at home nurturing young school-age children than older ones who are more independent. However, when only children less than six years old are present in the household, male heads undertake more episodes independently possibly because female heads are the primary caregivers

Table 4
Model estimation results

Variable	Couple, non-worker households		Couple, one-worker households		Couple, two-worker households	
	Coefficient	*t*-statistic	Coefficient	*t*-statistic	Coefficient	*t*-statistic
Independent activity episodes (*M*/*W*)[a]						
Constant term	2.9620	6.785	0.9676	1.864	1.6750	4.108
Socio-demographic characteristics						
Children $\geqslant 6$ years, $\leqslant 15$ years present	−1.9097	−2.657				
Age	−0.4458	−7.356	−0.2349	−3.553	−0.2288	−3.690
Household income			0.1167	2.347	0.0688	1.977
Work characteristics						
Multiple-vehicle household and drive alone to work			0.3231	1.884		
Transit to work			−0.6227	−1.785	−0.5709	−2.484
Work duration			−0.1895	−3.011	−0.2330	−4.595
Same work schedule as female					−0.2401	−1.939
Threshold values						
One and two episodes	0.9663	6.785	0.9749	8.481	0.9457	11.421
Two and three episodes					1.5693	12.958
Independent activity episodes (*F*/*N*)[b]						
Constant term	−0.7535	−4.774	−0.6431	−3.782	0.9586	2.299
Socio-demographic characteristics						
Licensed and vehicle present	0.3849	1.698				
Children $\geqslant 6$ years, $\leqslant 10$ years present			0.4229	2.297		
Reside in metropolitan Toronto			0.4635	2.868		
Licensed, one-vehicle household and vehicle unavailable while worker is at work			0.7866	3.462		
Licensed, one-vehicle household and vehicle available while worker is at work			1.4691	5.179		
Licensed and multiple-vehicle household			1.0268	5.606		
Age					−0.1612	−2.363
Household income					0.1019	2.962
Children $\leqslant 5$ years present					0.4944	2.783
Work characteristics						
Work duration					−0.2551	−5.091
Transit to work					−0.6468	−3.053
One-vehicle household and drive alone to work					0.4780	2.085
Multiple-vehicle household and drive alone to work					0.2887	2.002

Threshold values						
One and two episodes	0.8807	5.355	0.8247	9.561	0.8651	10.978
Two and three episodes			1.4799	12.659	1.7003	13.356
Three and four episodes			1.9157	13.571		
Joint Activity Episodes						
Constant term	−1.3408	−4.474	−1.5534	−9.808	−1.2155	−12.543
Socio-demographic characteristics						
Male licensed, female licensed and vehicle Present	0.6052	1.675				
Only male licensed and vehicle present	0.7584	2.113				
Only worker licensed and vehicle present			0.4662	1.974		
Children $\leqslant$ 5 years present			0.4777	2.063	−0.8153	−1.901
Work characteristics						
Household heads commute together					0.5206	2.146
Threshold values						
One and two episodes	0.6615	4.316	0.8942	4.663	0.8383	6.049
Correlation coefficients						
M/W and F/N	0.4356	3.657	0.1242	1.396	0.3909	6.060
F/N and joint	−0.3208	−2.023	−0.0132	−0.245	0.0331	0.542
M/W and joint	−0.0504	−0.333	−0.4417	−3.477	0.0103	0.198
Summary statistics						
n	120		249		369	
$L^*(0)$	−395.5		−947.8		−1428.4	
$L^*(c)$	−285.2		−650.8		−931.6	
$L^*(\beta)$	−264.5		−599.9		−850.8	
$-2[L^*(c) - L^*(\beta)]$	41.4		101.7		161.6	
ρ^2	0.0726		0.0781		0.0867	
$-2[L_I^*(\beta) - L_J^*(\beta)]$	14.6		11.8		30.4	

[a] Independent activity episodes for males (couple, non-worker and two-worker households) or workers (couple, one-worker households).

[b] Independent activity episodes for females (couple, non-worker and two-worker households) or non-workers (couple, one-worker households).

for very young children. For female heads, those with a driver's license and access to a vehicle are likely to engage in more independent out-of-home activity episodes than other female heads. The reason for this is that the legal ability to drive coupled with access to a vehicle greatly enhances personal mobility, thereby reducing constraints associated with participation in non-work, out-of-home activities.

For joint episodes, two variables are defined to capture interactions between male and female heads in terms of their mobility constraints. As shown in Table 3, both of these variables have significant positive effects on the propensity for household heads to participate in such out-of-home activity episodes. Moreover, their coefficient values are as anticipated. Specifically, male and female heads who are both licensed and have access to a vehicle are likely to engage in more joint episodes than household heads who do not have access to a vehicle. Furthermore, households in which only the male head is licensed and has access to a vehicle realize the greatest number of such episodes. This finding suggests that, in such households, female heads depend on male heads for mobility.

4.3. Couple, one-worker households

The model results for the heads of couple, one-worker households are presented in Table 4. Five explanatory variables are found to influence significantly the daily number of non-work, out-of-home activity episodes undertaken independently by working heads. Age has a negative impact on such episodes, as does work duration. Household income, on the other hand, increases the propensity for working heads to participate in independent episodes. This effect is well documented in the activity-based literature (e.g. Bhat and Singh, 2000; Strathman et al., 1994). With increasing income, there is likely more money available for participation in non-work, out-of-home activities, particularly those involving entertainment and socializing. The effects of the two work mode variables are as expected. Commuting to work by public transit reduces the number of independent activity episodes, whereas driving to work alone increases them. The magnitude of the latter effect depends on household vehicle ownership. Specifically, working heads who are members of multiple-vehicle households are likely to participate in more independent episodes than those who are members of one-vehicle households. The reason for this is that vehicle constraints are much greater in one-vehicle households than in multiple-vehicle households.

Five socio-demographic characteristics are found to have significant positive effects on the propensity for non-working heads to participate in independent, non-work, out-of-home activity episodes. As indicated in Table 4, such heads are responsible for dropping off and picking up young children (i.e. 6–10 years old) at school. Those who reside in Metropolitan Toronto are likely to undertake more independent episodes than are those who do not live there. Two factors account for this. First, commercial and retail densities are much higher in Metropolitan Toronto than elsewhere in the GTA. Second, personal mobility is much greater in Metropolitan Toronto than in the remainder of the GTA because of convenient public transit, which includes a subway system. The remaining three variables are defined to capture constraints relating to the availability of household vehicles while the worker is at work. The reference category consists of unlicensed non-working heads and households without a vehicle, as well as a combination of the two. The values of the coefficients are as expected. Specifically, the availability of a vehicle in a one-vehicle household greatly enhances the propensity for the licensed non-working head to undertake independent out-of-home activity episodes. This indicates that the vehicle has most likely been left at home exclusively for this purpose. Further evidence to support this finding is suggested by the coefficient for non-working heads that reside in multiple-vehicle households – that is, such heads participate in fewer activity episodes despite the fact that they always have access to a vehicle. Finally, a non-working head in a one-vehicle household without access to a vehicle while the working head is at work can use the vehicle to participate in independent out-of-home activity episodes only when the working head is at home. This constraint is reflected in the value of the coefficient for this variable – that is, it is the smallest of the three coefficients.

Two variables are found to influence significantly the propensity for household heads to participate in joint out-of-home activity episodes. The presence of young children (i.e. less than six years old) in the household has a positive effect on the number of such episodes. One possible reason for this is that the non-working head may require relief from the responsibilities of childcare. Thus, both household heads undertake non-work, out-of-home activities together. Alternatively, both heads may need to be present at some activity involving young children, such as a doctor's appointment. As shown in Table 4, the second variable also has a positive influence on joint episodes. Specifically, households in which only the working head is licensed and has access to a vehicle realize the greatest number of joint episodes for reasons that have already been suggested for couple, non-worker households.

A comparison of the joint and independent models estimated for couple, one-worker households yields a likelihood ratio test statistic of 11.8. With three degrees of freedom, the null hypothesis that all the correlation coefficients are zero is rejected. However, as shown in the table, only one of the correlation coefficients is significant. The error terms for the number of joint episodes and the number of independent activity episodes undertaken by working heads are negatively correlated. This suggests a substitution effect between the two activity settings – that is, unobserved interactions that increase the propensity for working heads to undertake independent episodes decrease the propensity for household heads to engage in out-of-home activity episodes together. The overall goodness-of-fit of the joint model as measured by ρ^2 is 0.078, which is higher than that for the independent model (i.e., 0.069).

4.4. Couple, two-worker households

Table 4 also presents the results for the heads of couple, two-worker households. Five independent variables are found to influence the daily number of independent, non-work, out-of-home activity episodes undertaken by male household heads. The effects of age, household income, work duration and commuting to work by public transit are the same as discussed for the working heads of couple, one-worker households. Moreover, the same variables are found to influence the propensity for female heads to participate in such episodes. Synchronization of the work schedules of male and female heads has a negative impact on the daily number of non-work, out-of-home activity episodes undertaken independently by male heads. A possible reason for this is that both working heads want to spend time together at home or time participating in joint out-of-home activities. If their work schedules are not the same, male heads have more freedom to engage in independent episodes.

Besides the explanatory variables already mentioned, the presence of young children (i.e. less than six years old) has a positive effect on the number of episodes undertaken by female heads.

This suggests that females, as opposed to their male counterparts, are largely responsible for dropping off and picking up children at daycare. Driving to work alone is also found to have a positive influence on the number independent episodes. However, the magnitude of this effect depends on household vehicle ownership. Specifically, female heads who reside in one-vehicle households are likely to undertake more independent episodes than are those who live in multiple-vehicle households. One possible explanation for this is that female heads who reside in the former household type are responsible for the majority of household maintenance activities, such as grocery shopping, which are chained to the work commute. For the latter household type, such activities can be shared more equitably because constraints involving vehicle allocation are virtually nonexistent. Alternatively, vehicles may be allocated to the female heads of one-vehicle households for the explicit purpose of undertaking particular activities on a specific day. For example, the female head may have a doctor's appointment after work.

Two variables are found to influence the propensity for household heads to engage in joint out-of-home activity episodes. The presence of young children (i.e. less than six years old) in the household has a negative effect on the number of such episodes, which is opposite to that found for couple, one-worker households. A possible reason for this is that working parents want to spend time at home with young children after work. Finally, commuting to work together in a vehicle has a positive impact on the number of joint episodes for obvious reasons.

A comparison of the joint and independent models estimated for couple, two-worker households yields a likelihood ratio test statistic of 30.4. Once again, with three degrees of freedom, the null hypothesis that all the correlation coefficients are zero is rejected. In other words, the daily number of independent and joint, non-work, out-of-home activity episodes is determined jointly by household heads. However, as shown in Table 4, only one correlation coefficient is significant. The error terms for the number of independent episodes undertaken by male and female heads are positively correlated, indicating a positive unobserved interaction between them. The overall goodness-of-fit of the joint model as measured by ρ^2 is 0.087, which is much higher than that for the independent model (i.e. 0.070).

4.5. Interpretation of findings

It is clear from the results presented in Table 4 and discussed in the preceding three sections that household heads interact when making decisions concerning the number of joint and independent, non-work, out-of-home activity episodes that they participate in on a daily basis. Moreover, the nature of these interactions is found to vary by household type. This result implies that decision-making structures and, more generally, household dynamics are anything but uniform across households. In turn, this means that a single model estimated for all households would fail to capture the full complexity of household dynamics that actually exists. The results presented in Table 4, in particular the correlation coefficients, which measure interaction effects, tell us much about the similarities and differences in decision-making structures and dynamics that exist among household types in terms of activity-episode generation. The remainder of this section elaborates on these similarities and differences.

The male and female heads of couple, non-worker and couple, two-worker households exhibit a significant positive interaction with respect to independent activities. This finding suggests both collective and opportunistic decision-making. On the one hand, household heads decide *who* must undertake *what* activities, thereby supporting the notion that, within a household context, certain activities are assigned to household members for execution (Bhat and Koppelman, 1993; Wen and Koppelman, 1999, 2000 use this approach in their modeling frameworks). On the other hand, the results suggest that some independent activities may be opportunistic in the sense that if one household head undertakes non-work, out-of-home activities independently, the other may view the situation as conducive to independent activity participation. For example, while the husband and children are at soccer practice, the wife decides to go to the mall.

The interaction effects for independent episodes also suggest that gender roles, and therefore household dynamics, vary by household type. In fact, it appears that traditional gender roles persist only in couple, one-worker households. Although the heads of such households are classified as worker and non-worker, the former are predominantly male and the latter, female. Workers are observed to undertake up to two independent, non-work, out-of-home activity episodes, whereas non-workers undertake up to four. Furthermore, the interaction effect for such episodes is insignificant, which means that neither collective nor opportunistic decision-making takes place. Together, these results suggest that non-workers, who are overwhelmingly female, are responsible for out-of-home maintenance activities. By comparison, male and female heads of couple, non-worker and couple, two-worker households exhibit a positive interaction with respect to independent activities, which, as mentioned before, is indicative of collective and opportunistic decision-making. The fact that collective decision-making occurs in such households suggests that traditional gender roles have been weakened. In other words, household heads share, to some extent, responsibility for out-of-home maintenance activities. For couple, two-worker households, temporal constraints imposed by work schedules necessitate the sharing of such responsibility, whereas altruism and mobility constraints explain the weakening of traditional gender roles in non-worker households, which, in this study, consist mostly of retired couples.

Model results in addition to the interaction effects for independent episodes corroborate the notion that gender roles vary by household type. For example, a significant negative interaction exists between independent and joint episodes for female heads of non-worker households. Given the fact that joint activity participation reflects collective decision-making, this finding suggests that male and female heads may participate in out-of-home maintenance activities together. This is even more likely the norm in households in which only the male is licensed and has access to a vehicle. In such households, female heads are likely to depend on their male counterparts for mobility. The model results also indicate that the presence of children between the ages of six and 15 reduces male participation in independent episodes. This finding suggests that unemployed male heads assume some responsibility for the in-home care of school-age children, which also reflects a weakening of traditional gender roles.

By comparison, the interaction effect between independent and joint episodes for non-workers in couple, one-worker households is negative and insignificant. This finding indicates that the two activity settings are not substituted for one another. In other words, it appears that out-of-home maintenance activities are unlikely to be undertaken jointly. Furthermore, a significant negative interaction exists between independent and joint episodes for workers. Together, these findings suggest that joint activities in one-worker households are undertaken mostly for entertainment and socializing. Additional evidence to support this notion is provided by the fact that the presence of young children (i.e. less than six years old) has a positive effect on joint activity participation. One reason that has already been suggested to explain this finding (see Section 4.3)

Table 5
Comparison of joint and independent models based on predictive ability

Number of activity episodes			Observed and predicted probability								
			Couple, non-worker households			Couple, one-worker households			Couple, two-worker households		
M/*W*[a]	*F*/*N*[b]	Joint	Obs.	Joint	Ind.	Obs.	Joint	Ind.	Obs.	Joint	Ind.
0	0	0	0.3750	0.3441	0.3153	0.2610	0.2455	0.2432	0.3659	0.3521	0.3046
0	0	1	0.0667	0.0693	0.0530	0.0281	0.0329	0.0251	0.0379	0.0372	0.0335
0	0	2	0.0417	0.0404	0.0294	0.0040	0.0071	0.0050	0.0081	0.0088	0.0081
0	1	0	0.0417	0.0708	0.0860	0.1647	0.1642	0.1704	0.0949	0.1156	0.1303
0	1	1	0.0083	0.0063	0.0148	0.0281	0.0198	0.0152	0.0081	0.0119	0.0133
0	1	2	0.0000	0.0022	0.0082	0.0040	0.0040	0.0028	0.0000	0.0029	0.0032
0	2	0	0.0167	0.0164	0.0314	0.0964	0.0954	0.1032	0.0461	0.0458	0.0671
0	2	1	0.0000	0.0008	0.0055	0.0120	0.0111	0.0087	0.0108	0.0044	0.0063
0	2	2	0.0000	0.0002	0.0030	0.0000	0.0022	0.0015	0.0000	0.0011	0.0015
0	3	0				0.0281	0.0377	0.0424	0.0190	0.0129	0.0247
0	3	1				0.0040	0.0043	0.0035	0.0000	0.0011	0.0021
0	3	2				0.0000	0.0008	0.0006	0.0000	0.0003	0.0005
0	4	0				0.0321	0.0364	0.0432			
0	4	1				0.0040	0.0042	0.0035			
0	4	2				0.0040	0.0008	0.0006			
1	0	0	0.1000	0.1436	0.1670	0.0602	0.0774	0.0779	0.0976	0.1099	0.1283
1	0	1	0.0250	0.0304	0.0289	0.0040	0.0034	0.0084	0.0081	0.0115	0.0139
1	0	2	0.0167	0.0177	0.0161	0.0040	0.0004	0.0017	0.0054	0.0027	0.0033
1	1	0	0.1167	0.0661	0.0472	0.0562	0.0663	0.0612	0.0894	0.0730	0.0635
1	1	1	0.0083	0.0071	0.0083	0.0040	0.0028	0.0057	0.0081	0.0076	0.0064
1	1	2	0.0083	0.0027	0.0046	0.0000	0.0003	0.0011	0.0054	0.0018	0.0015
1	2	0	0.0167	0.0251	0.0176	0.0482	0.0439	0.0389	0.0298	0.0413	0.0350
1	2	1	0.0000	0.0015	0.0032	0.0000	0.0018	0.0035	0.0027	0.0041	0.0032
1	2	2	0.0000	0.0004	0.0017	0.0000	0.0002	0.0006	0.0027	0.0010	0.0007
1	3	0				0.0321	0.0189	0.0163	0.0217	0.0166	0.0138
1	3	1				0.0000	0.0008	0.0014	0.0027	0.0015	0.0011
1	3	2				0.0000	0.0001	0.0003	0.0000	0.0004	0.0002
1	4	0				0.0241	0.0200	0.0167			
1	4	1				0.0000	0.0008	0.0014			
1	4	2				0.0000	0.0001	0.0003			
2	0	0	0.0667	0.0564	0.0902	0.0361	0.0272	0.0301	0.0217	0.0264	0.0403
2	0	1	0.0250	0.0120	0.0152	0.0000	0.0005	0.0032	0.0000	0.0027	0.0043
2	0	2	0.0083	0.0071	0.0084	0.0000	0.0000	0.0006	0.0000	0.0006	0.0010
2	1	0	0.0167	0.0428	0.0258	0.0281	0.0276	0.0253	0.0298	0.0247	0.0213
2	1	1	0.0000	0.0053	0.0045	0.0000	0.0005	0.0024	0.0054	0.0026	0.0021
2	1	2	0.0000	0.0022	0.0025	0.0000	0.0000	0.0004	0.0000	0.0006	0.0005
2	2	0	0.0417	0.0264	0.0097	0.0120	0.0202	0.0165	0.0271	0.0176	0.0122
2	2	1	0.0000	0.0019	0.0017	0.0000	0.0003	0.0015	0.0000	0.0018	0.0011
2	2	2	0.0000	0.0006	0.0010	0.0000	0.0000	0.0003	0.0000	0.0004	0.0003
2	3	0				0.0080	0.0093	0.0070	0.0081	0.0091	0.0049
2	3	1				0.0000	0.0002	0.0006	0.0000	0.0008	0.0004
2	3	2				0.0000	0.0000	0.0001	0.0000	0.0002	0.0001
2	4	0				0.0120	0.0106	0.0072			
2	4	1				0.0000	0.0002	0.0006			

Table 5 (*continued*)

Number of activity episodes			Observed and predicted probability								
			Couple, non-worker households			Couple, one-worker households			Couple, two-worker households		
M/W[a]	F/N[b]	Joint	Obs.	Joint	Ind.	Obs.	Joint	Ind.	Obs.	Joint	Ind.
2	4	2				0.0000	0.0000	0.0001			
3	0	0							0.0136	0.0100	0.0201
3	0	1							0.0027	0.0010	0.0021
3	0	2							0.0000	0.0002	0.0005
3	1	0							0.0108	0.0126	0.0113
3	1	1							0.0027	0.0013	0.0011
3	1	2							0.0000	0.0003	0.0002
3	2	0							0.0108	0.0113	0.0066
3	2	1							0.0027	0.0011	0.0006
3	2	2							0.0000	0.0003	0.0001
3	3	0							0.0000	0.0077	0.0027
3	3	1							0.0000	0.0007	0.0002
3	3	2							0.0000	0.0002	0.0000
Summary statistics											
Expected percent right				19.2359	18.4311		14.4885	14.4745		19.9763	18.6084
r[c]				0.9738	0.9386		0.9939	0.9909		0.9947	0.9749

[a] Independent activity episodes for males (couple, non-worker and two-worker households) or workers (couple, one-worker households).

[b] Independent activity episodes for females (couple, non-worker and two-worker households) or non-workers (couple, one-worker households).

[c] Correlation between observed and predicted probability.

is that non-workers may require relief from childcare responsibilities. Thus, both household heads undertake out-of-home activities together. Finally, the presence of young, school-age children (i.e. 6–10 years old) is found to have a significant positive impact on the independent episodes of non-workers suggesting that such heads are largely responsible for dropping off and picking up children at school.

In couple, two-worker households, the interaction effects between independent and joint episodes for both male and female heads are insignificant. In other words, joint activity engagement does not in any way influence either member's participation in independent activity episodes and vice versa. This finding likely reflects a strategy whereby household heads optimize, to the extent possible, their out-of-home activities such that the amount of time that they spend together and with children is maximized. Such a strategy would require considerable flexibility in decision-making that is only possible by removing barriers imposed by traditional gender roles. The three interaction effects for couple, two-worker households reflect such a decision-making structure, as do other model results. For example, the presence of young children (i.e. less than six years old) reduces the likelihood that household heads will participate in joint out-of-home activities even when they commute together. A possible reason for this is the need for parents to spend time with their young children. However, this situation does not preclude one of the heads from undertaking an out-of-home maintenance activity. In this instance, the model results indicate that young children increase the likelihood of female heads undertaking such an activity. In turn, male heads likely assume at home responsibility for the children.

In summary, the model results suggest that decision-making structures and, more generally, household dynamics vary by household type. The heads of couple, one-worker households exhibit traditional gender roles in which non-workers are responsible for most of the out-of-home maintenance activities. Decisions to participate in joint episodes, which appear to be undertaken mostly for entertainment and socializing, reduce the likelihood that workers will undertake independent episodes. At the same time, such decisions have no impact on the independent activities of non-workers. By comparison, the heads of couple, two-worker households cope with the temporal constraints imposed by their daily work schedules through flexible decision-making, which allows them to maximize the amount of time that they spend with one another and with their children. Traditional gender roles also appear to be weak in couple, non-worker households, which consist mostly of retirees. Specifically, such households are predisposed toward collective decision-making in which couples decide whether or not female heads will participate alone in out-of-home maintenance activities. A decision to undertake such activities jointly reduces the propensity for female heads to engage in independent episodes, whereas the same decision has no impact on male participation in independent activities. Finally, some couple, non-worker households are especially predisposed toward joint participation in out-of-home maintenance activities – notably, those in which only the male is licensed and has access to a vehicle.

4.6. Assessment of predictive ability

The joint and independent models estimated for each household type are compared based on predictive ability. Two measures are used for this task: expected percent right and aggregate probability. The former is computed as follows:

$$\text{Expected percent right} = \frac{100}{H}\left(\sum_{h=1}^{H}\sum_{j=0}^{J}\sum_{k=0}^{K}\sum_{l=0}^{L} P_{hjkl}y_{hjkl}\right), \tag{8}$$

where P_{hjkl} is the predicted probability that the male/working and female/non-working heads of household h undertake, respectively, j and k independent, non-work, out-of-home activity episodes, as well as l joint episodes. y_{hjkl} is one if the heads are observed to select j, k and l episodes – zero otherwise. The latter measure is also obtained from the predicted probabilities such that:

$$P^A_{jkl} = \frac{1}{H}\sum_{h=1}^{H} P_{hjkl}, \tag{9}$$

where P^A_{jkl} is the aggregate probability that the male/working and female/non-working heads participate, respectively, in j and k independent, out-of-home activity episodes, as well as l joint episodes. For each household type, the aggregate and observed probabilities are compared using a correlation coefficient.

The results of the model comparison are found in Table 5. Both measures confirm that the joint models predict more accurately than the independent models. Further analysis also reveals that the joint models predict significantly better than naïve models (i.e. models containing only constant terms and threshold values). In terms of expected percent right, the joint model estimated for couple, non-worker households predicts 22% better than the corresponding naïve model, which has an expected percent right of 15.83%. This finding is similar to that for couple, one-worker households. The joint model for this household type predicts 23% better than the naïve model, which has an expected percent right of 11.80%. Finally, the greatest difference between joint and naïve models is found for couple, two-worker households – 19.98% compared to 14.79%, which means that the joint model predicts 35% better than the naïve model.

5. Conclusions

At the outset of this paper, we argued that interactions among household members must be incorporated in activity-based forecasting models if they are to be behaviorally sound. As was mentioned, however, very little research has been undertaken in this important area. Our study, therefore, represents one effort to redress this issue. Specifically, we extend McKelvey and Zavoina's seminal work on the ordered probit model to account for three ordered decisions whose outcomes are determined by a joint decision-making process (cf. McKelvey and Zavoina, 1975). The trivariate ordered probit model that we develop is used to model the daily number of non-work, out-of-home activity episodes for household heads. In this application, the model has three primary strengths. First, it accounts for two activity settings (i.e. independent and joint), which are based on the number of household heads participating in activities. Second, the model considers both the discrete and *ordinal* nature of the decisions confronting household heads – namely, the *number* of independent and joint out-of-home activity episodes. Finally, the model accounts for interactions between household heads in terms of their participation in such activities. To our knowledge, the modeling framework presented in this paper and that used by Gliebe and Koppelman (2001) are the first in the activity-based literature to incorporate explicitly both activity setting and interactions between household heads. In so doing, our approach is the first to provide a realistic, behavioral representation of the decisions underlying the daily number of non-work, out-of-home activity episodes undertaken by household heads.

The value of our framework is demonstrated by the empirical findings. We use data from a trip diary survey conducted in the GTA during 1987 to estimate trivariate ordered probit models for the heads of three household types: couple, non-worker; couple, one-worker; and couple, two-worker households. Significant interactions between household heads are found. Moreover, the nature of these interactions is shown to vary by household type implying that decision-making structures and, more generally, household dynamics also vary by household type. For example, our results suggest that traditional gender roles persist only in couple, one-worker households. In terms of predictive ability, the models incorporating interactions are found to predict more accurately than models excluding interactions.

Our findings emphasize the need to incorporate interactions among household members in activity-based forecasting models. However, much work remains to be done before existing individual-level models can be replaced with such household-level models. A promising avenue for future research in this general direction concerns the identification and modeling of interactions among household members in terms of their activity-scheduling behavior. As a starting point, we suggest an investigation of how household members organize joint activities throughout the day.

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