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Modeling household activity–travel interactions as parallel constrained choices

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Abstract. The daily activity-travel patterns of individuals often include interactions with other household members, which we observe in the form of joint activity participation and shared rides. Explicit representation of joint activity patterns is a widespread deficiency in extant travel forecasting models and remains a relatively under-developed area of travel behavior research. In this paper, we identify several spatially defined tour patterns found in weekday household survey data that describe this form of interpersonal decision-making. Using pairs of household decision makers as our subjects, we develop a structural discrete choice model that predicts the separate, parallel choices of full-day tour patterns by both persons, subject to the higher level constraint imposed by their joint selection of one of several spatial interaction patterns, one of which may be no interaction. We apply this model to the household survey data, drawing inferences from the household and person attributes that prove to be significant predictors of pattern choices, such as commitment to work schedules, auto availability, commuting distance and the presence of children in the household. Parameterization of an importance function in the models shows that in making joint activity-travel decisions significantly greater emphasis is placed on the individual utilities of workers relative to non-workers and on the utilities of women in households with very young children. The model and methods are prototypes for tour-based travel forecasting systems that seek to represent the complex interaction between household members in an integrated model structure.

1. Introduction

The activity-travel patterns of individuals often include interaction with other household members, which we observe in travel surveys as joint activity participation and shared rides. Despite the fact that a relatively large share of metropolitan travel involves some form of joint interaction between household members, explicit representation of joint activity-travel decisions is conspicuously absent from regional travel demand forecasting modeling systems. Failure to account for such linkages between household members could lead to model system mis-specification. For example, Vovsha et al. (2003) reported that, in late 1990s regional household travel surveys for New York and Columbus, Ohio, one-third to one-half of observed weekday tours involved some form of intra-household joint travel.

Early empirical research in the area of joint activity participation and travel was primarily descriptive in nature, such as Kostyniuk and Kitamura (1983) and Jones et al. (1983). More recent studies have used models of time allocation to lend insight into the importance of and motivation for joint activity participation, such as Golob and McNally (1997), Chandraskharan and Goulias (1999), Fujii et al. (1999), Simma and Axhausen (2001), Zhang et al. (2002), and Meka et al. (2002). In Gliebe and Koppelman (2000, 2002), we found that higher levels of employment and the presence of children reduce the propensity to allocate time to joint activities between adults, and that full-time workers wield more decision-making influence in joint choices.

With a few exceptions, even the more advanced activity generation and scheduling models developed to date account for correlation between household members only indirectly, through the inclusion of household attribute variables in the utility specifications of individuals. Wen and Koppelman (1999), however, proposed a nested logit model of the household-level choice of daily maintenance stops and the allocation of stops and autos to household members, but did not account for joint activities and travel. Scott and Kanaroglou (2002) were the first to explicitly model joint activity episode generation, using a tri-variate ordered probit model to generate an expected number of individual and joint non-work activity episodes for two household heads.

Recently, a tour-based modeling system was developed for the Columbus, Ohio region in which joint activity episode generation and scheduling have been modeled explicitly through a series of sub-models: a joint tour frequency model, a travel party composition model, and a person-participation model (Vovsha et al. 2003). Joint tours are generated for each household; then it is decided whether the tour will include only adults, only children or a mix of adults and children; finally, whether each household member participates in the tour is determined, depending on their time window availability after the scheduling of mandatory activities. The primary drawback to this approach is the lack of a structural linkage between model components and reliance upon iterative simulation to ensure consistency between tours and between household members.

The approach explored here is to identify joint activity participation and travel patterns in the full-day travel patterns of individuals. Limiting our study to a two-decision maker case, we develop a structural discrete choice model that produces separate probability predictions of full-day pattern choices for each individual, subject to their joint choice of a mutually exclusive subset of pattern alternatives. Joint outcomes are identified as patterns of spatial interaction between two household members, such as various combinations of joint activity participation and shared rides that affect both individuals on the same day.

The remainder of this paper is organized into four sections. The next section describes the identification of tour types, full day tour pattern alternatives and joint outcomes in survey data. This is followed by a mathematical formulation of the model used in the research. We then discuss model estimation results and conclude with a summary and directions for future research.

2. Creating activity pattern variables

This research utilizes 1989–1997 household survey data from Puget Sound Transportation Panel (PSTP), a two-day travel diary collected by the Puget Sound Regional Council, Seattle, Washington. Since PSTP travel diaries were not designed as an activity survey *per se*, several tasks were required to create an estimation dataset to support the analysis of activity-travel patterns and the identification of joint activity participation. These tasks included the identification of activity stops by purpose, home-based tours, work-based sub-tours, joint activity episodes and patterns on tours, and shared rides between adult household members. For brevity, we describe only the identification of joint activity patterns and shared rides.

2.1. *Identifying joint activity patterns*

An activity stop was considered to be joint if it involved two adult household members and the purpose was not work or education. We did not consider a stop to be joint participation if an adult household member provided a ride to another adult household member, but was not physically present to participate jointly in the activity at the destination. Children were not modeled as one of the two decision makers, partially because only persons of driving age were surveyed and partially because the parent–child relationship represents a different decision paradigm. Cases in which two adult household members participated in serving a third passenger, such as a child, were considered to be joint participation between the two adults in a "serve passenger" activity. Joint commutes to work, school or college and return trips home from these activity types were considered to be independent activity episodes with a shared ride. Shared rides between adult household members were treated as separate from joint activity participation, but were recognized as outcomes of joint choices, because they imply agreed upon spatial interaction between the participants.

We identified joint activities by matching each household member's daily trip records, comparing reported starting and ending times, origin and destination locations, trip purposes, travel modes, driver/rider status and passenger relationships. We then identified five general patterns of intra-tour spatial interaction between two adult members of the same household that showed up repeatedly in the dataset. Figure 1 shows how, in each case, the two adult household members interact on all or a portion of their individual tours. Separate bold and dashed lines represent the paths of the two persons.

2.1.1. *Type J1: The fully joint tour*

This pattern type may include one or more activity stops, each involving joint participation and joint travel. As defined above, this tour pattern type would be composed of only maintenance and leisure activity episodes. Stops for the purposes of work and education are considered to be independent activities and would not be included in a fully joint tour.

2.1.2. *Type J2: Joint, independent tour*

This pattern represents a joint activity sequence in which two adults leave home together, engage in a discretionary activity jointly, then part ways, eventually returning home separately. This pattern does not include shared travel home, implying that the joint activity location is within walking distance of home, or that one individual can take public transit, obtain a ride from a friend, or has an auto waiting at the activity location.

2.1.3. *Type J3: Independent, joint tour*

This pattern depicts a joint activity sequence in which two adults meet at an out-of-home activity location, engage in activities jointly and return home together. At least one participant pursues activities independently prior to the joint activity stop, such that they do not travel to the joint activity location together. One person may arrive by a non-auto mode, while the other arrives using a household auto and is able to drive them home.

2.1.4. *Type J4: Independent, joint, independent tour*

This is a pattern in which two persons meet for a joint activity, such as lunch, then part and follow independent paths. Joint activity sequences that take place as part of a work-based sub-tour are an example. At least one of the persons participates in an independent out-of-home activity prior to the meeting, such that an out-of-home meeting is necessary, and at least one of

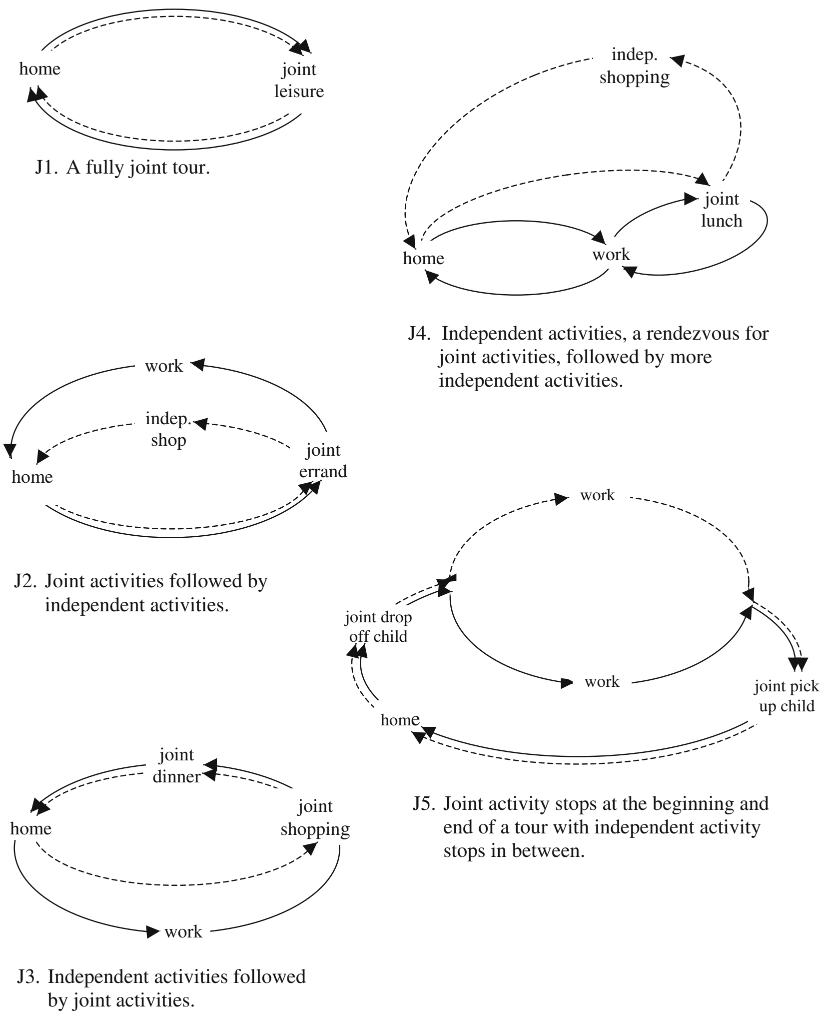

Figure 1. Five spatial arrangements of joint activity participation on tours.

the persons engages in an independent activity following the joint activity, such that separate travel home occurs.

2.1.5. *Type J5: Joint, independent, joint tour*

The fifth joint activity pattern is a combination of the second and third patterns. Figure 1 illustrates an activity sequence in which both persons begin and end a home-base tour with joint activity stops, traveling together to the first activity stop and traveling home together from the last joint activity stop. In the middle of the tour, they separate for an interval to engage in one or more activities independently. Type J5 is prevalent when two household heads commute to work together, making joint activity stops before and after work, possibly at a daycare center.

2.2. *Identifying shared rides*

Tours in which one adult household member provides a ride to the other adult household member without any joint activity participation at the drop off or pick up location were defined as 'shared rides.' For the purposes of identifying shared rides on tours, three simple patterns emerge:

- Shared rides to an activity location (drop off);
- Shared rides home from an activity location (pick up); and
- Shared rides both to and from an activity location (drop off/pick up).

We do not differentiate between driver and rider, the important element being that a shared ride has been agreed upon and both persons will participate. For round-trip shared rides, the person receiving the ride experiences both rides in the same tour, whereas the driver may accomplish both drop-off and pick-up in the same tour, or may actually go home in between the rides, forming two separate tours.

2.3. *Coding daily activity patterns*

The construction of daily activity-travel patterns proceeds from the identification of individual tour attributes and joint activity pattern types. Each tour in a person's daily record can be dimensioned in terms of tour type and joint activity pattern type, including the presence of shared rides to and from independent activities. Tours were defined based on the primary activity stop type, according to the following hierarchy:

- work;
- education; and
- discretionary.

We constructed daily activity pattern variables for each individual in the dataset by concatenating the individual tours in sequence, thereby creating a new dataset in which each record represents an individual's full-day activity-travel pattern. The observed choice of a single daily activity-travel pattern is the dependent variable in our model.

For expository convenience, we adopted single-character shorthand to describe these daily patterns. A key to this notation may be found in Figure 2.

For example, the daily pattern 'J-D' represents a day in which an individual reported an all-joint home-based discretionary tour followed by an independent discretionary tour. A daily pattern in which one household member

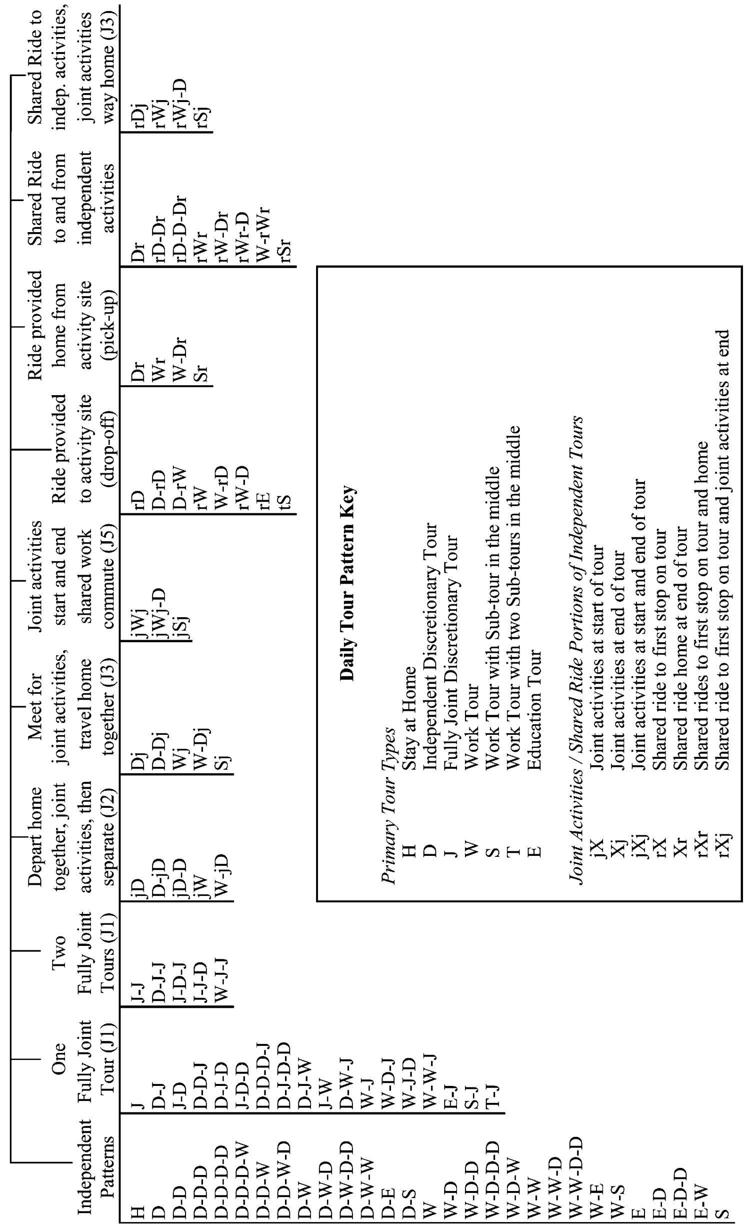

Figure 2. Relationship between individual daily tour pattern alternatives and 10 household joint outcome alternatives.

provides a ride to and from work to another household member is represented as 'rWr' for the worker, but could be represented by two tours for a non-working person who gives the rides, such as 'rD-Dr'. In addition, there are many observations in which the respondent stayed home all day, coded as 'H'.

Using this coding scheme, we identified 728 unique daily patterns in a sample of 26,492 weekday person records from two-person households. Of these, 626 included either joint activity participation and/or a shared ride sequence; however, this accounts for just 29% of one-day person records. The daily patterns observed most do not include joint activities or shared rides, which is to be expected for a weekday survey. The 100 most frequently observed individual daily patterns, those with 12 or more observations each, account for 95% of observations. Half of the remaining unique patterns observations are observed just once.

2.4. *Identifying joint choices*

The daily patterns, described above using the tour type coding scheme, represent the choices of individuals in the execution of their daily activity program. Each daily pattern also includes a latent joint choice between pairs of decision makers, a household-level decision that is reflected in the travel patterns of both household members. For example, both household members may include a single fully-joint discretionary tour in their daily pattern choice. Another example is a shared ride to work, followed by a joint activity after work and a shared ride home. Another joint decision might be no out-of-home interaction, in which case the couple has made the implicit decision to pursue independent activity-travel paths. Joint outcomes must be consistent between household members for the same observation day.

Table 1 shows the frequencies of the 10 joint outcome choices included in the final estimation dataset. The joint outcome of 'independent daily patterns' represents 77% of one-day household observations. A day with one fully joint tour is found in 17% of observations, whereas a day with two fully joint tours accounts for just 2% of one-day observations. Partially joint tours and shared ride arrangements comprise the remaining 4% of observations.

2.5. *Selecting the estimation data set*

In selecting which daily activity pattern types and joint outcomes to define as choice set alternatives, the objective of representing variation in observed patterns was balanced against the practical needs of computational tractability

Table 1. Frequencies and shares in estimation set of 10 latent joint outcomes.

Joint outcome	One-day household observations	%
Independent daily patterns	8780	76.7
One fully joint tour (J1)	1902	16.6
Two fully joint tours (J1)	239	2.2
Depart home for joint activities, then separate (J2)	30	0.3
Rendezvous for joint activities and travel home together (J3)	70	0.6
Joint activities at start and end of shares work commute (J5)	48	0.4
Ride provided to activity site (drop off)	71	0.6
Ride provided home from independent activity site (pickup)	42	0.4
Shared ride to and from independent activity site (drop off/pickup)	163	1.4
Shared ride to site of independent activity, with joint activity on way home (drop off/J3)	98	0.9
Total	11,443	100.0

and the ability to estimate statistically significant parameters. As a rule, we selected full-day tour patterns as alternatives for the estimation choice set if they represented joint choices that were observed a minimum of 30 times. In addition, we limited the estimation set to households with two adult decision makers (age 18 and over) that could be identified as being related to one another based on their survey responses. For a household's one-day observation to be selected, both members of the household had to have an observed daily pattern alternative that met the minimum number of observations and both persons were required to indicate the same joint outcome event. Identification of these joint events was facilitated by survey questions that asked respondents to report the number of co-travelers and their relationship (spouse, child, other relative, friend/co-worker). Discrepancies in which only one adult household member reported traveling with the other were accepted and treated as a joint outcome event if both adults reported the same, or nearly so, trip locations and timing, and considering stated driver/rider relationships. If a discrepancy could not be reconciled, the observation was discarded.

The final estimation set included 11,443 household one-day records, representing 2773 households with the observed choices of two adult decision makers indicated on each record. The final dataset includes 94 elemental full-day pattern alternatives, accounting for 88% of the total observations in the initial eligible sample of two-adult households. In addition, 10 joint outcome alternatives are represented. Most of the patterns not included were similar to those that were in terms of the total number of tours, differing primarily by the sequencing of tour types and joint outcome events.

Figure 2 is a diagram illustrating the membership of each of the 94 full-day pattern alternatives in one of ten subsets corresponding to the joint outcome choices. Tour Type J4, described above and shown in Figure 1, did not qualify for the estimation dataset due to insufficient observations after screening rules were applied.

3. Model formulation

3.1. *Assumptions*

Let p and p' represent two decision makers in a single household h. Let Y_{pm} and $Y_{p'm}$ represent the choices of joint outcome m by persons p and p', respectively, from N, a set of possible joint outcomes. We observe m in the daily activity travel patterns of both decision makers. By maintaining two decision variables to represent the joint outcome, we acknowledge that both persons are making a decision and receive separate levels of utility from the result.

Let Y_{ipm} and $Y_{i'p'm}$ represent the choices of individual daily activity-travel pattern alternatives i and i' by persons p and p', respectively. The chosen alternative i is a member of the set of alternatives J_m that satisfy the joint outcome m for person p, and chosen alternative i' is a member of the set of alternatives J'_m that satisfy joint outcome m for person p'.

In this research, N represents the set of 10 joint outcomes identified above, and each m represents one of those outcomes. Each of the 94 individual daily pattern alternatives satisfies one and only one joint outcome m. For any pair of decision makers representing an observed household, there is one chosen activity-travel pattern alternative for each decision maker per observation day. For person p, let Y_{ipm} equal one if chosen and equal zero otherwise, for all i, and similarly for person p'. Since each elemental daily activity-travel pattern belongs to a mutually exclusive joint outcome subset, we submit that,

$$\sum_{i \in m} \mathrm{Prob}(Y_{ipm} = 1) = \sum_{i' \in m} \mathrm{Prob}(Y_{i'p'm} = 1), \quad \forall m \in N \tag{1}$$

is a constraint to be incorporated into the derivation of a random utility model for a choice situation in which two agents make parallel individual choices subject to an overarching joint choice. The sum of the probabilities of the alternatives comprising an individual's choice set for a particular joint outcome must equal the sum of the probabilities of the alternatives available in the choice set of his/her fellow decision maker for the same joint outcome.

3.2. *Model derivation*

McFadden (1978) established a process by which the generalized extreme value (GEV) distribution is used to generate closed-form discrete choice models. The method hinges on the formulation of an appropriate error term generating function, which can be specified to represent different error correlation structures, provided that the function is consistent with the principals of stochastic utility maximization.

For this research, we consider the joint distribution of error terms for the choice alternatives of two household members p and p'. We thus specify a two-decision-maker function, $G(Y_{1p}, \ldots, Y_{jp}, \ldots, Y_{Jp}; Y_{1p'}, \ldots, Y_{jp'}, \ldots, Y_{Jp'})$, that represents the joint distribution of the error terms for every alternative, for each decision maker. Further, we partition alternatives into mutually exclusive and collectively exhaustive nests that correspond to the 10 joint outcomes defined in shown in Figure 2. The primary purpose of these nests is not to define a substitution relationship, but rather to enforce the structural constraint specified by the equation in 1. This generator function can be written as:

$$
\begin{aligned}
&G(Y_{1p}, \ldots, Y_{jp}, \ldots, Y_{Jp}; Y_{1p'}, \ldots, Y_{jp'}, \ldots, Y_{Jp'}) \\
&= \sum_{m=1}^{M} \left[\left(\sum_{j \in C_{pm}} Y_{jp}^{\lambda_m} \right)^{\theta_p} \left(\sum_{j' \in C_{p'm}} Y_{j'p'}^{\lambda_m} \right)^{\theta_{p'}} \right]^{1/\lambda_m}
\end{aligned}
\tag{2}
$$

where θ_p and $\theta_{p'}$ are decision maker importance weights that effectively re-scale the utilities of one household member's alternatives relative to the other household member's utility, The λ_m parameters represent nesting similarity parameters, similar to those estimated for a nested logit model. The generator function of equation (2) is consistent with the McFadden's (1978) principles of stochastic utility maximization under certain conditions found in Gliebe (2004). It is sufficient to note that we constrain $\theta_p + \theta_{p'} = 1$, and require that $\lambda_m \geq 1$ in order to guarantee this consistency. Because it involves two decision variables, Equation (2) is not a GEV function *per se*, but rather an extension thereof with similar properties.

Probability models for the choice of daily activity-travel patterns for each household decision maker are derived separately from the same household generating function by taking derivatives with respect to the individual and the alternative. The probability of the choice of alternative i by person p is defined by

$$
P_{ip} = \frac{Y_{ip} G_{ip}(Y_{1p}, \ldots, Y_{jp}, Y_{1p'}, \ldots, Y_{jp'})}{\theta_p G(Y_{1p}, \ldots, Y_{jp}, Y_{1p'}, \ldots, Y_{jp'})} \tag{3}
$$

in which $G_{ip} = \partial G/\partial Y_{ip}$. Gliebe (2004) has shown that equation (3) leads to the probability expression

$$P_{ip} = \frac{\exp(\lambda_m V_{ip})}{\sum_{j \in C_{pm}} \exp(\lambda_m V_{jp})} \times \frac{\exp\left(\frac{\theta_p}{\lambda_m}\Gamma_{pm} + \frac{\theta_{p'}}{\lambda_m}\Gamma_{p'm}\right)}{\sum_{m=1}^{M} \exp\left(\frac{\theta_p}{\lambda_m}\Gamma_{pm} + \frac{\theta_{p'}}{\lambda_m}\Gamma_{p'm}\right)} \tag{4}$$

in which Γ_{pm} and $\Gamma_{p'm}$ represent the composite utilities for persons p and p', respectively, for each nest-subset of daily activity-travel pattern alternatives, and are defined as follows:

$$\Gamma_{pm} \equiv \ln\left(\sum_{j \in C_{pm}} \exp(\lambda_m V_{jp})\right), \qquad \Gamma_{p'm} \equiv \ln\left(\sum_{j' \in C_{p'm}} \exp(\lambda_m V_{j'p'})\right), \ \forall m \tag{5}$$

The left-most term in equation (4) is the conditional probability of person p choosing daily pattern alternative i, given the choice of joint outcome m, and the right-most term is the unconditional probability of the joint choice of outcome m. Thus, equation (4) represents the probability expression, $P_{ip} = P_{ip|\,m} \times P_m$.

Since Γ_{pm} and $\Gamma_{p'm}$ represent the expected utility of each joint outcome m for persons p and p', respectively, their weighted sum represents the total utility to be derived by the two-person household. That is, each decision maker has a separate expected utility for the shared decision, and the parameters θ_p and $\theta_{p'}$ weight the importance of each decision maker's expected utility in the joint choice of m.

To obtain the daily pattern choice probabilities for the other person in the household, we differentiate the household generator function, G in equation (2) with respect to person p' and alternative i' to obtain $G_{i'p'} = \partial G/\partial Y_{i'p'}$. and derive a parallel probability expression for the second decision maker:

$$P_{i'p'} = \frac{\exp(\lambda_m V_{i'p'})}{\sum_{j' \in C_{p'm}} \exp(\lambda_m V_{j'p'})} \times \frac{\exp\left(\frac{\theta_p}{\lambda_m}\Gamma_{pm} + \frac{\theta_{p'}}{\lambda_m}\Gamma_{p'm}\right)}{\sum_{m=1}^{M} \exp\left(\frac{\theta_p}{\lambda_m}\Gamma_{pm} + \frac{\theta_{p'}}{\lambda_m}\Gamma_{p'm}\right)} \tag{6}$$

For each household, we derive separately the probability of each member's individual choices from the same joint distribution of error terms, represented by the function G, shown in equation (2). For forecasting purposes, this formulation has the advantage of maintaining separate, proper probability expressions for each decision maker.

The importance weights are formulated as parametric functions that allow us to determine which person-specific attribute variables are correlated with one household member's utility being treated as more important than the other's. The functional form of the importance weights is a logit model in which the two weights sum to one. For persons p and p', these functions are expressed as

$$\theta_p = \frac{\exp(Z_p\omega)}{\exp(Z_p\omega) + \exp(Z_{p'}\omega)} \quad \text{and} \quad \theta_{p'} = \frac{\exp(Z_{p'}\omega)}{\exp(Z_p\omega) + \exp(Z_{p'}\omega)} \tag{7}$$

The variables Z_p and $Z_{p'}$ are vectors of person-specific attributes, and ω is a vector of parameters representing the importance of these attributes to a person's influence on shared utility. Under the null hypothesis that person-specific attributes have no differential effect on the composite utility of joint outcomes, the ω vector would have values that are not statistically different from zero.

We refer to the model system derived above as the parallel choice constrained logit (PCCL), owing to the joint outcome constraints imposed on multiple decision makers, acting in parallel. The PCCL assumes error correlation between household decision makers, allowing correlation across subsets of daily activity pattern alternatives. For example, if the utility of a non-joint daily activity pattern alternative were to increase for person p (e.g., a single work tour), the utility of independent daily activity patterns would increase for *both* persons, thereby reducing the probability of choosing any daily activity pattern that includes a joint activity sequence. A detailed description of the PCCL's direct and cross-elasticities can be found in Gliebe (2004).

The PCCL reduces to an IID multinomial logit model (MNL) in the degenerate case in which there are no alternative joint outcomes. Further, if we remove the joint outcome constraints, a joint error-term distribution function for multiple household members could be used to derive MNL models for each decision maker.

4. Estimation results

The parameters of the PCCL model can be estimated using maximum likelihood methods. For a data set composed of h one-day observations of two-decision-maker households, the log likelihood function is the sum of the log likelihood calculations for both individuals in every household.

The final model specification includes 104 estimated parameters, representing the effects of various household and person attribute variables on the utility of specific components of the daily pattern alternatives, such as number of tours by type, presence of a shared ride or joint activity pattern as well as interaction terms. We decided to estimate tour-component-specific rather than alternative-specific parameters, because it provided more interpretable, intuitive parameters, the drawback being a slight loss in goodness of fit. The complete specification is shown in Tables 2–6; however, due to space considerations we will discuss only the most interesting results below.

4.1. *Model fit statistics*

Table 2 shows the log-likelihood at convergence for the final model specification, along with comparison statistics. The likelihood ratio index (rho-squared) of .459 represents a relatively good fit to the data, considering that we are modeling 94 alternatives. The reference model is the MNL, applied separately to the choices of both decision makers. The adjusted likelihood ratio index of .045 is relative to a PCCL market shares specification, and indicates that our 104 tour-component-specific attribute parameters provide a modest improvement in predictive power over what could be obtained with 93 alternative-specific constants. Table 2 also shows the results of a likelihood ratio test (chi-square) between zero-coefficients versions of the MNL and the PCCL, in which the PCCL soundly rejects the MNL specification, based purely on the information provided by the PCCL constraint nest structure over the assumption of independent choice sets between pairs of household decision makers.

4.2. *Constraint nest parameters*

The parameter estimates for the importance weighting function attributes and for the nest dissimilarity parameters are also shown in Table 2. The attributes specified in the importance weighting function were worker status and the number of pre-school-age children in the household interacted with the female decision maker. The significant positive parameter for worker status indicates that when deciding between joint outcomes, households place more value on the utility of a worker's daily activity schedule relative to a non-worker, which may be interpreted as the utility of the worker's time in providing income.

The significant positive parameter estimate for the effect of being a mother with young children gives us a hint as to the importance of the role of child care provider in household decision making. That similar effects of the presence of children on the male decision maker proved to be non-significant testifies to the continued relevance of gender-based roles.

Table 2 also includes parameter estimates for four of the 10 joint outcome nest dissimilarity parameter. Estimates were specified in the final model only for those nests for which the parameter was estimated to be significantly greater than one, keeping with the utility maximizing requirements

Table 2. Model fit statistics and constraint nest parameters.

Model fit statistics		
Log likelihood for PCCL with final parameter estimates	−50783.76	
Log likelihood for MNL with zero coefficients	−93935.78	
Log likelihood for PCCL market shares	−53166.58	
Log likelihood for PCCL with zero coefficients	−93743.45	
Rho-squared (Final model vs. MNL zero coefficients)	0.459	
Rho-squared adjusted (Final model vs. PCCL market shares)	0.045	
Likelihood ratio statistic (PCCL vs. MNL zero coefficients)	384.66	
Chi-square for 10 degrees of freedom at .01 significance	23.21	
Constraint nest parameters	Coefficient	Est./S.E.
Individual importance function attributes		
Full-time worker	0.798	4.897
Adult female by number of children up to 5 years	0.442	3.076
Dissimilarity parameters by joint outcome		
Independent daily patterns	1.000	fixed
One all-joint discretionary tour (J1)	1.088	3.643
Two all-joint discretionary tours (J1)	1.542	5.771
Joint activities before non-joint activities in a single tour (J2)	1.000	fixed
Joint activities after non-joint activities in a single tour (J3)	1.000	fixed
Joint discretionary activities before & after work in single tour (J5)	1.000	fixed
Shared ride to non-joint activity	1.178	2.256
Shared ride home from non-joint activity	1.465	3.131
Shared ride to and from non-joint activity in a single tour	1.000	fixed
Shared ride to non-joint activity & joint discr. activities after in single tour	1.000	fixed

discussed above. The dissimilarity parameters for joint outcome nests that were not significantly greater than one were fixed to one. The four estimated parameters correspond to the joint outcome nests for:

- one fully joint tour;
- two fully joint tours;
- a single shared ride to a non-joint activity site (drop off); and
- a single shared ride home from a non-joint activity site (pick up).

These parameters indicate correlation within each nest between the unobserved attributes of the elemental full-day tour pattern alternatives, and that alternatives within the nest are viewed by decision makers as close substitutes for one another.

4.3. *Variables affecting tour frequencies*

Parameter estimates for variables affecting tour frequencies are shown in Table 3 (discretionary tours) and 4 (education tours, work tours and sub-tours). Note that we restricted the availability of full-day tour pattern

Table 3. Variables affecting discretionary tour frequencies.

Parameter	Coefficient	Est./S.E.
Number of home-based discretionary tours		
Full-time worker		
1 Tour	−0.145	−2.645
2 Tours	−1.294	−18.915
3 Tours	−2.697	−24.654
4 Tours	−4.352	−18.081
Part-time worker		
1 Tour	0.207	3.477
2 Tours	−0.394	−5.594
3 Tours	−1.732	−17.029
4 Tours	−3.237	−18.116
Not employed		
1 Tour	0.271	7.330
2 Tours	−0.763	−14.969
3 Tours	−2.191	−29.251
4 Tours	−3.962	−29.812
Not employed & over age 65 (retired)	−0.273	−8.365
Adult student	−0.212	−3.130
Worker commuting distance (miles/10 one way)	−0.183	−10.489
More workers than vehicles available	−0.164	−3.090
Number of children up to 5 years old		
Adult female	.216	12.067
Number of children 6–17 years old		
Adult female	0.320	23.537
Adult male	0.193	11.046
Discretionary and work tour interaction effects		
Total discretionary plus work tours = 2	−1.674	−21.938
Total discretionary plus work tours = 3	−2.931	−34.895
Total discretionary plus work tours = 4	−3.771	−22.869
Discretionary tours before work tours*	−1.354	−19.340
Discretionary tours after work tours*	0.237	4.335
Discretionary and education tour interaction effects		
Total education plus discretionary tours = 2	−1.546	−9.543
Total education plus discretionary tours = 3	−2.016	−5.960
Education tour after discretionary tours**	−1.084	−3.742

* Reference is multiple interspersed work and discretionary tours.
** Reference case is education tour before discretionary tour.

alternatives that include education and/or work tours to individuals with positive values for student and employment status indicator variables.

Tour frequency constants are stratified by the number of tours and by worker status. Interpretation of these parameters requires consideration of both the main tour frequency effects as well as constants representing interaction between tours of different types. The results indicate what might be expected: full-time workers have a greater propensity to make work tours and work-based sub-tours than part-time workers; part-time workers make more

Table 4. Variables affecting education, work and work-based sub-tour frequencies.

Parameter	Coefficient	Est./S.E.
Presence of home-based education tour		
Constant	1.274	11.713
Not employed & over age 65 (retired)	−2.043	−3.176
Number of home-based work tours (up to two)		
Full-time worker		
1 Tour	2.610	54.954
2 Tours	0.914	8.858
Part-time worker		
1 Tour	1.453	26.084
2 Tours	−0.489	−2.824
Worker commuting distance (miles/10 one-way)		
Full-time worker making second work tour	−1.426	−13.847
Part-time worker making second work tour	−0.843	−4.516
More workers than vehicles, full-time worker	−0.595	−5.780
Number of children up to 5 years old		
Adult female	−0.280	−6.109
Adult male	0.141	3.329
Number of children 6–17 years old	0.191	7.651
Number of work-based sub-tours (up to two)		
Full-time worker		
1 Sub-tour	−1.599	−48.911
2 Sub-tours	−3.966	−42.277
Part-time worker		
1 Sub-tour	−1.925	−25.528
2 Sub-tours	−4.599	−15.929
More workers than available vehicles	−0.425	−3.511
Number of children 6–17 years old	−0.114	−3.871
Interaction with discretionary and work tours (one education tour and one work tour)		
Education tour before work tour*	−3.506	−12.635
Education tour after work tour*	−2.748	−13.473
Ordering of work tours with and without sub-tours		
Work tour with sub-tour before work tour without sub-tour	−0.723	−3.899
Work tour with sub-tour after work tour without sub-tour	−4.214	−17.766

* Reference case is work tours and education tours not in same day.

discretionary tours than full-time workers; and non-workers make more discretionary tours than full- and part-time workers, taking into account the negative interaction effect between work and discretionary tours. The utility of making multiple tours of any one type diminishes with frequency.

The more interesting results shown in Tables 3 and 4 relate to the effects of the presence of children and the gender of the adult decision maker. The parameter estimates indicate that females in households with very young children, up to five-years-old, have a significantly greater propensity to make discretionary tours and a lower propensity to make work tours, relative to males in households with or without children. In comparison, adult males in

Table 5. Variables affecting joint activity patterns on tours.

Parameter	Coefficient	Est./S.E.
Number of fully joint home-based discretionary tours (J1)		
1 or 2 Adult workers		
1 Tour	−0.426	−8.645
2 Tours	−1.051	−10.078
0 Adult workers		
1 Tour	−0.083	−1.542
2 Tours	−0.373	−3.646
Both adults not working & over age 65	0.448	8.048
1 or 2 Adult students (applies to one tour only)	−0.376	−3.970
Total number of children	−0.362	−14.542
Joint activities before non-joint activities in a tour (J2)		
2 Adult workers	−4.918	−19.768
1 Adult worker	−6.546	−16.012
0 Adult workers	−4.064	−18.882
More workers than available vehicles	1.087	2.397
Distance between workplaces (miles/10)	−0.822	−3.071
Joint activities after non-joint activities in a tour (J3)		
Constant (any number of workers)	−4.664	−35.496
Commuting distance if both work (miles/10 1-way)	0.415	3.364
Distance between workplaces (miles/10)	−0.408	−3.174
More workers than available vehicles	1.936	9.200
Total number of children	−0.242	−2.547
Joint discretionary activities before & after work in a tour (J5)		
Constant (available only if two workers)	−4.710	−16.886
Commuting distance if both work (miles/10 1-way)	0.998	9.499
Distance between workplaces (miles/10)	−3.174	−9.048
More workers than available vehicles	0.914	2.451
Number of children up to 5 years old	1.039	7.439
Number of children 6–17 years old	0.514	4.379
*Interaction between independent and joint tours**		
Independent tours before joint activity tours	0.218	5.046
Independent tours after joint activity tours	−0.947	−11.970
Joint tour between independent tours	−0.574	−4.864

* At least one independent and one joint tour. Reference case is independent and joint tours not included in same day.

households without children are unaffected in terms of discretionary tour making, but do seem to exhibit a significant propensity to make more work tours. The significant effects of older children, ages 6–17, include a greater propensity for both females and males to make discretionary tours, a reduced propensity by both genders to make work-based sub-tours, and an increased propensity among both genders to make work tours. Again, gender-based roles are evident, with mothers serving as primary care givers for very young children, and fathers acting as income providers.

Table 6. Variables affecting shared rides on tours.

Parameter	Coefficient	Est./S.E.
Shared ride to non-joint activity (drop off)		
Constant (any number of workers)	−4.394	−32.986
Commuting distance if both work (miles/10 1-way)	0.642	6.824
Distance between workplaces (miles/10)	−0.560	−5.184
More workers than available vehicles	2.389	13.603
Total number of children	−0.608	−5.378
Shared ride home from non-joint activity (pick up)		
Constant (any number of workers)	−4.516	−30.247
Commuting distance if both work (miles/10 1-way)	0.319	2.324
Distance between workplaces (miles/10)	−0.350	−2.639
More workers than available vehicles	2.221	10.085
Total number of children	−0.267	−2.421
Shared ride to and from non-joint activity n a single tour (drop off & pick up)		
2 Adult workers	−3.390	−27.495
0 or 1 Adult worker	−4.935	−22.987
Commuting distance if both work (miles/10 1-way)	1.048	17.126
Distance between workplaces (miles/10)	−1.203	−12.931
More workers than available vehicles	1.214	6.465
Number of children up to 5 years old	−1.911	−5.938
Number of children 6 to 17 years old	−0.526	−4.950
Shared ride to non-joint activity & joint discretionary activities afterwards in single tour (drop off & J3)		
2 Adult workers	−3.280	−23.646
0 or 1 Adult worker	−6.138	−15.008
Commuting distance if both work (miles/10 1-way)	0.952	12.913
Distance between workplaces (miles/10)	−1.373	−11.315
More workers than available vehicles	1.114	5.130
Total number of children	−1.419	−7.517

4.4. *Variables affecting joint activity patterns and shared rides*

Table 5 shows the parameter estimates for variables affecting the propensity for individuals to incorporate joint activities into their daily schedules. Table 6 shows parameter estimates for the incorporation of shared rides, without joint activity participation. In both cases, the marginal utility represented by these parameter estimates is added to the utility represented by the underlying tour type.

4.5. *Fully joint tours*

For fully joint tours, the constants are stratified by the number of tours and the number of adult workers in the household. The negative coefficients indicate that making a discretionary tour is viewed as more onerous than making the same tour independently, and that this marginal disutility is more negative with greater numbers of joint tours.

As shown in Table 5, the disutility of joint tours for households with zero or one worker is not as great as for two-worker households. In fact, for a household in which both adults are retired, there is a significant positive effect of the utility of making fully joint tours that completely offsets the disutility, relative to other zero-worker households, and makes a joint discretionary tour more attractive than an independent discretionary tour. These results suggest that older adults may value companionship more than younger adults, or that one spouse may depend on the other for rides. In contrast, households in which at least one adult is a student show a significant negative propensity to engage in fully joint tours, which might be attributed to unobserved at-home study.

The total number of children in the household has a significant negative effect on the utility of fully joint home-based tours (between adults). These results support the notion that the presence of children leads to task specialization. For example, one parent may stay home with a child while the other shops or escorts another child to athletic practice.

4.6. *Partially joint tours and shared rides*

Table 5 shows also shows parameters related to the effects of household and person attributes on the propensities of three partially joint tour patterns (J2, J3 and J5), which are similar to the effects shown in Table 6 for four different shared ride arrangements (drop off, pick up, pick up and drop off, and drop off with joint tour type J3 (see Figure 1). Across all seven patterns there are significant positive effects on the utility of being in a household with fewer cars than workers, a strong indicator of the primary motivation for partially joint tour patterns and shared ride arrangements. For the two partially joint tour patterns that involve joint activity participation on the home-bound half of the tour and in all of the shared ride arrangements, the utility of the pattern is positively influenced by workers' commuting distance, and offset by the negative effect of the separation distance between workplaces. These results seem to indicate that working couples who find themselves on relatively synchronous space-time paths because of proximate work locations will seek efficiency by incorporating shared rides and activities into their work tours.

Finally, Tables 5 and 6 show that both very young and older children have a significant negative effect on the propensity of their parents to choose all four shared ride arrangements and two of the three joint tour types, which is expected for the same reasons discussed above for fully joint tours.

An interesting exception is the significant positive effect of the number of children on the propensity of parents to choose joint tour type J5, which involves joint activities at both the beginning and end of a work tour. This suggests a pattern in which working parents are dropping off and picking up their children at day care centers and schools on their way to and from work and this effect is significantly greater for younger children, who likely depend on rides from parents, than for older children who may have access to alternative modes, such as school bus.

Conclusions

In this paper we have explored the ways in which household members decide how to incorporate joint activities and shared travel into their daily activity-travel patterns. To this end, we formulated a structural discrete choice model that explicitly accounts for correlation between decision makers through their joint choice of a shared outcome, which acts to constrain individual choice sets. Moreover, we showed that this model is superior to models that do not account for this correlation. In applying our model, we found strong evidence for the impact on both joint and independent activity-travel patterns of work schedules, commuting distances, automobile availability, and the presence of children.

The insights gained through this research could be improved through the use of a dataset that included observations of in-home activities and the activities of children in the household, which would require the addition of some daily pattern alternatives to account for school activities. Extensions of the current model structure to more than two persons are feasible, given the proper construction of joint outcome nests. The focus on tour pattern formation could be enhanced by considering the type and frequency of activity stops and the allocation of household maintenance tasks and automobiles. In addition, it would be worthwhile to consider additional nesting structures, either above or below the level of the constraint nests to model unobserved correlation between joint outcomes or increased substitution between elemental alternatives.

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