A MODEL FOR WORK ACTIVITY SCHEDULES WITH SYNCHRONIZATION FOR MULTIPLE-WORKER HOUSEHOLDS

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ABSTRACT

This paper presents a hybrid discrete choice-duration model for work activity scheduling with interactions between workers in a multiple-worker household. The model operates in discrete space with a fine level of temporal resolution. Main innovative component relates to intra-household interactions that are expressed in coordination and synchronization mechanisms between the workers. The model was estimated based on a large Household Travel Survey in the San Francisco Bay Area. The estimation results confirmed strong intra-household interactions including synchronizations for outbound and inbound commute as well as creating overlaps of available time windows for joint activities before and after work. Relative strength of the synchronization mechanisms proved to be a function of the person characteristics and household composition.

Keywords: Time of day choice, activity schedule, departure time, intra-household interactions

RESEARCH MOTIVATION, OBJECTIVES, AND METHODOLOGY

A new model is presented that represents a disaggregate choice of work activity schedule and incorporates interactions between workers in a multiple-worker household. The model represents a hybrid discrete choice-duration construct and operates in discrete space with a fine level of temporal resolution. The hybridization is based on a technique of “shift” variables that has been applied (with linear temporal shifting profiles) in several Activity-Based Models developed in US for Metropolitan Regions of Columbus, Atlanta, Sacramento, and San-Francisco. This technique is effectively combined with a tour-based approach that considers a combination of departure and arrival times (and corresponding tour duration) –

see *Vovsha & Bradley, 2004; Abou-Zeid et al, 2006; Popuri et al, 2008*. An innovative feature of the current research is non-linear temporal shifting profiles that significantly improve the statistical fit and make the model more behaviourally realistic.

Another innovative component relates to intra-household interactions that are captured by the synchronization mechanism between the workers. It has been recognized that activity scheduling cannot be understood and modelled at a single person level because of strong intra-household interactions. In particular, it proved that people value joint activity participation differently from individual participation in the same activity that results in synchronization of schedules between the household members – see *Zhang et al, 2005; Habib et al, 2008*.

The synchronization mechanism includes exact and fuzzy synchronization types. An exact synchronization relates to a joint departure from home for outbound commute or joint arrival back home for inbound commute and assumes joint travel arrangements as well as possible participation in joint activity on the way to work or on the way back home from work. A fuzzy synchronization relates to creating time window overlaps either before departure from home or after arrival back home and assumes participation in joint in-home and out-of-home activities that are not parts of the commuting episodes.

Main methodology and terminology adopted for the current research is illustrated in Figure 1. We consider daily schedules for two main workers in the household (household heads in most cases) in the active time frame that is set between 6 AM and 11 PM of the same day. For each of the workers, we identify an entire-work-tour framework starting with departure from home and ending with arrival back home. This framework includes travel time to and from work as well as some additional activities undertaken on the way to work (like dropping-of a child at school by the 1st worker) and/or from work (like a shopping episode of the 2nd worker). Additional home-based tours for non-work purposes (like the visiting-friend tour of the 1st worker) are not counted in the work tour framework. The formulation of work tour framework is specifically useful for operational Activity-Based Models.

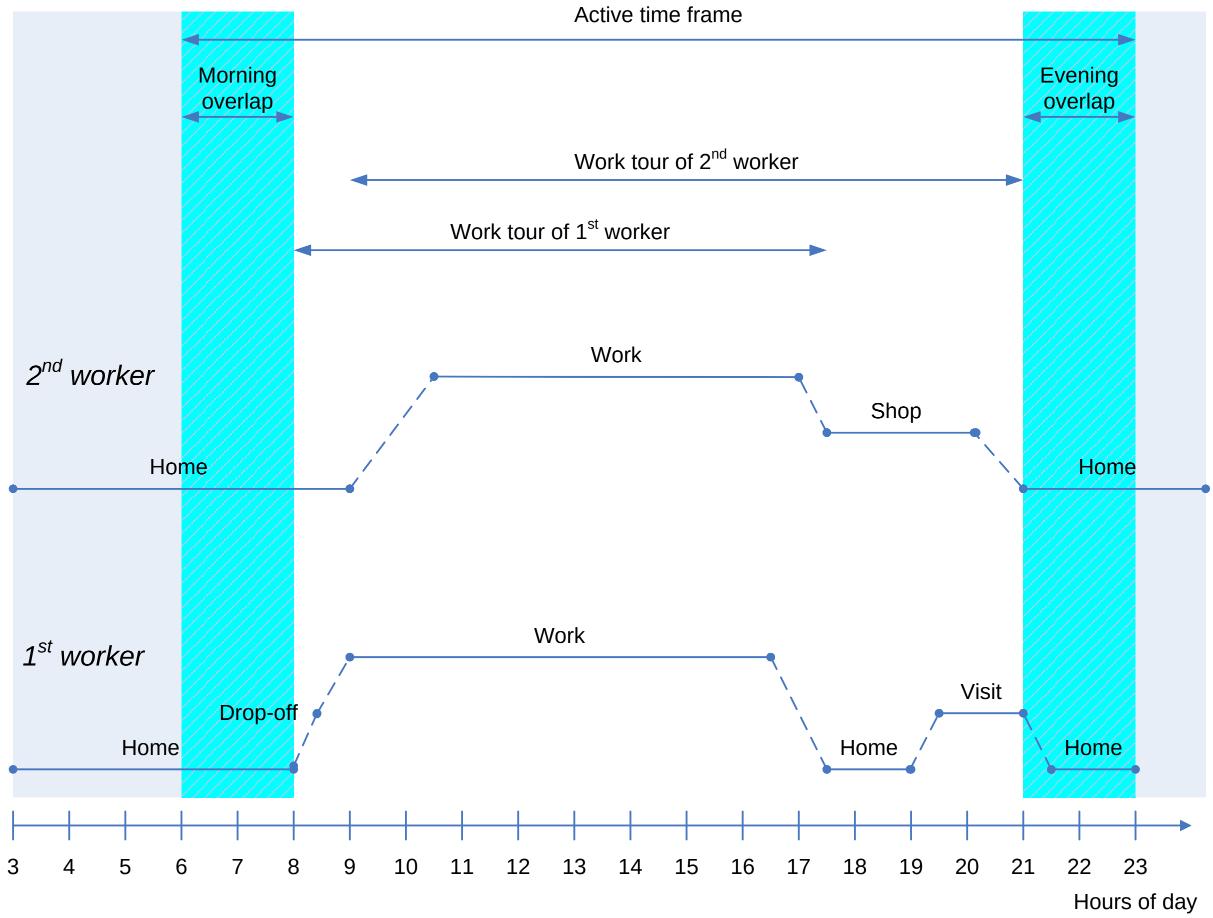

Figure 1 – Methodology of Analysis and Main Terms

Using the work tour frameworks for both workers we further calculate time window for each worker before and after work available for non-work activities either in-home or out-of-home as well as overlaps between these windows before work and after work. These overlaps serve as a time source for joint activities and travel not included in the work tours. The main research objective of the current study is to explore intra-household coordination mechanisms between two workers with respect to their work tour schedules. In particular, these mechanisms can be reduced to the following main types:

- Synchronization of travel arrangements for joint outbound commute to work. This may imply some joint activity on the way to work (for example, stopping at Starbucks) or just carpooling where one of the workers would drop-off the second one on the way to work.
- Exact synchronization of travel arrangements for joint inbound commute. This may imply some joint activity on the way from work (for example, shopping together) or just carpooling where one of the workers would pick-up the second one on the way from work.

- Fuzzy synchronization in a form of pre-commuting overlap of time windows that creates an opportunity for having joint activities (either in-home or out-of-home) before (travel to) work.

- Fuzzy synchronization in a form of post-commuting overlap of time windows that creates an opportunity for having joint activities (either in-home or out-of-home) after (travel from) work.

By modelling work departure and arrival time choices simultaneously for both workers, we can explore statistical significance of these mechanisms and see if the work tour schedules can be fully explained as individual choices of each worker or there are significant interactions and synchronizations between the workers. The choice model formulation that serves as the main vehicle for the current study represents a joint choice of outbound and inbound commute time by two workers where the utility function includes both individual and joint components. Each component is parameterized by a rich set of person, household, and travel-related attributes.

SEED HYBRID TIME-OF-DAY CHOICE-DURATION MODEL

The seed structure used in this research is a model for scheduling travel tours that can predict departure-from-home and arrival-back-home time for each tour with enhanced temporal resolution. The model formulation is fully consistent with the tour-based modelling paradigm and is designed for application in an individual micro-simulation framework. Time-of-day choice models of this type has been estimated and applied as a part of the Activity-Based travel demand model system developed in regions of US such as Columbus, Atlanta, San-Francisco Bay Area, Sacramento, and San-Diego.

The model is essentially a discrete choice construct that operates with tour departure-from-home and arrival-back-home time combinations as alternatives [*Vovsha & Bradley, 2004*]. The proposed utility structure based on "continuous shift" variables represents an analytical hybrid that combines the advantages of a discrete choice structure (flexible in specification and easy to estimate and apply) with advantages of a duration model (parsimonious structure with a few parameters that support any level of temporal resolution including continuous time). If the model is applied with a temporal resolution of 1 hour, it is normally expressed in 19 alternatives for departure and arrival time from 5:00 AM through 11:00 PM while the remaining hours can be collapsed together. This is expressed in 19×20/2=190 hour-by-hour departure-arrival time alternatives (Columbus and Atlanta implementation). Only feasible combinations where arrival hour is equal to or later than the departure hour are considered. If the temporal resolution is enhanced to 30 min the number of alternatives will be quadrupled up to 860 (San-Francisco, Sacramento, and San Diego implementations).

In the previous implementations, the model was applied sequentially for all tours in the individual daily activity-travel pattern according to the predetermined priority of each activity type. The enhanced temporal resolution allows for applying direct availability rules for each subsequently scheduled tour to be placed in the residual time window left after scheduling the tours of higher priority. This conditionality ensures a full consistency for the whole individual daily schedule as an outcome of the model. However, intra-household interactions have not been considered in full. Only travel tours implemented jointly by several household members for non-work activities where scheduled as one unit for all participants. Work tours for different persons where scheduled independently.

ANALOGUE BETWEEN DISCRETE CHOICE AND DURATION MODELS THROUGH "SHIFT" VARIABLES

Consider a discrete set of time-related alternatives, for example, alternative duration for some activity in hours $t = 1,2,3...$. A general form for the probabilistic model that returns the probability of activity duration is:

$$P(t) = f(t), \tag{1}$$

where $f(t)$ represent a probability density function for duration. This general form is not really operational because it incorporates any possible parametric or non-parametric density function and does not suggest any constructive method for model estimation.

Duration models operate with a special function $0 < \lambda(t) < 1$ that represents a termination rate (frequently called "hazard" in the literature) at time t assuming that the activity has not been terminated before, i.e. at one of the time points $1,2...,t-1$. The probability density function for a duration model in discrete space takes the following form:

$$P(t) = \lambda(t)\prod_{s=1}^{t-1}[1 - \lambda(s)]. \tag{2}$$

There is a direct correspondence between the general-form density function and the continuous duration model. Any duration model has the correspondent density function calculated by the formula (2), and any density function has the underlying termination rate calculated by the following formula:

$$\lambda(t) = \frac{f(t)}{1 - \sum_{s=1}^{t-1} f(s)}. \tag{3}$$

The duration-type formulation (2) has both operational and meaningful advantages over the general model formulation (1), because the termination-rate function $\lambda(t)$ is frequently easier to parameterize, estimate, and interpret than the density function itself. These advantages are especially clear when modelling processes with duration-related conditionality. Also having the termination-rate $\lambda(t)$ as an analytical function of t makes the duration model equally practical for any units of t.

Formulation of the duration model as a discrete choice model employs the following analytical form, assuming a multinomial logit model in this case:

$$P(t) = \frac{\exp(V_t)}{\sum_s \exp(V_s)}, \tag{4}$$

where V_t denotes the utility function that is a linear-in-parameters function of independent variables:

$$V_t = \sum_k \beta_{kt} x_{kt}, \tag{5}$$

where:

$k \in K$	=	household, person, zonal, and duration-related variables,
x_{kt}	=	values of the variables for each alternative,
β_{kt}	=	coefficients for the variables.

There is again a direct correspondence between the choice model (4) and the general-form density function (1). Any choice model has the corresponding density function calculated by formula (4), and also any density function (1) has an underlying set of utilities that are calculated by the following formula:

$$V_t = \ln f(t). \tag{6}$$

As in the case of duration models, discrete choice models (4) have advantages over the general formulation (1) because utility expressions (5) are easier to parameterize, estimate, and interpret than the density function itself. However, when the utility expression (5) is formulated in a general way with all alternative-specific coefficients and variables, the choice model (4) is getting more complex with the addition of temporal resolution, which is not the case with the duration model (2). Also, the multinomial-logit formulation with independent alternative-specific variables suffers from the IIA (independence from the irrelevant alternatives) property with respect to those variables, ignoring the fact that the duration alternatives are naturally ordered.

Both of these deficiencies of the discrete choice formulation can be overcome using a certain specification of the utility function (5). This specification stems from an analogy that can easily be established between the duration model (2) and discrete choice model (4). Consider a ratio of densities for two subsequent points in time stemming from the two models and restrict it to be equal in both cases:

$$\frac{P(t+1)}{P(t)} = \frac{\lambda(t+1)\times[1-\lambda(t)]}{\lambda(t)} = \exp(V_{t+1} - V_t). \tag{7}$$

Formula (7) contains several interesting and analytically convenient particular cases that lead to operational models that can be equally written and estimated in either duration form (2) or discrete choice form (4). We will consider only one (actually, the simplest) case that corresponds to a duration model with a constant termination rate λ. With this assumption, the expression (7) is simplified to the following formula:

$$\exp\left(V_{t+1} - V_t\right) = 1 - \lambda . \quad (8)$$

It means that there is a constant decrement in the utility function for each subsequent time point compared to the previous one and it is equivalent of the constant termination rate parameter of the duration model. Negative utility increment corresponds to the value of $1-\lambda$ that is less than 1. To ensure that the utility increment is independent of the time point, we should set variables x_{kt} and coefficients β_{kt} in the utility expression (5) in a specific way. One of the possible ways to do it is to define all coefficients as generic across duration alternatives ($\beta_{kt} = \beta_k$) while the variables are assumed to have the following form:

$$x_{kt} = t \times x_k . \quad (9)$$

This formulation for the variables is not very restrictive since most of the household, person, and zonal characteristics in the time-of-day choice model are naturally generic across time alternatives. However, it is not true for network level-of-service variables that vary by time-of-day and should be specified as alternative-specific. These variables, which are essentially time-specific, violate the constant termination-rate assumption. However, the discrete choice framework allows for easy hybridization of both types of variables (generic and time-specific).

Using generic coefficients and variables of the type (9) creates a compact structure of the choice model where the number of alternatives can be arbitrarily large (depending on the chosen time unit scale) but the number of coefficients to estimate is limited to the predetermined set K. These variables can be interpreted as “continuous shift” factors that parameterize the termination rate in such a way that a positive coefficient means the termination rate is getting lower and the whole distribution is shifted to the longer durations. Negative values work in the opposite direction, collapsing the distribution towards shorter durations.

In the current research, we also consider a non-linear generalization of shift variables in the following form:

$$x_{kt}^1 = t \times x_k ; x_{kt}^2 = t^2 \times x_k , \quad (10)$$

Where x_{kt}^1 and x_{kt}^2 are used in the utility function as independent variables with estimated coefficients β_k^1 and β_k^2 consequently. This extension of model structure allows for capturing some non-linear effects, in particular saturation effects where the impact of a certain variable x_k is expressed in differential shifts along the duration time line. Essentially, the resulted multiplier for original variable x_k in the utility function $\left(t \times \beta_k^1 + t^2 \times \beta_k^2\right)$ represents the timing profile for impact of this variable.

MODEL FORMULATION FOR A SINGLE INDIVIDUAL TOUR

Scheduling of an entire travel tour requires that the choice alternatives are formulated as tour departure-from-home and arrival-at-home hour combinations (g,h). Then, tour duration is derived as the difference between the arrival and departure hours ($h-g$). In the current research, tour duration incorporates both the activity duration and travel time to and from the main tour activity including intermediate stops.

The tour time-of-day choice utility for single tour can be operationalized in the following general form [*Vovsha & Bradley, 2004; Abou-Zeid et al, 2006; Popuri et al, 2008*]:

$$V_{gh} = V_g + V_h + D_{h-g}, \tag{11}$$

where:

g,h	=	departure from home and arrival back home times,
V_g	=	departure time choice specific component,
V_h	=	arrival time choice specific component,
D_{h-g}	=	duration-specific component,

Departure and arrival hour-specific components are estimated using generic "shift-type" variables (household, person, and zonal characteristics) according to the formulas (9-10) with a limited set of time-of-day period-specific constants. Just as duration "shift" variables are multiplied by the duration of the alternative, departure "shift" variables are multiplied by the departure alternative and arrival "shift" variables are multiplied by the arrival alternative:

Note that the index of the duration component is (*h-g*) rather than (*g*×*h*), making the estimation procedure much simpler since the number of duration alternatives is much less than the number of departure/arrival combinations. It should be noted that none of the estimated components of the utility function (10) has an index with dimensionality (*g*×*h*). Thus, the number of coefficients that have to be estimated is in general fewer than number of alternatives. This parsimonious structure, however, outperformed a model with a full set of (*g*×*h*) alternative specific constants [*Vovsha & Bradley, 2004*].

JOINT MODEL FOMULATION FOR TWO WORKERS

The purpose of the current research is to explore work tour scheduling process in multiple-worker households with a special emphasis on intra-household interactions. The main analytical vehicle for this is a model of joint choice of outbound and inbound commute time by two workers where the utility function includes the following main components:

$$V_{ghij}^{rq} = V_g + V_h + D_{h-g} + V_i + V_j + D_{j-i} + W_{\min(g,i)} + W_{\max(h,j)} + W_{\min(g,i),\max(h,j)} + S_{gi}^{r} + S_{hj}^{q} + S_{gihj}^{rq}, \quad (12)$$

where:

g, h = departure from home and arrival back home times for 1st worker,
i, j = departure from home and arrival back home times for 2nd worker,
$r = 0,1$ = exact synchronization (joint travel) indicator for outbound commute,
$q = 0,1$ = exact synchronization (joint travel) indicator for outbound commute,
V_g = departure time component for 1st worker,
V_h = arrival time component for 1st worker,
D_{h-g} = duration component for 1st worker,
V_i = departure time component for 2nd worker,
V_j = arrival time component for 2nd worker,
D_{j-i} = duration component for 2nd worker,
$W_{\min(g,i)}$ = pre-commuting overlap of time windows of both workers,
$W_{\max(h,j)}$ = post-commuting overlap of time windows of both workers,
$W_{\min(g,i),\max(h,j)}$ = compensatory effects between two window overlaps,
S_{gi}^{r} = outbound synchronization component for joint travel,
S_{hj}^{q} = inbound synchronization component for joint travel,
S_{gihj}^{rq} = Inter-dependence between outbound and inbound travel arrangements.

Each of the components in utility expression (12) is parameterized by person, household, travel and other variables with a frequent use of linear and non-linear shifts of form (9) and (10) for departure time, arrival time, work duration, and overlaps.

For this research, we consider only households with two or more workers of which at least one implemented a work tour on the given day. If there were three or more than workers in the household, two representative workers were choice based on the family relations (preferably, household heads). If only one worker made a work tour, the utility expression (12) was truncated to the basic one-person form (11) and these choice alternatives were separated from the two-worker alternatives. However, the individual utility components shared the same coefficients between two sets of alternatives and, thus, observations with only one of the workers going to work were still used to inform the individual utilities. If a worker had two or more work tours on the given day, both (or all) tours were combined and the departure time for the first tours and arrival time for the last tour were modelled. Cases of multiple tours for the same worker were infrequent.

The choice alternatives for this model are combinations (Cartesian product) of the choice alternatives for both workers. In order to make the choice structure manageable, the number of main choice alternatives for each worker was reduced to 36 by defining 6 main departure time periods and 6 main arrival time periods in the following way:

- For departure time from home (outbound commute):
  1. Earlier than 6:30 AM (labelled as 6 AM),
  2. 6:30 AM – 7:29 AM (labelled as 7 AM),
  3. 7:30 AM – 8:29 AM (labelled as 8 AM),
  4. 8:30 AM – 9:29 AM (labelled as 9 AM),
  5. 9:30 AM – 10:29 AM (labelled as 10 AM),
  6. 10:30 AM or later (labelled as 11 AM),

- For arrival time back home (inbound commute):
  1. Earlier than 3:30 PM (labelled as 3 PM or 15 HR),
  2. 3:30 PM – 4:29 PM (labelled as 4 PM or 16 HR),
  3. 4:30 PM – 5:29 PM (labelled as 5 PM or 17 HR),
  4. 5:30 PM – 6:29 PM (labelled as 6 PM or 18 HR),
  5. 6:30 PM – 7:29 PM (labelled as 7 PM or 19 HR),
  6. 7:30 PM or later (labelled as 8 PM or 20 HR).

This structure still covers most of the commuting cases with a temporal resolution of 1 hour while only relatively infrequent cases of very early or very late departure and/or arrival are collapsed together into broad open-ended intervals. Duration of work tour for each person alternative was calculated as shown in **Table 1**. The duration component loses its precision only for open-ended alternatives of departure and arrival.

Table 1 – Work Tour Duration Calculation for Each Choice Alternative (Hours)

Departure from home	Arrival back home					
	≤3:30 PM (3 PM)	3:30-4:29 (4 PM)	4:30-5:29 (5 PM)	5:30-6:29 (6 PM)	6:30-7:29 (7 PM)	≥7:30 PM (8 PM)
≤6:30 AM (6 AM)	9	10	11	12	13	14
6:30-7:29 (7 AM)	8	9	10	11	12	13
7:30-8:29 (8 AM)	7	8	9	10	11	12
8:30-9:29 (9 AM)	6	7	8	9	10	11
9:30-10:29 (10 AM)	5	6	7	8	9	10
≥10:30 AM (11 AM)	4	5	6	7	8	9

Pre-work and post-work window overlaps between two workers were calculated as shown in **Table 2** and **Table 3** respectively. Maximum overlaps that correspond to the latest departure after 10:30 AM were also used to calculate this variable when one of the workers did not go to work.

Table 2 – Pre-Work (Morning) Time Window Overlap between Two Workers (Hours)

1st worker departure	2nd worker departure					
	≤6:30 AM (6 AM)	6:30-7:29 (7 AM)	7:30-8:29 (8 AM)	8:30-9:29 (9 AM)	9:30-10:29 (10 AM)	≥10:30 AM (11 AM)
≤6:30 AM (6 AM)	0	0	0	0	0	0
6:30-7:29 (7 AM)	0	1	1	1	1	1
7:30-8:29 (8 AM)	0	1	2	2	2	2
8:30-9:29 (9 AM)	0	1	2	3	3	3
9:30-10:29 (10 AM)	0	1	2	3	4	4
≥10:30 AM (11 AM)	0	1	2	3	4	5

With respect to pre-work window overlaps we assume that no significant joint activity (either in-home or out-of-home) can be undertaken before 6:30 AM. Thus, if one of the workers has to leave to work by this time the couple does not have a chance to engage in any joint activity in the morning. The underlying assumption is also that the work activities themselves are individual. If two workers travel to work together they can have joint pre-work activities on the way as part of their work tours. This is accounted by the synchronization component of utility function (12).

Table 3 – Post-Work (Evening) Time Window Overlap between Two Workers (Hours)

1st worker arrival	2nd worker arrival					
	≤3:30 PM (3 PM)	3:30-4:29 (4 PM)	4:30-5:29 (5 PM)	5:30-6:29 (6 PM)	6:30-7:29 (7 PM)	≥7:30 PM (8 PM)
≤3:30 PM (3 PM)	8	7	6	5	4	3
3:30-4:29 (4 PM)	7	7	6	5	4	3
4:30-5:29 (5 PM)	6	6	6	5	4	3
5:30-6:29 (6 PM)	5	5	5	5	4	3
6:30-7:29 (7 PM)	4	4	4	4	4	3
≥7:30 PM (8 PM)	3	3	3	3	3	3

With respect to post-work window overlaps we assume that substantial joint activities (either in-home or out-of-home) are mostly completed by 11:00 PM. Thus, the maximum window overlap if both workers are back home before 3:30 PM is estimated as 8 hours. Since, the latest arrival back home is an open category (after 7:30 PM) we assume that the minimum window overlap is 3 hours. This is an approximation of the actual time overlaps but it still provides a wide range of alternatives for model estimation.

It should be explained that the crudeness in estimation of the window overlaps stems from the fact that we need to keep the total number of combined alternatives in the choice model in a reasonable range which requires aggregation of departure and arrival time alternatives. Only considering the possible combinations of work schedules of two workers each having 36 alternatives we already arrive at 36×36=1,296 combinations that corresponds to indices (*ghij*). Although, the observed arrival and departure times for each household-day in the survey are known exactly (and the actual window overlaps could be calculated exactly), we had to apply the same aggregation rules to all alternatives including observed and unobserved ones.

In addition to the alternatives defined in terms of departure and arrival hours for each worker we distinguish between synchronized and non-synchronized departures and arrivals. Synchronized departures can only occur when the departure time for both workers is the same and, in addition to that, they leave together for joint travel (most frequently, one of the workers drops-off the other one). Synchronized arrivals can only occur when the arrival time for both workers is the same and, in addition to that, they come together after joint travel (most frequently, one of the workers picks-up the other one). If we consider 36 departure time combinations (*gi*) for both workers, 6 of them (when *g*=*i*) are subject to a dichotomy of synchronized vs. non-synchronized departures. This leads to a total number of departure-related alternatives (*gir*) of 42. In the same vein, by considering arrival synchronizations we arrive at 42 arrival-related alternatives (*hjq*). Finally by combining all departure and arrival alternatives we obtain 42×42=1,764 choice alternatives when both workers go to work.

To complete the model specification, we also added 36 alternatives for household-days where only one of the workers goes to work. These alternatives include formal window overlaps (assuming that the second worker is available for any joint activity) but cannot include any synchronization components. It is important to include these alternatives because there is a significant number of observations of this type in the data set and they are useful for individual utility components. The person-related coefficients in individual components of the utility functions (first 6 components in expression (12)) are shared between the main 1,764 alternatives and additional 36 alternatives.

The suggested specification of the choice model allows for statistical testing of the main hypothesis that the work scheduling decisions in a multiple-worker household are not made independently but are subject to coordination between workers. If the work scheduling decisions are made independently, the observed choice would be explained by the 6 individual components of the utility function and the window overlaps would all be formed randomly. If we establish a statistically significant effect associated with window overlaps on the top of all individual components it would indicate on an intra-household interaction expressed in coordination of schedules between the workers. By parameterization of the window overlap components we also can explore particular details of this coordination and impact of household and person attributes on it.

DATA SET

The current study used a rich dataset from the San-Francisco Bay Area Household Travel Survey implemented in 2000. Total of 15,064 households with 34,680 persons were surveyed with all activities and trips recorded during two consecutive. Out of 34,680 surveyed persons, 18,703 are workers.

After screening out households with less than two workers, weekends, and cases were neither of workers went to work on the given day, the final dataset for model estimation included 7,637 household-days of households with two workers (or more workers of which two representative were chosen) where at least one worker went to work. Of these 7,637 household-days, in 4,949 cases both workers went to work, while in 2,688 cases only one of the workers went to work. The subsequent statistics and estimation results relate to this final dataset.

Some statistics important for substantiation of the choice model structure are shown below in Figures 2-6. Person-level distributions that include all workers who went to work in 7,637 household-days are shown in Figures 2-4. Two-worker interaction statistics that were calculated for 4,949 cases when both workers went to work are shown in Figures 5-6.

Distribution of work tours by departure-from-home hour is presented in Figure 2. Logically, (by far) the most frequent cases relate to 7, 8, and 9 AM. The six hours modelled explicitly (from 6 AM through 11 AM) constitute 89.9%. The earlier hours (5.1%) are collapsed with the 6 AM alternative and the later hours (5.0%) are collapsed with the 11 AM alternative.

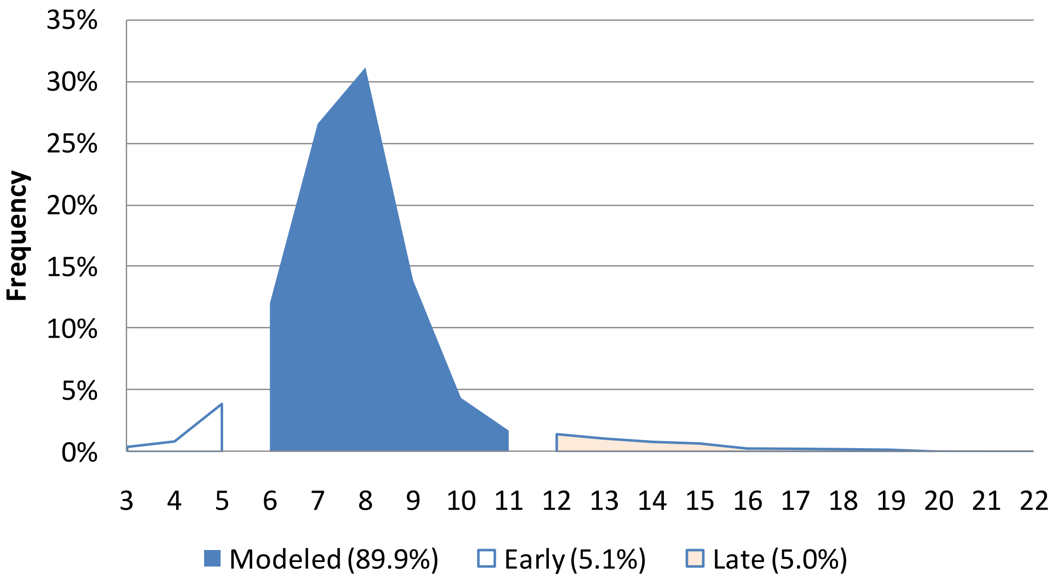

Figure 2 – Work Tour Distribution by Departure Hour

Distribution of work tours by arrival-back-home hour is presented in Figure 3. Logically, and symmetrically to departure hours, the most frequent cases relate to 4, 5, and 6 PM. The six hours modeled explicitly (from 3 PM through 20 PM) constitute 82.9%. The earlier hours (5.6%) are collapsed with the 3 PM alternative and the later hours (11.5%) are collapsed with the 8 PM alternative. The evening spread of arrival times for the later hours is somewhat more substantial than for departure times that results in a relative crudeness of the model with respect to late arrival hours.

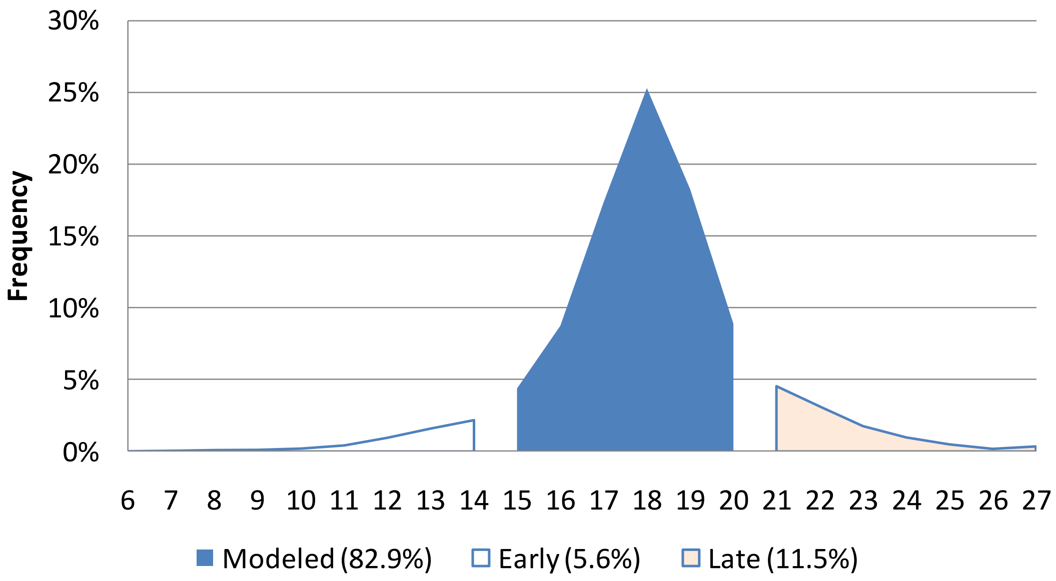

Figure 3 – Work Tour Distribution by Arrival Hour

Distribution of work tours by duration in hours is presented in Figure 4. Logically, and in line with the related distribution for departure and arrival hours, it has a sharp peak with the most frequent cases related to 10-11 hours (tour duration included work activity duration, travel time, and possibly some additional stops on the way to and from work). The eleven duration alternatives modelled explicitly (from 4 hours through 14 hours) constitute 93.8%. The shorter durations (2.6%) are collapsed with the 4-hour alternative and the longer durations (3.6%) are collapsed with the 14-hour alternative.

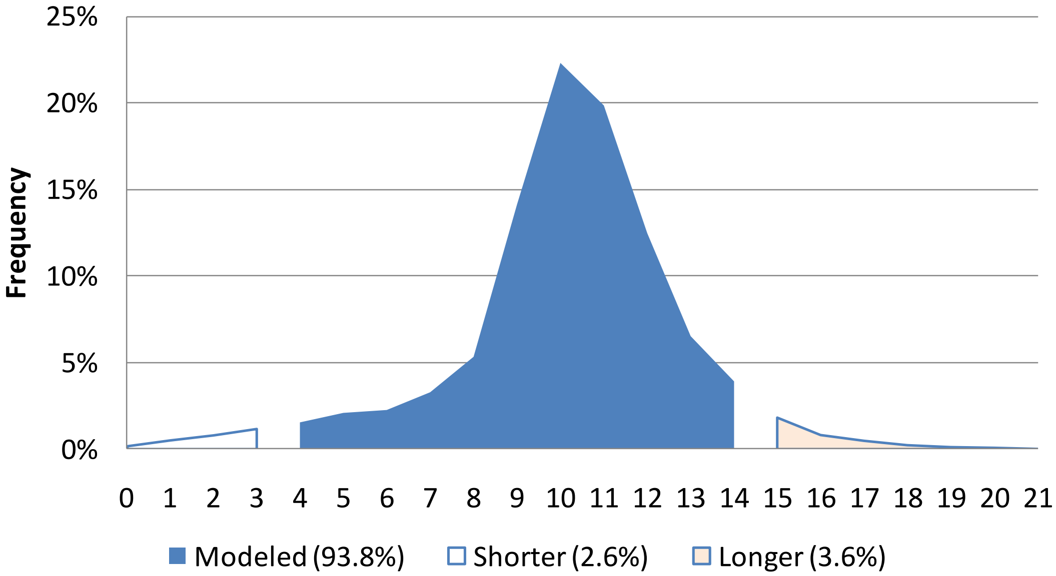

Figure 4 – Distribution of Work Tours by Duration in Hours

Distribution of window overlaps before work by duration in hours is presented in Figure 5. Logically, and in line with the related distribution for departure hour, it is highly skewed towards short durations with the most frequent cases related to 0-2 hours. (The mode of departure time distribution was at 8 AM and if both workers depart at 8 AM the morning window overlap would be 2 hours; however, if at least one of the workers departs earlier, it is enough to shorten the overlap). The six duration alternatives for window overlap before work that are modelled explicitly (from 0 through 5 hours) constitute 99.6% of the observed cases. There is no shorter duration and the longer durations (0.4%) are collapsed with the 5-hour alternative.

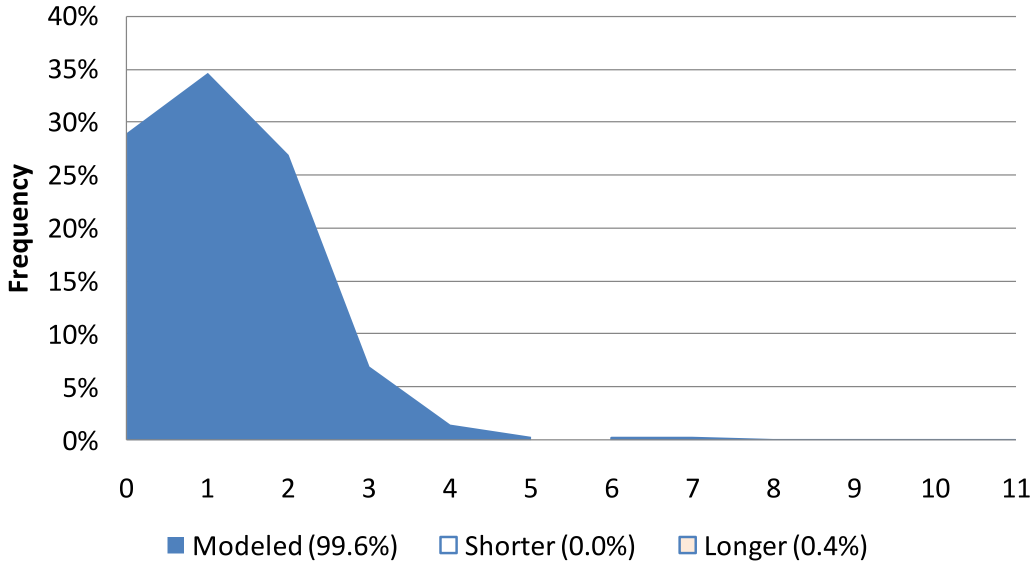

Figure 5 – Distribution of Window Overlaps before Work by Duration in Hours

Distribution of window overlaps before work by duration in hours is presented in Figure 6. It is wider than the distribution for morning overlaps discussed above. The morning overlap distribution is naturally truncated by a very narrow window of opportunities before work for conventional commuting hours. There is a wide range possible after work. Logically, and in line with the related distribution for arrival hour, the most frequent cases for evening overlaps correspond to 4-5 hours. (The mode of arrival time distribution was at 6 PM and if both workers arrive at 6 PM the evening window overlap would be 5 hours; however, if at least one of the workers arrives later, it is enough to shorten the overlap). The six duration alternatives for window overlap after work that are modelled explicitly (from 3 through 8 hours) constitute 80.1% of the observed cases. The shorter durations (19.3%) are collapsed with the 3-hour alternative and the longer durations (0.6%) are collapsed with the 8-hour alternative.

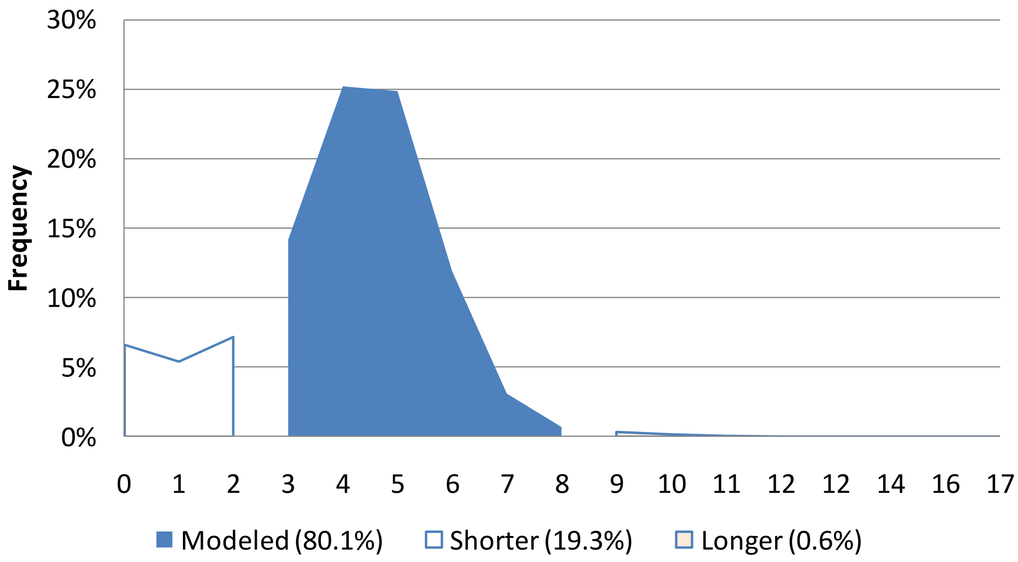

Figure 6 – Distribution of Window Overlaps after Work by Duration in Hours

In general, the calculated statistics from the survey confirm reasonability of the choice model structure with certain alternatives aggregated. Across all dimensions, aggregation would affect only a small portion of infrequent alternatives. In most cases, the share of aggregated alternatives is negligible. For two related dimensions – tour arrival time and evening (pos-work) window overlap – the share of aggregated alternatives is more substantial (10-20%). While it is acceptable for the current study, an extension of the choice model to consider more late-arrival alternatives and consequently, more short-evening-overlap alternatives explicitly would be welcome. It is considered for future research.

ESTIMATION RESULTS

Estimation results for the model specified above are summarized in Tables 4 and 5. The choice model itself was specified as multinomial logit. However, as was shown by *Vovsha & Bradley, 2004,* a model with shift variables does not have an IIA property with respect to the variables but rather mimics a continuous duration model. In general, most of the individual variables and effects associated with departure time, arrival time, or duration proved to be very much in line with individual work tour time-of-day choice models estimated before [*Vovsha & Bradley, 2004; Abou-Zeid et al, 2006; Popuri et al, 2008*]. However (and this is the most interesting aspect and contribution of the current research) on the top of all strong individual variables, many variables and effects that relate to intra-household interactions between the workers were found. This confirms the general hypothesis that activity scheduling process is subject to strong intra-household interactions and cannot be understood and modelled for each person separately [*Zhang et al, 2005; Habib et al, 2008*].

Most of the variables included in the model have a high statistical significance. In some cases, however, we decided to retain a variable with low statistical significance if it belongs to a logical group of variables and has a logical sign.

Main measures of statistical fit and constants are presented in Table 4. It is remarkable that a parsimonious model with about 100 estimated parameters outperformed a reference model with a full set of almost 2,000 alternative-specific constants. This is primarily achieved by using shift-type variables each of them affecting a range of alternatives in a logical way. The constants specified in the model are only one-dimensional, i.e. relate to either individual departure time, or individual arrival time, or individual duration, or joint window overlap, or synchronizations.

Behavioural interpretation of the constants has to be taken with caution because the values of constants are interrelated across dimensions as well as cannot be taken out of the entire model context where constants only complement shift variables summarized in Table 5. However, certain general effects and logical tendencies can be mentioned:

- Departure-time constants generally reflect the departure time distribution profile where the most frequent alternative (8 AM) represents the reference case. Positive values for earlier hours are compensated by the duration constants and shift variables.

- Arrival-time constants generally reflect the arrival time distribution profile where the most frequent alternative (6 PM) represents the reference case. Positive values for later hours are compensated by the duration constants and shift variables.

- Duration constants generally reflect the duration distribution profile where the most frequent alternative (10 hours) represents the reference case. Positive values for shorter durations are compensated by the departure & arrival constants and shift variables.

- Interestingly, constants for either morning or evening window overlaps for multiple-worker households do not directly follow the observed frequency distribution. The estimated values indicate on a tendency towards longer durations: 3-4 hours for morning and 6-7 hours for evening compared to the distribution peaks of 1-2 hours for morning and 4-5 hours for evening. This means that actually observed overlaps are not just products of independent choices made by each worker (in this case the window overlaps would have been shorter than the observed). There is a strong coordination tendency that compensate for the individual variation in schedules. Window overlaps for household-days when only one worker went to work were calculated assuming a full availability of the second worker to have a joint activity with the first worker either before or after work. These variables were introduced to bring these observations in line with the two-worker cases, but the coefficients were separated.

- Another strong manifestation of intra-household interactions is that the constants for the same departure hour and arrival hour proved to be positive and significant. Exact synchronization for joint travel is a comparatively rare case that is reflected in large negative constants for both outbound an inbound commute. However, these negative constants are largely compensated by the positive constant for synchronization in both directions. This means that if workers in the household carpool together they most frequently do it in both directions. This is logical since carpooling in one direction leaves the car passenger in a problematic situation. Either this person has to have a reasonable transit option or find a different carpool arrangement with a non-household member.

- A set of dummies was used to address some of the sharpest differences (that are further complemented by the shift variables). They relate to a specifically early arrival for part-time workers, tendency for low-income workers to depart earlier and arrive later while the opposite is true for high-income workers (some of these effects cannot be isolated from the shift effects discussed below). Also, workplace in CBD is associated with earlier departure and later arrival because of the generally longer travel times. Another behavioural explanation is that the nature of jobs in the CBD area (higher earnings and more management-type occupations compared to the other areas) results in somewhat longer work activity durations.

- Additional dummies reflect the fact that full-time workers in general rarely depart after 9:30 AM and normally have tour duration of at least 9 hours. Younger couples have a clear propensity to synchronize in outbound direction and carpool to work more frequently. This might be explained by a combination of factors for young couples like lower car ownership, lower income, and absence of children. These factors are all accounted for in the utility functions but in a linear additive way. The young couple dummy creates a unique combination of them. Additionally, there is a certain compensatory effect between the morning and evening window overlaps. While workers try to have at least one significant overlap, when it comes to the total of both, there is a satiation effect after 6 hours. This might be an indication of a certain behavioural threshold on the added utility of joint activity participation for discretionary and maintenance activities.

Table 4: Estimation Results – Alternative-Specific Constants and Variables

Variables	**Coefficient (T-stat)**
Measures of statistical fit:	
Likelihood with constants only	-46627.9528
Final likelihood	-40475.9919
Number of Observations	7,637
ρ^2 w.r.t. zero	0.1319
ρ^2 w.r.t. constants	0.015
Departure-time constants:	
Earlier than 6:30 AM	0.1760 (0.58)
6:30 to 7:29 AM	0.3772 (2.51)
7:30 to 8:29 AM	
8:30 to 9:29 AM	-1.1977 (-8.03)
9:30 to 10:29 AM	-2.3609 (-7.63)
10:30 am or later	-2.0488 (-4.72)
Arrival-time constants:	
Earlier than 15:30 PM	-2.1857 (-5.11)
15:30 to 16:29 PM	-1.8287 (-6.26)
16:30 to 17:29 PM	-0.8971 (-6.04)
17:30 to 18:29 PM	
18:30 to 19:29 PM	0.2715 (1.78)
19:30 or later	1.3887 (4.66)
Duration constants:	
Shorter than 6 hours	2.8274 (3.78)
6 hours	2.0755 (3.69)
7 hours	1.5580 (3.67)
8 hours	1.0112 (3.5)
9 hours	0.3637 (2.56)
10 hours	
11 hours	-0.7189 (-4.97)
12 hours	-1.5918 (-5.6)
13 hours	-2.4624 (-5.78)
14 hours or longer	-3.2608 (-5.73)
Morning window overlap-both workers go to work:	
No overlap	
1 hour	0.1623 (1.45)
2 hours	0.3988 (2.6)
3 hours	0.7449 (3.65)
4 hours	1.2107 (4.51)
5 hours or longer	0.6506 (1.93)
Evening window overlap-both workers go to work:	
3 hours or shorter	
4 hours	0.3422 (3.24)
5 hours	0.2895 (2.19)
6 hours	0.4795 (2.78)
7 hours	0.2815 (1.25)
8 hours or longer	-0.0119 (-0.04)
Morning window overlap-one worker goes to work:	
No overlap	

Variables	**Coefficient (T-stat)**
1 hour	0.0930 (0.87)
2 hours	0.2541 (2.01)
3 hours	0.4475 (2.82)
4 hours	0.5640 (2.78)
5 hours or longer	0.3902 (1.76)
Evening window overlap-one worker goes to work:	
3 hours or shorter	
4 hours	0.2321 (2.23)
5 hours	0.1182 (1.04)
6 hours	0.0938 (0.67)
7 hours	-0.1013 (-0.59)
8 hours or longer	-0.1284 (-0.64)
Synchronization between two workers:	
Same departure hour	0.2264 (4.55)
Same arrival hour	0.2708 (5.35)
Exact morning synchronization with joint outbound commute	-2.4094 (-22.7)
Exact evening synchronization with joint inbound commute	-2.5320 (-20.66)
Both morning and evening synchronization	4.1314 (26.17)
Dummies for extreme cases:	
Part-time worker- arrival before 3:30 PM	0.9528 (10.1)
Household income less than 75K - departure before 6:30 AM	0.2405 (3.25)
Household Income less than 75K - arrival after 7:30 PM	0.1845 (2.53)
Household Income greater than 150K - departure before 6:30 AM	-0.1936 (-1.8)
Household Income greater than 150K - arrival after 7:30 PM	-0.1461 (-1.51)
Workplace in CBD - departure before 6:30 AM	0.3447 (4.07)
Workplace in CBD - arrival after 7:30 PM	-0.2749 (-3.27)
Additional dummy variable effects:	
Full-time worker - departure after 9:30 AM	-0.6557 (-6.21)
Full-time worker - duration less than 9 hours	-1.0648 (-11.66)
Both workers 35 years of age or younger - morning synchronization	0.7963 (4.91)
Both workers 35 years of age or younger - evening synchronization	-0.0805 (-0.43)
Both Workers 55 years of age or older - morning synchronization	0.3484 (1.48)
Both Workers 55 years of age or older - evening synchronization	-0.0916 (-0.34)
Total window overlap greater than 6 hours - 2 workers going to work	-0.1037 (-1.67)

The companion shift variables and parameterized effect are presented in Table 5. The following major findings can be mentioned:

- With respect to impact of person attributes, part-time workers are characterized by strong non-linear shifts for departure time and duration. They tend to depart later but this mostly affects the earliest hours and they tend to have short durations more frequently while the negative term for squared durations cut their duration strongly for longer durations. University student tend to depart later since many of them are part-time workers. Younger workers tend to arrive later but the non-linear term cuts this for very late hours. Older workers tend to depart somewhat later and arrive earlier (not having that many additional stops on work tours); however, they are more prone to very late arrivals due to a positive squared term. These effects relate to the usual job arrangements for each group. The non-linear effects reflect on the difference between shifts between hours within the usual commuting range (say, between 7:00 AM and 8:00 AM for departure form home) and principally different work schedules like working a second shift. Shifting from hour to hour is within the elasticity of response for most of the population segments. Second shift is a special case that cannot be explained as a simple linear extension of the same explanatory variables.

- With respect to couple-age effects, workers in young couples tend to have longer morning overlaps but shorter evening overlaps. The latter can be a consequence of younger couples to meet immediately after work and have joint activities on the way home as part of their work tours. Older couples of workers tend both to depart later and arrive earlier. This is a manifestation of a more mature family lifestyle with (presumably) spending more time at home. This might also stem from the fact that younger couples live predominantly in a rent apartment while most of mature families own a house. Spending discretionary time in an owned house is more enjoyable compared to a rent apartment; also, an owned house might require more in-home maintenance activities.

- With respect to work tour attributes, having the workplace in CBD is strongly associated with a shift towards longer durations (in addition to earlier departure and later arrival captured by constants for extreme cases) because of the longer travel times, higher probability of having a stop for additional discretionary activity there as well as probably a different nature of jobs. Logically, if the daily commute consists of two or more tours it makes the entire commuting window longer that primarily affects very short durations. Longer travel times in general shift departure to an earlier hour and makes the tour duration longer.

- Several strong effects are associated with household attributes and composition. In general, higher income results in longer duration of work tours and stronger tendency for morning overlaps at the expense of evening overlaps while lower income results in greater evening overlaps at the expense of morning overlaps. This can be a manifestation of the fact that low-income workers have a wider range of fixed work schedules (some start very earlier, some very late) while high-income workers tend to have a more conventional schedule with greater flexibility. Presence of school children results in a shift towards earlier departure hours (for being on the same schedule with them in general and escorting them to school in particular). Additionally, presence of either school child or preschool child breaks the window overlaps between two workers and pushes them to implement different activities. It is complemented by a strong shift towards shorter durations for a female worker in presence of a preschool child.

- Additionally, there several strong effects related to other major activities undertaken by the worker or household on the same day. Workers engaged in school activities or joint non-work household activities adjust their work schedules in a logical way: they depart later and arrive earlier.

Table 5: Estimation Results – Generic Shift Variables

Variables	**Departure Time**	**Arrival Time**	**Duration**	**Morning Window Overlap**	**Evening Window Overlap**
Person attributes:					
Part-Time Worker (Linear Shift)	0.7595 (5.38)		0.5733 (4.12)		
Part-Time Worker (Squared Shift)	-0.0811 (-4.21)		-0.0336 (-4.3)		
University Student	0.1923 (2.04)		0.0354 (0.53)		
Age 35 years or younger (Linear Shift)	0.0249 (0.95)	0.1411 (1.97)			
Age 35 years or younger (Squared Shift)		-0.0078 (-0.82)			
Age 55 years or older (Linear Shift)	0.0536 (1.91)	-0.1713 (-2.25)			
Age 55 year or older (Squared Shift)		0.008 (0.77)			
Both workers are 35 years old or younger:					
Both Workers Go to Work				0.1095 (2.02)	-0.1013 (-1.96)
One Worker Goes to Work				0.039 (0.8)	0.0501 (1.13)
Both workers are 55 years old or older:					
Both Workers Go to Work	0.0536 (1.91)	-0.1713 (-2.25)		0.0616 (0.95)	0.058 (1.06)
One Worker Goes to Work				0.0264 (0.47)	-0.0272 (-0.55)
Work tour attributes:					
Destination in CBD	-0.0546 (-1.5)		0.2148 (8.37)		
Two or more Work Tours (Linear Shift)			0.2667 (1.59)		
Two or more Work Tours (Squared Shift)			-0.0091 (-1.07)		
Travel Time (min)	-0.0011 (-27.28)		0.00041 (12.06)		
Household attributes:					
Household Income Less than 75K – both workers go to work	-0.0095 (-0.23)		-0.0919 (-3.32)	-0.0844 (-1.45)	0.1012 (2.03)
Household Income greater than 150K – both workers go to work	0.0232 (0.4)		0.0903 (2.38)	0.3029 (3.51)	-0.1564 (-2.07)
Household Income Less than 75K – one worker goes to work	-0.0095 (-0.23)		-0.0919 (-3.32)	-0.0797 (-1.79)	0.0542 (1.35)
Household Income greater than 150K – one worker goes to work	0.0232 (0.4)		0.0903 (2.38)	0.0756 (1.12)	-0.0784 (-1.29)
Number of Non-Working Adults in the Household	-0.1028 (-2.03)		-0.0057 (-0.16)		

Variables	Departure Time	Arrival Time	Duration	Morning Window Overlap	Evening Window Overlap
Number of Driving Age Children in the Household	-0.0891 (-3.74)		-0.0116 (-0.66)		
Number of Pre-Driving Age Children in the Household	-0.0521 (-3.14)		-0.0647 (-5.39)		
Presence of Pre-Driving Age Child - Both Workers Go to Work				-0.0879 (-1.88)	-0.1265 (-3.16)
Presence of Pre-Driving Age Child - One Worker Goes to Work				-0.0079 (-0.2)	-0.0188 (-0.52)
Presence of Pre-School Age Child - Both Workers Go to Work				-0.0568 (-1.16)	-0.0124 (-0.29)
Presence of Pre-School Age Child - One Worker Goes to Work				0.0016 (0.04)	-0.013 (-0.35)
Female Worker with Preschool Child in the Household	0.0426 (1.66)	-0.0726 (-3.27)			
Effect of other major activities on the same day:					
School Activity	0.1754 (3.7)	-0.2633 (-6.08)			
Joint Activity Before Work	1.1839 (9.11)				
Joint Activity After Work		-0.3866 (-13.59)			
Joint Activity Before Work for Both Workers going to work				0.2224 (0.41)	
Joint Activity After Work for Both Workers going to work					-0.0008 (-0.01)
Joint Activity Before Work for Worker who is the only one going to Work				0.5573 (1.9)	
Joint Activity After Work for Worker who is the only one going to Work					0.1664 (3.16)

CONCLUSIONS

The paper presents a formulation and estimation results for a joint choice model for departure and arrival time of work tours for two workers in the household. The model builds up on the previously developed tour time-of-day models with hybrid discrete choice and continuous duration structures using “shift” variables. In the current research, the “shift” technique was further refined to incorporate non-linear shifts. The main innovative feature of the current approach is an explicit modelling of intra-household interactions through synchronization mechanisms. The estimation results confirmed that individual work schedules for workers in a multiple-worker household are subject to strong synchronization and should be modelled jointly rather than independently. In particular, workers in the same household tend to align up there schedules and create time window overlaps (presumably for joint in-home and out-of-home non-work activities). These coordination and synchronization mechanisms vary by person and household characteristics like age, income, presence of children, and others. There is also a certain compensatory effect between pre-work and post-work synchronization.

The joint model described in the current research can be applied as part of a regional Activity-Based Model. This model cannot completely replace a tour scheduling model that is currently applied since the joint specification required aggregation of departure time and arrival time alternatives into 6 main categories each. For a complete Activity-Based Model, it is necessary to predict departure and arrival time with more detail that results in about 20 alternatives with a temporal resolution of 1 hour and about 40 alternatives with a temporal resolution of 30 min. With this number of individual alternatives, a direct joint formulation is infeasible. However, a joint model of the type described in this paper can be applied first followed by more detailed individual scheduling models for each worker and tour. The more detailed individual models would be applied conditional upon the joint choice modelled by the current model (i.e. the individual alternatives will be constrained by the chosen joint alternative).

Having a model that considers coordination between workers and synchronization of their work schedules in the regional Activity-Based Model would improve the behavioural realisms of the time-of-day choice and particularly model sensitivity to congestion pricing scenarios and other policies that target time-of-day choice. Without this component, the model might be oversensitive to these policies since every worker could change his schedule individually. Coordination with the other household members can dampen person sensitivity to congestion and pricing policies. On the other hand, a pressure to switch to an earlier or later schedule that a policy imposes on certain workers (for example, those who work in the downtown area subject to pricing) can be transmitted through intra-household synchronization mechanisms to the other household members that are not directly subject to the pricing policy.

It remains to be explored in more details what could be the actual policy implications and how this type of model could improve a regional Activity-Based Model in practical terms. The best possible type of analysis would involve development of both types of scheduling models (with and without intra-household interactions) in parallel, application for certain policies (for example, congestion pricing), and comparison of the outcomes. This represents a good topic for future research and experimentation. If there is a significant and systematic difference (presumably for the model with intra-household interactions to be more conservative in response), it would be important information for planners and modellers that the congestion relief expected from pricing might be overstated by simplified models. On the other hand, from the revenue perspective it might mean that higher tolls can be applied without a risk of loosing too many highway users.

The proposed model can also be improved in many ways and enriched by additional explanatory variables. For example, there might be substantial geographic differences in timing profiles (between urban, suburban, and rural areas). In the current model formulation we have included only effects associated with the work location in the CBD and total commuting travel time. Both effects (work in CBD and longer travel time) result in certain logical shifts to earlier departure from home and longer duration of the entire tour. There could be more specific effects associated with urban density and mix of available modes. To account for the last factor, the simple travel time measure should be eventually replaced with a composite measure like mode choice logsum.

Another important aspect that has been left out in the current paper relates to trip chaining patterns. In the current paper, we operate with work tour departure and arrival times. There is no explicit analysis of trade-offs between multiple stops on the work tour and additional home-based tours, although shorter tour durations and bigger pre-work and post-work time windows can be interpreted as repackaging of trips. These issues can be addressed only in the framework of a complete Activity-Based Model system.

ACKNOLEDGEMENT

The authors would like to thank the anonymous reviewers for valuable suggestions with regard to the paper and directions for future research.

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