Hybrid Discrete Choice Departure-Time and Duration Model for Scheduling Travel Tours

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A new model for scheduling travel tours is described. The model is essentially a discrete choice construct that operates with tour departure-from-home and arrival-back-home time combinations as alternatives. The proposed utility structure, based on continuous-shift variables, represents an analytical hybrid that combines the advantages of a discrete choice structure (flexible 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). The hybrid model currently has a temporal resolution of 1 h, which is expressed in 190 hour-by-hour departure- and arrival-time alternatives. The model is applied sequentially for all tours in the individual daily activity-travel pattern according to a 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 the tours of higher priority are scheduled. This feature ensures a full consistency for the whole individual daily schedule. The model has been estimated and applied as a part of the new regional travel demand model developed recently for the Mid-Ohio Regional Planning Commission.

An operational model described for scheduling travel tours can predict departure-from-home and arrival-back-home times for each tour with enhanced temporal resolution. The model formulation is fully consistent with the tour-based modeling paradigm and is designed for application in a household or individual microsimulation framework. The model has been estimated and applied as part of the new regional travel demand model system recently developed for the Mid-Ohio Regional Planning Commission (MORPC).

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Transportation Research Record: Journal of the Transportation Research Board, No. 1894, TRB, National Research Council, Washington, D.C., 2004, pp. 46–56.

The model is 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 the tours of higher priority are scheduled. This conditionality ensures a full consistency for the whole individual daily schedule as an outcome of the model.

An overview of the existing approaches to tour scheduling and time-of-day (TOD) choice are given and followed by an outline of the analytical structure of the proposed model. The practical rules for model estimation and application and the model estimation results for all travel segments are discussed, and the last section contains general conclusions.

PROPOSED MODEL STRUCTURE

Background: Discrete Choice Models and Duration Models

The research literature on both discrete choice trip departure-time models and on activity-scheduling models in general is rich. However, there are only few reported application in the framework of regional travel demand models. It is possible to distinguish among several main directions:

- Aggregate peak-factor or peak-spreading models that mostly operate in the framework of conventional four-step trip-based regional model systems. Purvis gives an example (*1*), and a systematic survey of the state of the practice can be found in the report prepared by Cambridge Systematics for the U.S. Department of Transportation (*2*).
- Individual activity-scheduling models that consider time allocation, activity sequencing, and scheduling in the entire-day framework. Most recent examples include, but are not limited to, AMOS [Pendyala et al. (*3*)], Albatross [Arentze and Timmermans (*4*)], and research work by Doherty et al. (*5*) and Miller and Roorda (*6*).
- Departure-time and duration model for particular types of activities or particular fragments of the daily activity agenda. Examples include research by Pendyala et al. on timing and duration of maintenance activities (*7*), Steed and Bhat on departure-time choice for social-recreational trips (*8*), and Bhat and Steed on departure-time choice for shopping trips (*9*).

The first direction is mostly limited to either aggregate peak factors or TOD choice models that operate with crude 3- to 4-h intervals.

The framework of conventional four-step models does not allow for incorporation of a variety of behavioral aspects pertinent to the activity timing and duration choices. It also does not allow for explicit relation of different timing and duration choices made by individuals in the course of a day. However, one important positive feature of this approach is that it explicitly links time-related travel choices to the travel conditions in the network in an attempt to achieve a global demand-supply equilibrium.

The second and third directions relate to a growing body of research on activity scheduling that is based on a continuous representation of time and frequently employs duration "hazard" models. Comprehensive scheduling models (the second direction) frequently include rule-based algorithms instead of or in addition to duration models and discrete choice structures in order to reconcile various timing and duration decisions in a realistic entire-day schedule. The most important challenge of the comprehensive activity-scheduling models is the integrity of the daily schedule, which requires full consistency of all modeled time-related choices. The relative drawbacks of these models from the practical perspective are their complexity in application and presence of empirical components (postulated rules).

The third direction is focused on particular types of activities. The work in this direction provides important insights into the individual and household factors that affect timing and duration decisions. Focus on a particular type of activity and a limited number of episodes allows for a closed formulation of duration models and comprehensive statistical analysis and estimation. However, direct use of the duration models in regional travel demand models has been hampered by the seeming complexity of the estimation of these models, incompatibility with the rest of the models (mostly discrete choice) in the system, as well as the problem of consolidation of numerous activities in the entire-day schedule.

The proposed TOD modeling approach represents an attempt to combine the advantages of the existing approaches in the operational framework of a regional travel demand model. To position this approach in relation to the existing models, the following basic features and requirements should be mentioned:

- The model should be used within the tour-based, discrete choice microsimulation framework, a framework that has been used or is planned to be used in several U.S. metropolitan areas (New York, Portland, San Francisco, Columbus, Atlanta, Houston, Sacramento, and others).
- Similar to the first direction of aggregate TOD models, the model should be included in the overall network equilibrium framework and should be linked to the related destination, mode, and route choices.
- Similar to the second direction of daily activity-scheduling models, the approach should allow for modeling a realistic entire-day schedule that spans all tours and activity episodes of the individual in the course of a day; this approach in turn requires formulation of the model at the enhanced level of temporal resolution.
- Similar to the third direction of departure-time and duration models, the approach should allow for incorporation of various person and household attributes that affect timing and duration of tours and activities.

It should also be mentioned that there is a major difference between a tour-based and a trip-based TOD model in that the tour-based model must simultaneously predict when a tour leaves home and when it arrives back home. The few examples of tour-based TOD models in the practice to date, however, have used only four or five broad TOD periods across the day (e.g. a.m. peak, p.m. peak, midday, and off peak), with a discrete choice from among 10 to 15 feasible departure and arrival combinations of those broad periods (*10, 11*). With such coarse TOD resolution, it is not possible to take advantage of the continuous nature of choice dimensions such as departure time and tour duration.

From this point of view, the advantage of duration models that specifically address duration-related decisions is appealing (*12*). Decisions regarding the duration of an activity can be best described by a model that naturally incorporates the conditioning of the activity-termination probability at each time spell on the duration of the activity undertaken so far.

Analogue Between Discrete Choice and Duration Models

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

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

where $f(t)$ represents a probability density function for duration. This general form is not really operational because it incorporates any possible parametric or nonparametric 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 a hazard rate in the literature) at time t assuming that the activity has not been terminated before, that is, at one of the time points $s = 1, 2, \ldots, t-1$. 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 Equation 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 (Equation 2) has both operational and meaningful advantages over the general model formulation (Equation 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 one is modeling 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 variables for each alternative; and
- β_{kt} = coefficients for variables.

There is again a direct correspondence between the choice model (Equation 4) and the general-form density function (Equation 1). Any choice model has the corresponding density function calculated by Equation 4, and also any density function (Equation 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 (Equation 4) have advantages over the general formulation (Equation 1) because utility expressions (Equation 5) are easier to parameterize, estimate, and interpret than the density function itself. However, when the utility expression (Equation 5) is formulated in a general way with all alternative-specific coefficients and variables, the choice model (Equation 4) becomes more complex with the addition of temporal resolution, which is not the case with the duration model (Equation 2). Also, the multinomial-logit formulation with independent alternative-specific variables suffers from the independence-from-irrelevant-alternatives (IIA) property with respect to those variables, despite 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 (Equation 5). This specification stems from an analogy that can easily be established between the duration model (Equation 2) and the discrete choice model (Equation 4). If one considers a ratio of densities for two subsequent points in time stemming from the two models and restricts 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 leading to operational models that can be equally written and estimated in either the duration form (Equation 2) or the discrete choice form (Equation 4). Only one (actually, the simplest) case will be considered here, which corresponds to a duration model with a constant termination rate λ. With this assumption, the expression in Equation 7 is simplified to the following formula:

$$\exp(V_{t+1} - V_t) = 1 - \lambda \tag{8}$$

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

$$x_{kt} = t \times x_k \tag{9}$$

This formulation for the variables is not very restrictive since most of the household, person, and zonal characteristics in the TOD model are naturally generic across time alternatives. 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 that 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 in Equation 9 creates a compact structure of the choice model in which 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 if the coefficient multiplied by the variable is positive, the termination rate becomes lower and the whole distribution is shifted to the longer durations. Negative values work in the opposite direction, collapsing the distribution toward shorter durations.

Specification of Proposed Model Structure

In the MORPC model system, the tour-scheduling model is placed after destination choice and before mode choice. Thus, the destination of the tour and all related destination and origin-destination attributes are assumed known and can be used as variables in the model estimation. In contrast, mode is not known and only the composite mode-choice log-sum can be used as a variable.

The choice alternatives are formulated as hour combinations of tour departure from home and arrival at home (g, h), and mode choice log-sum and bias constants are related to multihour departure-arrival periods (s, t). Tour duration is calculated as the difference between the arrival and departure hours ($h - g$) and incorporates both the activity duration and travel time to and from the main tour activity, including intermediate stops.

The tour TOD choice utility has the following general form:

$$V_{gh} = V_g + V_h + D_{h-g} + \mu \ln\left(\sum_m V_{stm}\right) \tag{10}$$

where

- V_g, V_h = departure- and arrival-time-specific components,
- D_{h-g} = duration-specific components,
- m = entire-tour modes (single-occupant vehicle, high-occupancy vehicle, transit, bimodal, nonmotorized),
- V_{stm} = mode utility for tour by mode m leaving home in period s (containing hour h) and returning home in period t (containing g), and
- μ = mode-choice log-sum coefficient.

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

$$V_g = \alpha_g + \sum_k \beta_k \times g \times x_k \tag{11}$$

where α_g is the departure-time constant for the TOD period.

A full set of departure-time constants is not necessary; for example, all periods within a longer, composite period can be constrained to have the same constant. The variables examined in the departure and arrival components are mostly Boolean dummies [person types, presence of children and other household characteristics, destination in central business district (CBD), etc.].

In a similar way, the duration-specific component is estimated in the following form:

$$D_{h-g} = \alpha_{h-g} + \sum_k \beta_k \times (g - h) \times x_k \tag{12}$$

The coefficients are interpreted in terms of longer or shorter durations. It should be noted that the index of the duration component is $(h - g)$ rather than $(g \times h)$, making the estimation procedure much simpler since the number of duration alternatives is much less than the number of departure and arrival combinations. It should also be noted that none of the estimated components of the utility function (Equation 10) has an index with dimensionality $g \times h$.

SETTING ALTERNATIVES AND AVAILABLE TIME WINDOWS

For model estimation using the MORPC household survey data, the following practical rules were used to set the alternative departure- and arrival-time combinations:

- Each reported or modeled departure or arrival time is rounded to the nearest hour. So Hour 17 includes all times from 16:30 (4:30 p.m.) to 17:29 (5:29 p.m.).
- Any times before Hour 5 (5:00 a.m.) were shifted to 5:00, and any times after Hour 23 (11:00 p.m.) were shifted to 23:00. This procedure involved relatively few cases and limits the number of hours in the model to 19.
- Every possible combination of the 19 departure hours with the 19 arrival hours in which the arrival hour is the same as or later than the departure hour is an alternative. This rule gives 19 ∗ 20/2 = 190 choice alternatives.

To specify the model as parsimoniously as possible, departure and arrival constants were only applied for seven TOD periods (with minor adjustments discussed later in the section on the estimation results):

1. Hours 5 to 6 (early morning),
2. Hours 7 to 9 (a.m. peak),
3. Hours 10 to 12 (early midday),
4. Hours 13 to 15 (late midday),
5. Hours 16 to 18 (p.m. peak),
6. Hours 19 to 21 (evening), and
7. Hours 22 to 23 (late night).

The network simulations to obtain travel time and cost skims are currently implemented for four even broader periods:

1. A.M. peak,
2. Midday (including early and late midday),
3. P.M. peak, and
4. Night (including early morning, evening, and late night).

The mode-choice log-sums were used for all relevant combinations of those four time periods.

The predetermined hierarchy of tours by travel purpose and activity setting (individual or joint) was assumed in the scheduling procedure. This hierarchy is based on the general principle on which the MORPC modeling structure is built [see work by Vovsha et al. (*13, 14*) for more details about the whole model system]. According to this principle, people first make decisions regarding their mandatory activities (work, university, school). Then, conditional upon scheduling the mandatory activities, they schedule joint nonmandatory activities, both maintenance and discretionary, of which maintenance (shopping, escort other persons, and various other household maintenance activities) is generally considered of higher priority compared with discretionary activities (leisure and eating out). Finally, having scheduled mandatory and joint activities, each household member schedules individual activities within the residual time window remaining after any mandatory and joint tours are made.

When a person undertakes several activities (tours) of the same priority in the course of the day, those tours are priority-ranked in chronological order; that is, the earlier tour is scheduled first, and the later tour is scheduled next conditional upon the departure- and arrival-time combination of the first tour and also forcing the second tour to be scheduled after the first tour (even if there is an available residual window before the first tour).

By using those rules, all tours of each surveyed individual can be unambiguously ordered by scheduling priority. The residual time window and set of available TOD alternatives are defined for each subsequent tour conditional upon scheduling of the previously processed tours.

ESTIMATION RESULTS

Home-Based Tours for Mandatory Purposes

Estimation results are shown in Table 1 for three mandatory purposes—work, university, and school. The most interesting variables in the model are the continuous-shift variables, with the variable multiplied by the departure hour or the duration, or both, to move the departure time or arrival time, or both, earlier or later. It is important to note that applying shift variables to any two of the three measures—departure time, arrival time, and duration—will give identical predictions because any one is a linear combination of the other two. For these models, the combination of departure time and duration was selected for ease of interpretation and because this combination gave the lowest correlation between the parameter estimates. Because the arrival time is equal to the departure time plus the duration, the sum of the departure-time and duration shift variables can be interpreted as the arrival-time shift.

In the work-tour model, significant shifts were found for all five person types relative to full-time workers—part-time workers, university students, nonworking adults, children aged 16 and up, and children aged 6 to 15. In general, the departure-time shift variables are positive, moving the tours later in the day relative to those of full-time workers. The duration shifts are negative for some person types and positive for others.

TABLE 1 Estimation Results: Home-Based Tours for Mandatory Purposes

Purpose	Work		University		School	
Observations	5993		433		2011	
Final log-likelihood	-24275.5		-1865.3		-6006	
Rho-squared (0)	0.207		0.134		0.428	
Rho-squared (constants)	0.065		0.010		0.009	
Person/household/tour shift effects	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**
Part-time worker - departure	0.05197	3.2				
Part-time worker - duration	-0.0101	-0.5				
Nonworking adult - departure	0.0298	0.7				
Nonworking adult - duration	-0.1513	-3.1				
University student - departure	0.1423	3.8				
University student - duration	0.1324	3.1				
Child age 16-17 - departure	0.1844	3.3			-0.5271	-6.9
Child age 16-17 - duration	0.1214	1.9			0.0503	1.5
Child age 6-15 - departure	-0.0817	-1.5				
Child age 6-15 - duration	-0.2518	-3.3				
All adults work full time - departure					-0.0953	-2.0
All adults work full time - duration					0.1338	5.6
Household income ($K) - departure	-.000273	-1.2	.00043	0.6	.00233	3.2
Household income ($K) - duration	.000972	5.4	.001777	3.1	.001718	4.5
Destination in CBD - departure	0.0694	2.3				
Destination in CBD - duration	0.1330	5.6				
Pattern-specific shift effects						
First tour of 2+ for same purpose - departure	-0.3364	-13.8	-0.2348	-2.8	-0.4075	-2.5
First tour of 2+ for same purpose - duration	-0.2894	-10.5	-0.2426	-3.6	-0.5517	-6.3
Higher priority of mixed pattern - departure	0.2175	4.3	0.0347	0.7	-0.5424	-3.3
Higher priority of mixed pattern - duration	-0.00133	0.0	-0.3002	-4.9	-0.360	-4.6
Subsequent tour of same purpose - departure	-0.09234	-3.5			-0.6021	-2.1
Subsequent tour of same purpose - duration	-0.08178	-2.7			-0.1084	-1.3
Lower priority of mixed pattern - departure	-0.0632	-1.4				
Lower priority of mixed pattern - duration	0.3052	4.7				
Travel time effects						
Travel time (min) - departure	-.000629	-2.0	-.000309	-0.2	-0.00398	-2.0
Travel time (min) - duration	0.001555	5.7	0.002048	1.7	0.004452	5.7
Mode choice logsum parameters						
Adjusted logsum from mode choice model	0.2372	5.6	0.0830	0.8	0.0	
Dummy variables for "extreme" periods						
Household income > $75K - depart 5 to 6	-0.7047	-7.5			-0.7059	-1.7
Household income > $75K - arrive 22 to 23	-0.6194	-5.2			-0.8919	-2.4
Destination in CBD - depart 5 to 6	-0.2515	-1.8				
Destination in CBD - arrive 22 to 23	-0.8595	-4.3				
Rural household - depart 5 to 6	0.3077	3.8				
Rural household - arrive 22 to 23	-0.1501	-1.4				

(continued)

For the school-tour model, relative to children aged 6 to 15, children aged 16 and up tend to leave home earlier and stay away from home a bit longer. Children who live in households in which all adults work full time also tend to leave home earlier and stay away from home longer.

For all three tour purposes, those in higher-income households tend to stay away from home for longer durations. For work tours, the reason for this finding may be that such people tend to work longer hours. For all purposes, the reason may also be that those with higher incomes tend to make more intermediate stops and have more-complex tours. Work tours with CBD destinations tend to be of longer duration. This result may be due to the fact that intermediate stops are more common near urban destinations, increasing the total duration of the tour. The effect may also be due to a high percentage of office-based jobs frequently associated with managerial positions and overtime work.

The next set of shift variables is related to the full-day mandatory tour pattern of the individual. Shift variables for those making the first of two or more mandatory tours for the same purpose were significant for all purposes. These tours tend to begin earlier and are of shorter duration. Because this tour is always the earlier of two tours,

TABLE 1 *(continued)* **Estimation Results: Home-Based Tours for Mandatory Purposes**

	Work		University		School	
Purpose	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**
Departure time constants						
Early (up to 6)	-0.6509	-6.7	-2.906	-8.2	-5.126	-20.9
AM peak 1 (7)	-0.0175	-0.4	-0.7681	-4.2	-0.8758	-10.2
AM peak 2 (8)	Base		Base		Base	
AM peak 3 (9)	-0.7635	-13.8	-0.2558	-1.5	-0.103	-1.1
Midday 1 (10-12)	-1.318	-12.3	-1.052	-4.8	-1.986	-8.2
Midday 2 (13-15)	-1.678	-13.1	-1.286	-3.6	-0.9985	-2.4
PM peak (16-18)	-1.847	-10.1	-1.566	-3.0	-0.4682	-0.6
Evening (19-21)	-1.585	-6.1	-2.306	-3.2	NA	
Late (22 on)	-0.1774	-0.6	NA		NA	
Arrival time constants						
Early (up to 6)	-1.236	-4.2	NA		NA	
AM peak (7-9)	-1.596	-8.7	-1.329	-2.5	NA	
Midday 1 (10-12)	-1.376	-11.4	-0.6119	-1.9	1.378	4.4
Midday 2 (13-15)	-0.8211	-11.6	0.0553	0.3	1.735	8.7
PM peak 1 (16)	Base		Base		Base	
PM peak 2 (17)	0.2900	5.5	-0.2902	-1.3	-0.5839	-2.8
PM peak 3 (18)	0.1559	2.4	-0.5588	-2.2	-1.156	-4.9
Evening (19-21)	-0.4159	-3.6	-1.020	-3.3	-3.247	-10.7
Late (22 on)	-0.2211	-1.4	-1.359	-3.2	-4.630	-11.5
Duration constants						
0 to 2 hours	-0.6329	-2.9	-1.055	-5.4	-4.869	-11.8
3 to 4 hours	0.1479	0.8	Base		-3.075	-12.6
5 to 6 hours	0.08876	0.6	-0.5506	-3.0	-2.855	-18.5
7 hours	0.2339	1.9	-0.2387	-1.0	-0.4155	-5.3
8 hours	0.2339	*	-0.2387	*	Base	
9 hours	-0.1351	-2.7	-0.4806	-1.4	-0.2334	-2.3
10 hours	Base		-0.4806	*	0.4098	2.5
11 hours	-0.2694	-5.1	-1.331	-2.6	0.4098	*
12 to 13 hours	-1.12	-15.5	-1.331	*	0.5036	1.8
14 to 18 hours	-2.039	-16.9	-1.257	-1.8	0.8472	2.3
Additional dummy variable effects						
Full-time worker - duration < 9 hours	-1.431	-11.2				
Full time worker - depart 10 to 12	-0.7841	-7.2				
Part time worker - arrive 13 to 15	0.6131	5.7				
Driving age (16-17) child – duration < 7 hrs					1.053	4.7
Child 6-15 – arrive at 4 pm					1.435	7.5
First tour of 2+ work tours - duration < 8 hrs	1.867	9.8				
Subsequent of 2+ work tours - duration < 8 hrs	2.055	7.8				
Higher priority of mixed pattern - duration < 8 hrs	0.7047	1.2				
Lower priority of mixed pattern - duration < 8 hrs	1.781	3.8				

NA: Not available (not observed in the data).
* : Jointly estimated with the coefficient above.

the result is not surprising. The same type of result was found for the higher-priority of two mandatory tours for different purposes, but the effect was not as strong as for two tours of the same purpose (the higher-priority tour in the mixed pattern quite frequently occurs earlier than the lower-priority tour, but that is not always true). Similar variables were also tested for the later or lower-priority of two mandatory tours. These findings were less significant than the coefficients for the higher-priority tour, indicating that the blocking out of the available time window based on the first tour was in part adequate to explain the timing of the second tour.

Another important shift variable is related to travel time, reflected by the network car travel time to the destination and back during the off-peak (night) period. This measure was used because it is least correlated with the mode choice logsum effects; it is more of a distance-related effect. Not surprisingly, those with longer distances to work tend to depart from home earlier and make tours of longer duration for all three tour purposes. It should be noted that this variable captures only the duration effect of travel times and not the switching effect, in which one might choose to travel at times of day when there is less congestion. This latter switching effect may be captured using the logsum measures from the tour mode choice model. A significantly positive logsum parameter was estimated for work tours, with a coefficient of 0.24. The coefficient for university tours is 0.08, but it is not significant. The logsum coefficient for school tours was just slightly negative, so it was constrained to 0.0. An important implication in the model application is that improvement in the peak-period accessibilities to major employment centers (premium transit) may result in induced commute traffic in these hours. For the same reason, the further worsening of peak-hour congestion in future years may result in peak (and consequently, congestion) spreading to the adjacent hours (mostly midday or evening, or both).

Table 1 shows the rest of the variables in the model, most of which are alternative-specific constants. In addition to the seven periods described earlier, separate constants were estimated for all three a.m. peak hours for departure and for all three p.m. peak hours for arrival, giving nine periods in all. The base alternatives were specified as the most common departure and arrival hours—8:00 a.m. and 4:00 p.m., respectively—and eight departure constants and eight arrival constants were estimated relative to these base times. Also, to make sure that the tours are of the correct duration, duration constants were estimated. The number of constants and the base alternative varied by purpose since different purposes have different duration profiles. Eight duration constants were estimated for work and school and only six for university. So the models are quite parsimonious—only 24 constants are required for a model with 190 alternatives.

Because the base alternatives were specified as the most common departure and arrival periods and durations, the estimates for the constants are generally negative, indicating that these alternatives are less likely to be chosen than the base alternatives. However, it should be noted that these are residual constants after all other variables in the model have been accounted for (for example, person-type-specific constants for particular durations and arrival hours), so the interpretation is not always so straightforward.

After models with the constants and shift variables were estimated, the observed TOD and duration distributions were compared with the ones predicted by the model along several different segmentation variables (person type, income, area types, etc.). It was found that the models could be improved considerably by adding a few dummy variables:

- Full-time workers are unlikely to have work tour durations less than 9 h,
- Full-time workers are unlikely to depart for work in the period from 10 to 12,
- Part-time workers are likely to arrive home from work in the period from 13 to 15,
- Children of driving age are more likely to have school tours of less than 7 h,
- Children aged 6 to 15 are likely to arrive home from school around 4:00 p.m., and
- Those with patterns with two mandatory tours are likely to have work tours with durations less than 8 h. (No such effects were found for other purposes.)

For all purposes, the resulting estimated models are able to match the observed departure-time, arrival-time, and duration distributions fairly closely along several different person-type, household-type, and tour-type segmentations. All models perform better than the constants-only model, which would have 189 parameters. The university model is the least successful in terms of model fit and the number of significant parameters. In general, university trips tend to be much more varied than work and school trips in terms of departure times, arrival times, and durations, and the sample of university tours is much smaller than that for work or school tours.

Home-Based Tours for Nonmandatory Purposes

Estimation results are shown in Table 2 for three segments defined for a set of nonmandatory purposes: escort, individual, and joint tours. Escort tours were singled out because of the specific timing attributes, in particular, a very short average duration, which stems from the fact that the duration of activity per se for the escort tour is virtually zero, leaving only the travel time component in the total tour duration. Joint tours exhibit some specific timing attributes (they tend to start and end later) compared with individual nonmandatory tours. Additional differences across nonmandatory purposes (shopping, maintenance, discretionary, and eating out) are captured by purpose-specific shift variables; however, these differences are not extreme enough to justify estimating completely separate models by tour purpose.

Significant shift effects were found for several person and household variables as well as for purpose-specific dummies. For escort tours made by adults, the presence of children in the household moves the tour start to an earlier hour and also makes the duration shorter. This finding is definitely a manifestation of the school-related activity of the escorted child. The same variable (presence of children) for individual nonmandatory tours made by adults works in the opposite direction (later start and longer duration). The presence of children in the household may require more activities by the adult while out of the home (shopping, etc.) but may also require child care in-home activities before one goes out.

Interestingly, if the traveler is a child, the tour start is shifted to a later hour and there is a positive impact on the tour duration for individual nonmandatory tours. This finding may appear counterintuitive for a single particular tour (one would rather expect that the nonmandatory activity schedule for children would be shifted to earlier hours compared with that for adults). However, in the framework of a whole daily activity agenda that may span several tours, adults make multiple nonmandatory tours more frequently than children do. As a result, successive scheduling of several tours with conditional residual time windows for adults would work in favor of later hours for each additional tour.

Tours for shopping and maintenance purposes tend to start earlier and not last as long compared with discretionary tours (the base purpose). This effect is a logical one that is equally strong for individual and joint tours. Eating out for individual tours tends to occur earlier but with somewhat longer duration. There is also a logical shift toward longer durations for joint tours as a function of the travel party size. Bigger groups are associated with planned activities and require consolidation of the schedules of several household members, so these activities would tend to be more substantial.

Shift variables for those making the first of multiple tours for the same purpose were significant for escort and individual mandatory tours (for joint tours there are only a few observed cases in which more than one tour was made for the same purpose). These tours tend to begin earlier and are of shorter duration. The result, also found for mandatory tours, is logical because it is always the earliest of multiple tours. Similar variables were also tested for the subsequent (the

TABLE 2 Estimation Results: Home-Based Tours for Nonmandatory Purposes

Purpose	Escort		Individual		Joint	
Observations	1155		4841		1059	
Final log-likelihood	-3621.5		-17723.3		-3660.5	
Rho-squared (0)	0.261		0.124		0.164	
Rho-squared (constants)	0.074		0.101		0.077	
Person/household/tour shift effects	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**	**Coefficient**	**T-stat.**
Adult with children in HH - departure	-0.0463	-2.2	0.0453	3.5		
Adult with children in HH - duration	-0.1256	-2.6	0.0553	3.3		
Child age 16+ - departure			0.0724	2.3		
Child age 16+ - duration			0.1089	2.7		
Child age 5-15 - departure			0.0970	3.7		
Child age 5-15 - duration			0.1941	6.6		
Purpose is shopping - departure			-0.0472	-2.9	-0.1445	-3.9
Purpose is shopping - duration			-0.2132	-6.0	-0.3644	-5.2
Purpose is maintenance - departure			-0.1272	-9.3	-0.2406	-8.0
Purpose is maintenance - duration			-0.0817	-4.6	-0.0572	-1.4
Purpose is eating out - departure			-0.0334	-1.8		
Purpose is eating out - duration			0.0617	2.3		
Number of adults on tour - departure					0.0121	0.5
Number of adults on tour - duration					0.1187	3.9
Number of children on tour - departure					0.0092	0.5
Number of children on tour - duration					0.1311	5.7
Household income ($K) - departure	0.00118	4.4	-0.00063	-4.0		
Household income ($K) - duration	-0.0001	0.0	-1.39E-04	-0.7		
Destination in CBD - departure	0.0047	0.1	-0.1465	-1.7		
Destination in CBD - duration	0.1221	3.4	0.2384	2.3		
Pattern-specific shift effects						
First tour of 2+ for same purpose - departure	-0.2169	-8.9	-0.2493	-13.7		
First tour of 2+ for same purpose - duration	-0.4130	-5.8	-0.2558	-9.5		
Subsequent tour of same purpose - departure	-0.0975	-3.5	-0.1222	-4.5		
Subsequent tour of same purpose - duration	-0.3795	-5.5	-0.0128	-0.4		
Number of mandatory tours made - departure	0.0173	1.0	0.0149	1.5		
Number of mandatory tours made - duration	-0.1552	-2.6	0.0765	4.3		
Number of joint tours made - departure	0.0098	0.5			-0.0437	-2.2
Number of joint tours made - duration	-0.1095	-1.6			-0.1007	-3.1
Number of individual tours made* - departure	0.0516	3.6	0.0061	0.8	0.0225	2.6
Number of individual tours made* - duration	-0.1563	-4.3	-0.0691	-4.8	-0.0680	-4.3
Travel time effects						
Travel time (min) - departure	0.00067	0.1	0.00067	1.8	-0.00028-	-0.3
Travel time (min) - duration	0.00343	3.2	0.00485	12.2	0.00720	7.8
Mode choice logsum parameters						
Adjusted logsum from mode choice model	0.2924	2.8	0.0		0.0	

HH = household.
* For Escort, this is the total number of shopping, maintenance, discretionary plus eating out tours made by the individual. For Individual, the definition is the same, but it does not include tours of the same purpose as the tour being modeled. For Joint, this is the total number of individual nonmandatory tours made by all members of the travel party.
** Jointly estimated with variable above.

(continued on next page)

TABLE 2 *(continued)* Estimation Results: Home-Based Tours for Nonmandatory Purposes

	Escort		Individual		Joint	
Purpose	Coefficient	T-stat.	Coefficient	T-stat.	Coefficient	T-stat.
Departure time constants						
Early (up to 6)	-2.973	-8.3	-1.631	-10.5	-2.304	-4.6
AM peak 1 (7)	-1.502	-8.1	-0.6182	-4.3	-0.6788	-1.6
AM peak 2 (8)	Base		Base		Base	
AM peak 3 (9)	0.1744	1.3	0.5489	6.1	0.5921	2.6
Midday 1 (10-12)	-0.7562	-3.5	0.6382	6.7	0.9362	3.9
Midday 2 (13-15)	-0.7339	-2.4	0.6420	4.9	1.192	3.6
PM peak (16-18)	-1.074	-2.8	1.318	7.5	2.011	4.6
Evening (19-21)	-1.916	-3.9	0.9690	4.7	1.690	3.3
Late (22 on)	-1.838	-3.0	0.0223	0.1	0.2657	0.4
Arrival time constants						
Early (up to 6)	-0.4865	-0.8	-1.663	-4.9	-2.096	-1.8
AM peak (7-9)	0.3601	0.9	-0.8588	-4.6	-0.6774	-1.4
Midday 1 (10-12)	-0.6343	-2.0	0.0704	0.6	0.1635	0.5
Midday 2 (13-15)	-0.3730	-1.8	0.2656	3.0	0.3963	1.8
PM peak 1 (16)	0.524	3.5	0.2630	3.2	0.1036	0.5
PM peak 2 (17)	Base		Base		Base	
PM peak 3 (18)	-0.3192	-2.1	-0.2794	-3.4	-0.5004	-2.6
Evening (19-21)	-0.1801	-0.8	-0.6389	-7.3	-0.2110	-1.1
Late (22 on)	-1.307	-3.7	-0.8776	-7.4	-0.1839	-0.6
Duration constants						
0 hours	-0.3805	-3.6	-0.2423	-3.6	-0.071	-0.5
1 hour	Base		-0.2423	**	-0.071	**
2 to 3 hours	-0.8429	-6.2	Base		Base	
4 to 5 hours	-1.528	-5.3	-0.5791	-9.7	-1.255	-8.6
6 to 7 hours	-1.999	-4.4	-1.030	-10.1	-2.452	-8.8
8 to 10 hours	-1.691	-3.1	-1.242	-8.3	-3.951	-8.8
11 to 13 hours	-2.563	-2.8	-1.392	-6.4	-5.991	-8.9
14 to 18 hours	-2.563	**	-1.132	-3.8	-7.257	-7.7
Dummy variables for "extreme" periods						
No. of individual tours made - depart 5 to 7	0.8435	5.3				
No. of individual tours made - arrive 22 to 23	0.3727	2.1				
Shopping - depart 5 to 8			-0.7622	-3.6	-1.567	-2.3
Shopping - arrive 22 to 23			-0.5661	-3.6	-0.9763	-2.5
Maintenance - depart 5 to 7			-0.8421	-4.9	-1.282	-2.6
Eating out - arrive 22 to 23					-1.102	-4.1
Child 6-15 (on tour) – arrive 22 to 23			-1.243	-7.3	-0.9580	-4.3
University student (on tour) - arrive 22 to 23			0.7844	4.1	0.9096	2.1
All adults on tour work full time - arrive 22 to 23					-0.5059	-2.4
All adults work, kids in HH – depart 5 to 7			0.7349	2.9		
Additional dummy variable effects						
Adult with kids in HH – arrive 19 to 21			0.3101	3.6		
Nonworking adult – depart 16 to 18			-0.5481	-6.3		
Shopping tour- duration < 2 hrs			0.9436	7.4		
Discretionary tour- duration < 2 hrs			-0.6657	-7.1	-0.4172	-2.3

HH = household.
* For Escort, this is the total number of shopping, maintenance, discretionary plus eating out tours made by the individual. For Individual, the definition is the same, but it does not include tours of the same purpose as the tour being modeled. For Joint, this is the total number of individual nonmandatory tours made by all members of the travel party.
** Jointly estimated with variable above.

second, third, etc.) of multiple escort or individual nonmandatory tours. They were less significant because of the blocking out of the available time window based on the first and other previously scheduled tours, which already serves to shift the subsequent tours to later hours. A shorter duration is a logical outcome. It is less obvious why a departure-time shift to earlier hours was also observed for subsequent tours. However, this shift variable works only within the residual time window left after the first (and other earlier scheduled) tours. Thus, the outcome suggests that those who make multiple tours for the same purpose tend to bunch those tours together in time, beginning the second tour closer in time to the first than would be indicated by availability alone.

Several variables were tested that relate to the intensity of the daily activity agenda of the modeled person: the total number of mandatory tours, individual nonmandatory tours, and household joint tours. As expected, almost all of these variables worked in a logical way, shifting the departure time to a later hour and shortening the duration. In this way, the model tends to leave time to make the other tours, some of which have not been scheduled yet in the modeling hierarchy.

There are some exceptions, however. The number of mandatory tours made proved to have a positive impact on the duration of individual nonmandatory tours. This result appears counterintuitive in view of the overall time-space constraints on the individual activity. However, it may be a consequence of the trade-offs between the number of nonmandatory tours made and the number of activities undertaken during each tour. A relatively busy person with one or even two mandatory tours tends to make fewer individual nonmandatory tours compared with a person with no mandatory tours. However, the result of this limitation for busier people may be chaining activities together and making tours of longer duration. Also, a larger number of joint tours made by all persons in the household tends to shift toward earlier and shorter joint tours. This result may indicate the same sort of bunching behavior that was found for multiple mandatory and individual tours. This behavior can be explained by the desire to leave a larger continuous window for subsequent in-home activities. Alternatively, there can be the special role of short stops at home between tours and for joint tours associated with, for example, eating and the unloading of shopping.

As was found for mandatory tours, longer distance or travel time from the destination is related to significantly longer tour duration. The effect is quite strong for individual and joint nonmandatory tours and is slightly weaker for escort tours. Interestingly, the departure-time shift associated with a longer travel time proved to be positive (i.e., to a later rather than earlier departure) for escort and individual mandatory tours, a counterintuitive result. However, these departure-time shifts (especially for escort tours) proved to be not statistically significant, and when applied simultaneously with the strong duration shifts, the combined result is a shift to an earlier departure, since alternatives of longer durations tend to start earlier, all else being equal. In addition, as was found for mandatory tours, the logsum from the tour mode choice model was only positive and significant for one purpose—escort tours. The resulting logsum parameter for escort tours (0.29) is very similar to that found for work tours, perhaps not surprisingly since escort tours are often made during commute hours to take people to or from work or school.

The constants for departure and arrival hours were specified in the same way as those for mandatory activities—eight departure constants and eight arrival constants not including the base-hour constants for 8:00 a.m. (departure) and 5:00 p.m. (arrival), which were set to zero as reference points.

The duration-specific constants were slightly reorganized to account for the generally shorter duration of nonmandatory activities compared with mandatory activities. In particular, it was important to single out 0- and 1-h durations, which are quite frequent. The 1-h duration category served as the base (the most frequent case) for escort tours, and the 2- to 3-h duration category served as the base for the other nonmandatory tours. Six duration constants were estimated for each of the segments, resulting in a parsimonious structure of 22 constants covering all 190 possible alternatives.

Similar to the estimation of the models for mandatory tours, after models for nonmandatory tours were estimated with the constants and shift variables, the observed TOD and duration distributions were compared with the predicted ones along several different segmentation dimensions (travel purpose, person type, etc.). The models were then improved by adding the following variables:

- A larger number of individual nonmandatory tours increases the probability of escort tours to leave home early in the period 5 to 7 or arrive home late in the period 22 to 23.
- Shopping tours (individual and joint) have a low probability of starting early in the period 5 to 8 or to end late in the period 22 to 23, or both, a result presumably related to retail opening hours.
- Maintenance tours (individual and joint) have a low probability of starting early in the period 5 to 7. This variable may also be related to the opening hours of banks, offices, and so on.
- Joint eating-out tours are unlikely to arrive back home late in the period 22 to 23.
- Children under 16 either individually or as participants in joint tours are unlikely to arrive back home late in the period 22 to 23 (it should be recalled that the model relates to a regular weekday).
- University students are more likely to arrive back home late in the period 22 to 23 (or later) after either an individual or a joint nonmandatory tour.
- If all adults participating in a joint tour are full-time workers, it is unlikely for this tour to end late in the period 22 to 23.
- If all adults in the household are workers and in addition there is at least one child in the household, it is more likely that an individual nonmandatory tour would start at an early hour (5 to 7) or end in the period 19 to 21, presumably just before or after work.
- Nonworking adults are less likely to start individual nonmandatory tours in the period 16 to 18 (perhaps choosing to start earlier to avoid p.m. peak congestion).
- Discretionary tours (both individual and joint) are less likely to have a duration less than 2 h.
- Individual shopping tours are more likely to have a duration less than 2 h.

CONCLUSIONS

The statistical analysis and estimation of the TOD choice model implemented for the MORPC model system can be summarized with respect to the following main conclusions:

- The adopted structure for the tour-scheduling model has several advantages over conventional TOD choice models:
  - It suits the general framework of the MORPC travel demand model, which is an advanced tour-based microsimulation system. The developed TOD choice model returns the entire-tour schedule (a combination of departure and arrival times) and is applied in a microsimulation fashion for each tour.

–It is a hybrid choice-duration analytical structure that combines positive features of a discrete choice model (easy to estimate and apply) and a duration model (can be applied at any level of temporal resolution). The model has a temporal resolution of 1 h. It predicts departure and arrival times at the level of 19 available hours (from Hour 5 to Hour 23). The result is 190 available departure- and arrival-time combinations.

–It has a parsimonious structure with a limited set of constants (22 to 24) and a set of additional variables (20 to 30) that explains timing shifts of the tour start, end, and duration as a function of the person, household, and travel attributes. This model makes the whole model system more sensitive to land use, demographic, and network changes.

–It is applied sequentially for all tours implemented by the person and household. The sequencing rules reflect the priority of the associated activity (mandatory activities come first, followed by joint activities, and then by individual nonmandatory activities). Each subsequent tour can be scheduled only within the residual time window left after all tours of higher priority are scheduled. Thus, the model outcome is fully consistent and realistic at the individual level. In this way, additional sensitivity of the model system is achieved as well.

• The TOD choice model structure has been analyzed statistically and estimated for all travel segments:

–Mandatory tours for work, university, and school purposes;

–Home-based nonmandatory tours, broken into the following segments: escort tours, other individual nonmandatory tours, and joint tours; and

–Non-home-based subtours at work (not included in this paper).

• The estimation results have shown statistical significance of various shift-type variables that ensure the model sensitivity. Though the model has 190 alternatives and only 22 to 24 constants, the achieved statistical fit is much better than that for the reference choice model with a full set of 189 constants.

ACKNOWLEDGMENT

The authors thank the anonymous reviewers for valuable suggestions.

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Publication of this paper sponsored by Traveler Behavior and Values Committee.