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Weekly Rhythm in Joint Time Expenditure to all At-Home and Out-of-Home Activities: Application of Kuhn-Tucker Demand System Model using a Multi-Week Travel Diary Data

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ABSTRACT

This paper uses the Kuhn-Tucker demand system modeling technique to investigate the capacity of a typical week in capturing rhythms in activity-travel behavior. It considers all possible activity types within a weeklong modeling time frame. Complex interactions in time expenditure between at-home versus out-of-home activities and among different out-of-home activities are captured by introducing behavioral elements in the model in terms of baseline preference, time translation, and satiation effects. The Kuhn-Tucker demand system model used in this paper is a random utility maximization model with the inherent assumption that every individual maximizes his/her total utility in allocating time to the activities under consideration within the modeling time frame. Models are developed for each individual week of a six-week travel diary, the MobiDrive dataset for Karlsruhe and Halle, Germany. Each model contains 83 variables and reveals behavioral details of our complex activity-travel behavior. Based on the performances of the models in terms of fitting observed data and parameter values of specific variables, it is clear that typical week modeling time frame is capable of capturing rhythms of our activity-travel behavior sufficiently. The paper concludes with the recommendation that the availability of activity diary data for a multiweek time period would further enhance our understanding on this issue.

INTRODUCTION

Availability of multi-week travel diary survey data makes it possible to investigate temporal rhythms of activity-travel behavior over a prolonged period of time. [1, 2, 3] Identifying temporal rhythms of our different activity-travel behavior is crucial to conceptualize a modeling framework for activity-based travel demand. Our activity-travel behavior is a complex phenomenon, especially in the case of defining an appropriate modeling time frame for activity-based travel demand modeling. [4] Researchers often concentrate on specific activity types separately to identify temporal rhythms, which have specific policy implications and also help to understand specific behavioral processes. [5, 6, 7] Although individual activity types may have individual temporal rhythms, our overall activity generation and scheduling processes that create our travel demand are not just collections of isolated univariate activities. From an activity-based travel demand modeling point of view, investigation of all possible activity participation behavior combined within a specific time frame is of importance. Ongoing debate on the appropriate time frame for activity-based travel demand modeling warrants detailed investigation of our joint time expenditure or activity participation behavior. Investigation into joint activity-travel decisions within a specific time frame would reveal the overall rhythm of activity-travel behavior that results from different types of trade-offs, including both at-home versus out-of-home activities and trade-offs between different out-of-home activities.

This paper concentrates on joint activity-travel decisions within a specific time frame: a typical week. The objective is to investigate the weekly rhythm of joint activity-travel decisions using a multi-week travel diary survey, MobiDrive. A utility-based econometric modeling framework is used to model a whole-week activity-travel pattern that clearly identifies two distinct behavioral trade-off processes: the trade-off between at-home versus out-of-home activity time expenditure, and trade-offs among different out-of-home activity time expenditures. Models are developed for each of the 6 weeks of MobiDrive survey data and results are compared to identify how much a typical week modeling time frame can capture rhythms of all activity-travel behavior.

The paper is organized as follows: the next section discusses modeling time expenditure within a specific time period (time budget constraints) in general, followed by sections discussing the utility-based modeling framework, mathematical formulations, description of data

and variables consider in the models, and interpretations of the estimated models. The paper concludes with a summary of the key findings.

JOINT TIME EXPENDITURE MODELING WITHIN SPECIFIC TIME PERIOD

Causal processes as well as dynamics of travel demand are deeply rooted in our trade-offs between earnings and consumption of resources and commodities. Other than material or service type resources or commodities, time plays the most critical role in earning and consumption processes. [8, 9, 10, 11, 12] For short-term travel demand modeling, time is the continuous quantity with which we mainly deal, considering income and consumption of goods and services as other influential factors. Although for medium- to long-term mobility decisions the money budget (representative of income and expenditure) is also critical, for short-term travel demand we mainly deal with time as the key constraint on behavior. [8] In addition, scarcity of information concerning detailed day-to-day money expenditure restricts researchers' to focusing on time constraints in the modeling of activity-travel behavior.

It is important to recognize that time expenditures on different activities are interrelated. The interrelationships among time expenditures to different alternative activities are due to the limitation of time resources and competition of different activities to be performed within a short period of time. [13] Time limitation in our daily life creates rhythms of our daily activity behavior that consequently causes dynamics of our travel demand. [14]

The investigation of time expenditure behavior under specific time-budget constraints requires an appropriate econometric modeling framework. Simple statistical data analysis does not always reveal the behavioral processes. It is necessary to model the behavioral processes to investigate the critical interrelationships in time expenditure to different alternative activities. The first step of investigation is to recognize the two broad categories of our activities: at-home and out-of-home. Although in travel demand modeling we are mainly interested in out-of-home activities, it is very important to recognize that the dynamics of out-of-home time expenditure are mainly influenced by the total time left to spend at-home. Trade-off in time allocation to at-home versus out-of-home activities is crucial in modeling rhythms of activity-travel behavior. [15] Given the overall trade-offs between at-home and out-of-home activities, an appropriate modeling technique is also necessary to address the competitions among different out-of-home activities. A utility-based modeling framework for modeling time expenditure on different

activities under time budget constraints is an attractive approach in this regard. With increasing complexities of our daily life and changing dynamics of transportation system behavior, application of utility-based modeling approach in travel demand modeling seems to be almost unavoidable. [13] The next section concentrates on the utility-based demand system modeling approach for time expenditure.

UTILITY-BASED MODELING FRAMEWORK

The definition of activity utility depends on role of time in activity planning and scheduling. Following explanations of Winston (1987), Habib and Miller (2006) argue that specifications of activity utility should be different based on the stage of time allocation. In the case of planning for different activities within a limited time period, people actually allocate limited time among different activities, which is similar to allocating resources. [16, 8] When people start participating in or executing different activities, they basically spend time, which is similar to consuming any commodity. So, we can assume that in activity planning (activity generation) time plays the role of a resource, but in activity execution (activity scheduling) time plays the role of a commodity. In either stage when we deal with allocating or expending time to alternative activities, it becomes an optimization problem with the assumed time limitation (time budget). For such a mathematical optimization problem several properties should be enforced:

- Time expenditure to specific activity can not be negative.
- We do not always participate in all types of activities (time expenditure to any specific activity can be zero) within a given time period.
- Total time expenditures must sum up to the total time budget for the time period being modeled.

The Kuhn-Tucker demand system model is a mathematical optimization approach that can satisfy all three of these conditions. This model uses the optimality conditions proposed by Kuhn and Tucker (1951) to derive likelihood function to estimate model parameters [17] In mathematical optimization; the allocation of zero time to a given activity is called a corner solution. First proposed by Wales and Woodland (1982), the Kuhn-Tucker model has been widely used in resource expenditure problems in economics. [18, 19] In transportation Bhat (2005), and Habib and Miller (2006) are the first to apply this technique with different distributional assumptions for activity-based travel demand analysis. [8, 14, 20, 21]

In activity-based travel demand modeling the Kuhn-Tucker demand system framework allows us to investigate complex inter-activity trade-offs in time expenditure in a very tractable way. This framework ensures the time budget constraint by introducing the composite activity concept. [8] The composite activity refers to the broad set of activities that are not important to the researcher individually but the total time expended on such activities is important to model so as to ensure that the total time budget constraint holds. This is derived from the Hicksian composite good concept. [22] For this investigation, we are not interested in at-home activities separately, but the total time allocated to all at-home activities is important to ensure the multidimensional trade-offs in activity behavior among at-home and out-of-home activities and among different out-of-home activities is properly accounted for.

As mentioned before, the utility function definition should depend upon the stages of time allocation. At the activity planning stage we basically allocate time to alternative activities, but at the scheduling stage we actually consume or spend time. So, the utility function defined for the activity scheduling stage should consider more about taste and satiation effects than that for activity planning (generation) stage. [8] Habib and Miller (2006) proposed a utility function specification for activity planning (generation) stage, where the marginal utility in time allocation to specific activities are specified as logarithmic functions multiplied with a baseline utility component. In this study we are using a travel diary survey that collected only the revealed time expenditure information. Data from the travel diary survey are of final scheduled information of individual participants. So, time expenditure study using this data requires utility function specification that reflects satiation effects of time expenditure to different types of activities more precisely. Bhat (2007) proposed a specification based on a generalized version of translated continuous expenditure system (CES) utility function to accommodate details of marginal utility variations across the activity types. [20] So, for the travel diary data used in this study, the Bhat (2006) specification is used in this paper. The specification is described in the next section in detail. [20]

MATHEMATICAL FORMULATION

Equation 1 defines the total utility function for weeklong time expenditure of an individual. The utility function is composed of a number of additively separable sub-utility functions for the out-of-home activities (specific activities) under consideration and the sub-utility function for the at-

home time expenditure: the composite activity. Each specific activity sub-utility function is composed of a baseline utility component and an additional utility component. The base line utility component models the baseline preference in involving a specific out-of-home activity with respect to the composite activity. The additional utility component of a specific out-of-home activity is specified so as to ensure the possibility of a corner solution in the mathematical optimization and capturing satiation effects in time expenditure behavior. Two specific parameters are used in the specific utility component. The φ parameter is mainly the translating parameter that ensures the potential for a corner solution, but it also reflects the satiation effect in time expenditure to the specific out-of-home activities with respect to the composite activity. On the other hand the ρ parameter purely reflects the satiation effects in time expenditure. Considering the total modeling time frame (T) as a typical week, the total utility function stands as:

$$\begin{aligned}
 U_{Total} &= \sum_{j=1}^{No. of Specific Activities} \left(\frac{\varphi_j}{\rho} \right) \exp((\beta_p X_p)_j + \varepsilon_j) \left((Y_j / \varphi_j + 1)^\rho - 1 \right) + \frac{1}{\rho} \exp(\varepsilon_z) (z)^\rho \\
 S.T. \quad &\sum_j Y_j + z = T \\
 &Y_j \geq 0
 \end{aligned} \tag{1}$$

ε is the error term

Y_j is the total time spent on activity $j = d_j x_j$

Where, d_j is the average duration and x_j is the frequency

z is the composite activity time

T is the total time budget

$\exp(\beta_p X_p + \varepsilon)_j$ is the baseline marginal utility of activity j

$\varphi_j = \exp(\beta_a X_a)$ is the translating satiation parameter for activity j

and it must be positive

$\rho = 1 - \exp(-\beta_z X_z)$ is the satiation parameter for the composite activity, z

and it must be less than 1

X represents variables and β represents corresponding parameters

To derive the likelihood function for estimating the structural parameters of the model, Kuhn-Tucker optimality conditions can be applied: [17]

Kuhn–Tucker Optimality Conditions (LEMMA 1):

$$\begin{aligned} \frac{\partial U}{\partial Y_j} - d_j \lambda &\leq 0 \\ &\& \\ \frac{\partial U}{\partial z} - \lambda &\geq 0 \end{aligned} \quad (2)$$

Where λ is the Lagrange Multiplier

Using the above-mentioned condition the utility function can be transformed to specify the deterministic utility component of specific and composite activities as follows:

the deterministic part (transformed) of the specific activity sub - utility is

$$V_j = (\beta_p X_j) + (\rho - 1) \ln(\varphi^{-1} Y_j + 1) - \ln(d_j)$$

the deterministic part (transformed) of the composite activity sub - utility is

$$V_z = (\rho - 1) \ln(z) \quad (3)$$

Now, using the ‘transformation of variable theorem’ and the error term (ε) distributional assumption as Type I extreme value distribution, the probability of spending positive amounts of time (Y) to a set of out-of-home activities can be derived as: (readers are suggested to see [8] and [20] for details mathematical formulation of the derivations)

$$\begin{aligned} p(Y_1, Y_2, Y_3, Y_4, \dots, 0, 0, 0, Y_J) \\ = \frac{1}{\sigma^{A-1}} \left(\prod_{j=1}^A \frac{1-\rho}{Y_j + \varphi_j} \right) \left(\sum_{j=1}^A \frac{d_j(Y_j + \varphi_j)}{1-\rho} \right) \left(\frac{\prod_{j=1}^A \exp(V_j / \sigma)}{\sum_{k=1}^K \exp(V_k / \sigma)} \right) \end{aligned}$$

Here σ is the scale parameter of Type I Extreme Value distribution, ε

A indicates number of activities with non - zero frequency (4)

K indicates the number including all specific as well as composite activity

This gives a closed form likelihood function and can be estimated using any conventional estimation technique. In this paper we used the BFGS gradient search algorithm to estimate the model parameters. [23]

DATA

The data source for the analyses of this paper is derived from the MobiDrive data, which is a six-week travel diary data archived at the Institute of Transport Planning and Transportsysteme (IVT), ETH Zürich. [1, 2, 3, 24, 25] This data set was collected in Karlsruhe and Halle of Germany in the spring and fall of 1999 with the aim of understanding the rhythms of daily life. This is the most recent data source that has a span of 6 weeks. A total of 160 households participated in the survey. A total of 360 individuals who were over 6 years old in the households completed the weekly survey form, which captured information concerning all trips made during the six-week survey period. The survey began with a 40 to 60 minute face-to-face interview to explain the weekly diary form to the participants. The survey form was designed following the well-known ‘KONTIV’ form to provide sufficient space to the respondents to report weekly travel information. [24] Respondents returned the forms every week by post-paid envelop. The filled forms were checked thoroughly and phoned back to the respondents in case of any query or question about the completed forms.

The participation rate in the survey was very high with only 1 or 2 households dropping out. The paper-based travel diary survey instrument was supplemented by further survey elements to cover the socio-demographic characteristics of the households, household’s auto ownership, household members’ transit usage as well as many other attributes.

After cleaning the sample data set for some missing values a total of 333 individuals were selected for the investigation. All at-home activities are considered in general as the composite activity and all out-home activities are broadly classified into 8 types. The specific out-of-home activity types are:

1. Basic Need: Walk/Stroll, Household Obligation Type Activities etc.
2. Work / School activities
3. Pick up / Drop off person
4. Shopping (Including Window Shopping)
5. Services: Car care, Refueling, Gardening / Cottage, Private business
6. Recreation / Entertainment: Active sports, Excursion (Nature)
7. Social: Disco, Pub, Restaurant, Cinema, Excursion (Culture), Group / Club meeting, Meeting Friends, Meeting Relatives / Family etc.
8. Others: All other out-of-home activities that do not fall into above types

For each individual of the sample data set, the total time ($24 \times 7 = 168$ hours) is considered as the time budget for weekly time expenditure. The average duration of any activity type of any individual is considered to be the observed weekly average duration of that particular person. The different components of the utility function are specified as functions of different variables. Variables considered are in general: person-specific variables, household-specific variables, location-specific variables and activity-specific variables. For person-specific variables age, genders, driving license possession, job status, student status, etc. are considered. For household-specific variables household size, household annual income, number of household automobiles, number of household children, etc are considered. For location-specific variables, location of households in the city (CBD, Sub-urban location, etc.), distance of bus stop from home, city specific dummy variables, etc. are considered. For activity-specific variables activity-specific dummies (constants), number of people involved in the activity and travel ratio are considered.

The travel ratio variable is defined as the ratio of the summation of the activity episode duration and travel time to the activity episode location. [26] It refers to the price of activity time expenditure in terms of travel time expenditure and by definition it is greater than one. The longer the travel time required getting to an activity location, the higher the value of the travel ratio. It thus also acts as an indicator of accessibility of the individuals to different activity locations. This variable brings information of transportation system performance inside the total utility function in a normalized way making the models sensitive to transportation system performances.

Complying with the objective of this paper, each week of the MobiDrive survey is considered as a random week. Investigation is done on each week individually and all 6 weeks pooled together. Parameters are estimated and results are compared. The next section discusses the estimated models in details.

INTERPRETATIONS OF THE EMPIRICAL MODELS

For eight types of out-of-home activity and weeklong modeling time frame, the models become complex with a large number of parameters. However, the large number of parameters also reveals considerable behavioral detail. A total of 7 models are estimated: one for each week and one for all weeks pooled together. Recognizing the fact that we have relatively small data set compared to the large number of parameters to be estimated, the standard for statistical

significance of the parameters is considered as 90 percent confidence limit for which the ‘ t ’ statistics should be greater than or equal to 1.64 for a two-tailed test. However, variables with statistically insignificant parameters are also retained in the model when they provide insight into the behavioral process under the assumption that if a larger data set were available these parameters might show statistical significance. An adjusted likelihood ratio index (Adjusted Rho-Square) is computed to measure the goodness-of-fit values as follows:

$$\text{Adjusted Rho-Square} = 1 - \frac{\text{Loglikelihood of Full Model} - k}{\text{Loglikelihood of Constant-Only Model}}$$

Where,

k = Number of Parameters in Full model over the Constant-Only Model

This value ranges from 0 to 1. A summary of all estimated models is presented in Figure 1. It is clear that the loglikelihood values are almost the same for all random weeks. The goodness-of-fit measures are plotted, indicating that the variations across the weeks are very low. Although the models have not considered any special events occurred during the survey time period, the overall performances of the individual weekly models are almost the same. This indicates that considering all possible activity types within a specific time period captures inter-activity interactions. The utility-based modeling framework for all possible activity types presented in this paper captures more behavioral details than models for individual activities individually.

Table 1 presents the estimated parameters of the models. The following sub-sections discuss the parameters in details.

Baseline Utility Component: The baseline utility component refers to the marginal utility at the point of no time expenditure. To ensure the positivity of utility it is expressed as an exponential function. Baseline utility has two components: deterministic and random. The deterministic part is expressed as a linear in parameter function of different variables. The random component is assumed to have a Type I extreme value distribution that facilitates having a closed form likelihood function. As shown in equation 4, it is possible to estimate the scale parameter of the random error component. However, in this case it was found that normalization of the scale parameter to 1 gives better specification in terms of a higher number of statistically significant parameters and higher goodness-of-fit values. The baseline utility functions of specific activities are estimated with respect to the composite activity. For the composite activity all parameters of

the deterministic part of baseline utility functions are assumed zero and hence the baseline reference utility for all specific activities is $\exp(0) = 1$.

The deterministic component of baseline utility function for each out-of-home activity types is composed of a constant term and a number of socio-economic variables. The final specifications of the models include a generic constant term for all specific activities. Constant terms of the random week vary from -12.8 to -18.8 with an average value of -14.8 (for the pooled data model). Exponential of these constants of the weekly models indicate that the baseline marginal utility for out-of-home activities with respect to at-home activities is very low and the variation across the week is also very low (exponential of the constant terms of the individual random weeks do not vary significantly).

Among other variables in the baseline utility function component, the city specific dummy variable refers to the city of Karlsruhe with respect to the city of Halle. Individual out-of-home activity specific components of the city specific dummy variable reveal that people in Karlsruhe spend more time in out-of-home basic need type activities compared to the people of Halle. For work/school activity, it is found difficult to get statistically significant parameters except for the 5th week. According to the 5th week model it seems that people in Halle spend more time for work/school activity than the people of Karlsruhe. This finding is consistent with the findings of Jara-Díaz *et al* (2007) who compared value of time variations across a number of cities for work activities. [27] However considerable variations in values and parameter sign are visible across the weeks. This is probably due to the fact that we did not consider whether any specific event (holiday, etc.) occurred during the survey time period that affected work/school activities of the survey areas.

Gender-specific dummy variables capture the difference of males in spending time on out-of-home activity relative to females. For work/school activities, considerable variations are visible across the weeks; the only statistically significant value is for the 3rd week, in which it is indicated that males spend more time on work/school activities than females. For shopping activities, statistically significant parameters are found in 5th week and in the pooled data model only. It is clear that males are less willing to spend time on shopping activities than females. For services activities, statistically significant parameters are found in the 3rd week and pooled data model only, in which males are found to be more willing to spend time on services or private business activities than females. In case of social activity males prefer spending more time than

female (statistical significance limit is achieved for 3rd week, 5th week and pooled data model). In case of other activities females prefer spending more time than male (statistical significance limit is achieved for 1st week, 2nd week and pooled data model)

Having a driving license is consistently found to result in spending more time on out-of-home activities across all weeks with high '*t*' statistics. Having more than one automobile in the household does not show significant influence on household members' activity-travel behavior, except for the first week in which higher numbers of household automobiles results in more time spent out of home. Employed household members spend more time in out-of-home activities than at-home consistently across the weeks. On the other hand, being a parent results in spending less time on out-of-home relative to at-home activities, which is intuitive. Having transit service in the neighbourhood also affects the activity-travel behavior; it is clear that longer the distance from home to the nearest transit stop the lower the possibility of spending more time in out-of-home activities. People who live in the CBD have lower utility gain in spending time in out-of-home activities compared to people living outside the CBD, and this effect is consistent across the random weeks.

An individual's employment status influences his/her time expenditure on out-of-home activities. It is clear that people having full time employment have higher baseline utility for basic need, work/school and shopping activities, and they have lower baseline utility for drop off / pick up, services and recreation type activities compared to people with other types of employment status. This behavior is consistent across the random weeks. In the case of social and other types of activities, considerable variations exist in baseline preference compared to at-home activities.

The number of household children has a very strong influence on household members' activity-travel behavior. Number of household children has a negative effect on time expenditure to all out-of-home activities except work/school. This is intuitive because work/school activity is a fundamentally different type of activity than all other out-of-home activities. In particular, by working people earn money, whereas other out-of-home activities generally involve spending money. It makes sense that a higher number of children in the household demands more income and influences household member to spend more time working. This behavior is consistent across the weeks.

The individual's age is a highly significant variable in influencing baseline utility perception. Age is considered as a cohort-specific dummy variable in the models to capture nonlinear effects. It is clear that older people have lower baseline utility in all out-of-home activities than the younger people, and this behavior is consistent across the random weeks

The φ Parameter: The φ parameter captures activity-travel behavior by translating time to ensure corner solutions and also addresses the satiation effects in time expenditure to specific out-of-home activities. This parameter is further expressed as an exponential function of a number of activity-specific variables. The higher the value of the φ parameter the lower will be the time expenditure on the specific out-of-home activity, or, in other words, a higher φ value indicates lower willingness to spend more time on the specific activity. The constant term of the φ parameter captures the unexplained behavior in satiation effect. All constants in all models across the weeks are highly significant. Although there are variations in parameter values, the general trend is the same across the random weeks. It is clear that work/school activity has higher constant values. This indicates that work/school activity is more the part of regular or skeleton type activities and time allocation to this type of activity is more or less fixed. On the other hand, service/private business activities have lower constant values indicating that people are willing to spend more time on this type of activity though we always have different constraints (as reflected in the baseline utility component: this activity type has lower baseline marginal preference). Similarly shopping and recreation type activities have lower constant values indicating people's higher willingness in spending more time in these activities. Conversely, the 'others' activity type contains all different types of activities that were not included in the general classification and shows low satisfaction in spending more time.

Travel ratio captures the influence of transportation system performance on an individual's activity-travel behavior. It has negative sign for all out-of-home activities for all random weeks. Also for all cases it has highly significant parameter values. In all cases this variable has a negative effect on the φ parameter, indicating that a higher value of travel ratio reduces satisfaction in spending time on specific out-of-home activities. The variable has consistent effects across the random weeks.

The number of people involved in the specific out-of-home activities increases the φ parameter values, indicating increasing satisfaction in spending time. This variable also has

highly significant coefficients for all specific out-of-home activities and for all random weeks except for the ‘other’ type. Although variations in coefficient values are visible across the random weeks the general trends are the same for the same out-of-home activities across the random weeks.

The ρ Parameter: The ρ parameter is purely a satiation factor that defines the marginal rate of utility gain/loss in spending each additional unit of time on the activity types under consideration. This parameter is the same for all activities, including the composite activity. In the utility function formulation used in this paper; this parameter obtains a balancing effect from the satiation parameter for the composite activity. [20] However, the requirement for this parameter is that it must be less than 1 and hence is specified as mention in equation 1. Although different socio-economic variables were tested within the specification, it was difficult to get statistically significant parameter values. The reason of this may be because the satiations effects are already captured by the ϕ parameters for all specific out-of-home activities with respect to the composite activity. However, the constant term in the ρ parameter specification is highly significant and has the same sign and almost same values across the random weeks. The possible reason of having a highly statistically significant constant parameter in the ρ specification without any significant number of socio-economic variables may be that there are some behavioral elements not captured by the variables collected in the survey.

CONCLUSIONS

This paper uses a Kuhn-Tucker demand system model to analyze variations in weekly time expenditure behavior among all possible activities. Activities are first classified into two general types: at-home and out-of-home activities. Out-of-home activities are then further classified into eight general activity types. MobiDrive data, which is a six-week travel diary data for two cities in Germany, are used for the investigation. The main objective of this paper is to investigate whether a typical random week modeling time frame can capture sufficient rhythms of our activity-travel behavior or not. Although it is almost impossible to quantify the rhythm of activity-travel behavior very precisely, comparing estimated model parameter for a number of individual weeks, we can get insight into the extent that activity pattern rhythms can be captured with a ‘typical’ week.

Contrary to focusing on a specific activity type this paper models all possible activity types jointly. [7] The Kuhn-Tucker demand system model is designed to capture complex trade-offs in time expenditure on the activity types under consideration. The fundamental assumption of the formulation of Kuhn-Tucker demand system model is that every individual maximizes his/her total utility in allocating time to all specific activity types under time budget constraints. The time budget is defined as the 7-day time period or a typical week. The idea is to compare the model results developed for each individual week of the MobiDrive survey. All six-week data are also pooled together to develop the pooled data model in order to capture the average week behavior.

In terms of fitting the observed data, individual weekly models show excellent performance (Adjusted Rho-Square values is above 0.2, which is very high considering the complexity of the models), which indicates the appropriateness of the modeling technique used in this paper. Most importantly, it is clear that the goodness-of-fit values are almost the same across the individual weeks of the six-week travel diary survey, which supports the hypothesis that a typical week captures rhythms of activity-travel behavior sufficiently, especially when inter-activity interactions are modelled properly.

Inter-activity interactions in time expenditure are modelled in several stages: baseline preference in spending time to specific activity and satiation effect in spending time to the specific activities. Satiation effects in time expenditure are captured in two ways: satiation effect combined with translating time (to ensure corner solutions) and pure satiation effects. All of these major elements of the models are further specified as functions of different socio-economic and activity-specific variables. Comparing the model parameters of the individual models that are statistically significant, it is clear that individual weeks do have variations but the general trend is similar across the weeks. It cannot be concluded that a typical week captures the complete rhythm of activity-travel behavior, but based on the results presented in this paper we can argue that if we consider a typical week as a random week, it captures the rhythms of activity-travel behavior sufficiently.

However, in this paper we used a travel diary survey data not an activity diary survey data. Given a detail activity diary survey with more detailed behavioral information (spatial, socio-economic and activity specific), including a more detailed classification of out-of-home activities we can expect that model results could be further improved.

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Figure 1: Summary of the Models

Table 1: Estimated Models Parameters

	Full Model No. of Parameters	Null Model No. of Parameters	Full Model LogLikelihood	Null Model LogLikelihood	Rho-Square	Adjusted Rho-Square
Week 1	84	3	-5913.8802	-7860.1653	0.2476	0.2373
Week 2	84	3	-5920.827	-7859.511	0.2467	0.2364
Week 3	84	3	-6130.8576	-7950.096	0.2288	0.2186
Week 4	84	3	-5795.3306	-7531.6171	0.2305	0.2198
Week 5	84	3	-5781.8072	-7660.3902	0.2452	0.2347
Week 6	84	3	-5769.1137	-7650.1054	0.2459	0.2353
6 Weeks Pooled	84	3	-35668.465	-46531.7745	0.2335	0.2317

Figure 1: Summary of the Models

Table 1: Estimated Model Parameters

	Week 1		Week 2		Week 3		Week 4		Week 5		Week 6		Pooled	
<i>Baseline Utility Component</i>														
Variable	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'
<i>CONSTANT: GENERIC</i>														
All Specific Activity	-14.4	-17.28	-18.78	-16.2	-12.8	-15.129	-13.5	-16.14	-18.1	-17.73	-17.3	-16.901	-14.8	-57.246
<i>CITY: Karlsruhe (Dummy)</i>														
Basic Need	0.75	3.38	0.18	0.85	0.77	3.39	0.95	4.16	0.18	0.78	0.42	1.94	0.56	7.34
Work / School	-0.19	-0.89	-0.29	-1.31	0.27	1.22	0.32	1.32	-0.53	-2.28	-0.32	-1.38	-0.10	-1.32
Drop off Pick Up	-0.18	-0.84	-0.74	-3.21	0.02	0.07	0.11	0.48	-0.65	-2.83	-0.28	-1.24	-0.29	-3.70
Shopping	0.09	0.39	-0.11	-0.56	0.29	1.26	0.23	1.06	0.14	0.62	-0.02	-0.07	0.13	1.71
Services / Private Business	-0.17	-0.77	-0.60	-2.93	0.12	0.55	0.14	0.64	-0.29	-1.31	-0.63	-2.90	-0.22	-3.03
Recreation	0.51	2.23	0.09	0.40	0.51	2.02	0.64	2.51	0.27	1.07	0.58	2.24	0.43	4.99
Social	0.77	3.35	0.30	1.38	1.11	5.16	0.82	3.46	0.28	1.20	0.25	1.18	0.61	8.06
Others	0.29	0.51	-0.25	-0.58	0.79	1.75	0.81	1.51	0.29	0.53	0.32	0.50	0.34	1.98
<i>GENDER: Male (Dummy)</i>														
Basic Need	0.41	1.74	0.34	1.52	0.66	2.38	0.23	0.86	0.35	1.64	0.28	1.27	0.39	4.87
Work / School	0.00	-0.02	0.02	0.11	0.41	1.69	0.11	0.40	0.06	0.28	-0.07	-0.29	0.12	1.45
Drop off Pick Up	0.02	0.08	-0.29	-1.22	0.31	1.34	0.01	0.03	-0.26	-1.08	-0.06	-0.24	-0.03	-0.32
Shopping	-0.03	-0.12	-0.30	-1.45	0.11	0.44	0.11	0.42	-0.43	-2.18	-0.35	-1.60	-0.14	-1.75
Services / Private Business	0.23	1.02	0.22	1.08	0.61	2.60	0.39	1.62	0.10	0.47	-0.11	-0.52	0.26	3.45
Recreation	-0.23	-0.90	-0.25	-1.05	0.15	0.60	-0.06	-0.21	-0.30	-1.26	-0.28	-1.14	-0.13	-1.45
Social	0.26	1.08	0.10	0.48	0.59	2.38	0.39	1.47	0.53	2.45	-0.01	-0.03	0.32	4.00
Others	-1.14	-2.00	-1.13	-2.10	-0.24	-0.52	-0.08	-0.19	-0.89	-1.60	-0.99	-1.51	-0.71	-3.95
<i>HOUSEHOLD INCOME</i>														
Basic Need	0.07	1.34	0.25	4.69	0.11	2.08	0.20	3.39	0.12	2.11	0.23	4.73	0.16	9.45
Work / School	-0.04	-0.63	0.11	1.97	-0.06	-0.95	0.03	0.41	-0.06	-0.97	0.05	0.88	0.00	0.15
Drop off Pick Up	-0.30	-5.09	-0.14	-2.33	-0.29	-4.92	-0.19	-2.81	-0.23	-3.66	-0.16	-2.82	-0.21	-10.59
Shopping	-0.03	-0.63	0.12	2.15	0.01	0.19	0.09	1.36	-0.02	-0.31	0.10	2.15	0.05	2.58
Services / Private Business	0.00	-0.04	0.18	3.49	-0.02	-0.32	0.09	1.52	0.02	0.32	0.13	2.52	0.07	3.81
Recreation	-0.18	-3.09	-0.04	-0.69	-0.15	-2.59	-0.06	-0.92	-0.14	-2.49	-0.13	-2.24	-0.11	-5.86
Social	-0.08	-1.61	0.02	0.30	-0.12	-2.40	0.02	0.38	-0.08	-1.45	0.12	2.38	-0.02	-1.37
Others	-0.92	-7.32	-0.64	-6.01	-0.95	-8.51	-0.92	-7.38	-1.00	-7.02	-0.83	-5.80	-0.86	-21.47
<i>DRIVING LICENSE HOLDER (Dummy)</i>														
All Specific Activity	0.35	1.02	0.59	2.23	0.46	1.60	0.40	1.53	0.68	2.55	0.72	2.65	0.47	4.81

Table 1 Continued.....

<i>HOUSEHOLD VEHICLE : More than or Equal to 1 (Dummy)</i>														
All Specific Activity	0.51	1.72	0.06	0.21	0.10	0.35	-0.03	-0.12	0.21	0.87	-0.10	-0.33	0.13	1.46
<i>EMPLOYED HOUSEHOLD MEMBER (Dummy)</i>														
All Specific Activity	0.60	2.13	0.78	2.50	0.23	0.84	0.37	1.19	0.72	2.68	0.78	2.58	0.51	5.26
<i>PARENT IN HOME (Dummy)</i>														
All Specific Activity	0.14	0.45	-0.13	-0.42	-0.42	-1.61	-0.59	-1.99	-0.54	-1.97	-0.69	-2.47	-0.32	-3.54
<i>LN(Distance of Bus Stop From Home)</i>														
All Specific Activity	-0.03	-0.36	-0.04	-0.41	-0.11	-1.28	-0.04	-0.53	-0.04	-0.45	0.00	0.02	-0.03	-1.17
<i>HOME LOCATION IN CBD (Dummy)</i>														
All Specific Activity	-1.48	-3.98	-0.95	-2.64	-1.22	-3.40	-1.40	-3.93	-1.08	-3.47	-1.02	-3.16	-1.13	-9.01
<i>STUDENT (Dummy): GENERIC VARIABLE</i>														
All Specific Activity	-0.79	-2.26	-0.07	-0.17	0.40	0.94	-0.12	-0.30	0.21	0.49	0.80	2.00	0.11	0.84
<i>FULL TIME EMPLOYEE (Dummy)</i>														
Basic Need	0.33	1.18	0.20	0.69	0.79	2.30	0.52	1.61	-0.07	-0.26	0.15	0.57	0.31	3.25
Work / School	2.04	7.65	1.70	6.25	2.30	7.59	1.72	5.35	1.75	6.24	1.97	7.00	1.87	20.04
Drop off Pick Up	-0.44	-1.66	-0.03	-0.11	0.41	1.34	-0.27	-0.83	-0.69	-2.27	-0.45	-1.57	-0.23	-2.37
Shopping	0.02	0.09	0.19	0.67	0.64	1.93	0.10	0.32	0.20	0.73	0.23	0.88	0.24	2.62
Services / Private Business	-0.41	-1.54	-0.64	-2.51	0.05	0.15	-0.35	-1.20	-0.64	-2.45	-0.20	-0.83	-0.37	-4.17
Recreation	-0.11	-0.38	-0.26	-0.82	0.28	0.80	-0.18	-0.53	-0.34	-1.01	-0.03	-0.09	-0.11	-1.07
Social	0.03	0.11	0.69	2.51	0.91	2.96	0.51	1.63	-0.16	-0.52	0.00	0.01	0.34	3.57
Others	-1.49	-1.00	0.17	0.29	0.57	0.97	0.20	0.32	-0.35	-0.54	-0.74	-0.83	-0.14	-0.67
<i>NO. OF HOUSEHOLD CHILDREN (More than or Equal to 1 Dummy)</i>														
Basic Need	-0.90	-1.81	-0.42	-0.80	-0.42	-0.87	-0.87	-1.82	-0.74	-1.67	-0.85	-1.46	-0.42	-2.79
Work / School	0.32	0.63	0.60	1.04	0.68	1.63	-0.14	-0.28	0.32	0.67	0.36	0.60	0.60	3.80
Drop off Pick Up	-1.74	-3.47	-1.21	-2.10	-1.40	-2.99	-1.72	-3.38	-1.40	-2.94	-2.10	-3.62	-1.31	-8.16
Shopping	-1.88	-3.54	-1.49	-2.67	-1.39	-3.03	-2.24	-4.72	-1.41	-3.03	-2.11	-3.79	-1.48	-9.69
Services / Private Business	-2.55	-5.35	-2.10	-4.18	-1.96	-4.68	-2.41	-5.36	-2.26	-5.30	-2.04	-3.81	-1.94	-13.60
Recreation	-0.98	-2.08	-0.30	-0.57	-0.52	-1.16	-1.12	-2.43	-0.88	-2.06	-0.90	-1.54	-0.50	-3.29
Social	-1.01	-2.19	-0.05	-0.10	-0.45	-0.92	-0.83	-1.99	-0.72	-1.62	-0.89	-1.69	-0.36	-2.51
Others	-1.85	-2.01	-1.61	-1.99	-1.08	-1.53	-1.00	-1.37	-1.07	-1.40	-1.46	-1.95	-1.03	-4.12

Table 1 Continued.....

AGE DUMMY: GENERIC VARIABLE														
21-30	-1.99	-3.45	-1.58	-2.75	0.18	0.45	-0.99	-1.77	-1.06	-2.09	-1.09	-1.83	-0.80	-5.24
31-40	-2.15	-3.46	-1.51	-2.47	-0.60	-1.19	-0.93	-1.42	-0.63	-1.01	0.22	0.33	-0.60	-3.34
41-45	-2.91	-4.44	-1.76	-2.76	-1.16	-2.11	-1.61	-2.37	-1.32	-2.00	-0.88	-1.19	-1.25	-6.41
46-50	-1.51	-2.41	-1.30	-1.88	0.72	1.39	-0.43	-0.66	-0.27	-0.42	-0.12	-0.18	-0.20	-1.06
51-55	-3.22	-4.47	-1.82	-2.85	-0.43	-0.84	-1.45	-2.16	-0.67	-1.08	-0.61	-0.89	-1.04	-5.61
56-60	-3.28	-4.76	-1.76	-2.55	-0.75	-1.47	-1.15	-1.71	-0.90	-1.36	-0.69	-0.94	-1.03	-5.24
61-65	-3.21	-4.33	-2.14	-2.79	-1.00	-1.64	-1.30	-1.93	-1.27	-1.80	-1.03	-1.24	-1.24	-5.70
65+	-3.69	-5.02	-2.06	-2.66	-1.17	-1.95	-2.12	-2.86	-1.98	-2.87	-1.59	-1.95	-1.70	-7.37
Satiation Parameter of Specific Activities Only, ϕ														
Variable	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'	Par	t'
CONSTANT														
Basic Need	2.57	12.98	3.23	14.91	2.55	11.45	2.41	12.09	2.87	15.91	2.81	13.92	2.57	39.97
Work / School	2.86	5.92	7.43	11.64	6.23	7.77	6.49	7.76	3.63	7.30	3.54	7.34	3.77	22.34
Drop off Pick Up	3.90	15.58	3.22	16.69	2.14	10.85	1.95	7.16	1.97	9.86	2.83	13.70	2.52	36.06
Shopping	2.13	9.17	2.62	10.88	1.91	9.00	2.58	9.49	1.56	7.30	1.44	6.70	1.90	24.39
Services / Private Business	1.27	5.64	2.44	12.75	1.11	5.92	1.50	6.35	1.72	9.64	1.32	7.28	1.42	21.60
Recreation	3.68	3.65	2.54	3.51	1.96	4.71	2.41	2.92	2.21	3.48	1.88	3.37	1.93	15.72
Social	3.19	6.00	2.47	6.72	3.18	4.68	1.94	4.10	2.13	7.55	2.48	5.31	1.97	25.53
Others	4.84	1.28	3.13	1.73	4.24	2.01	3.79	2.76	2.97	1.72	2.75	0.51	3.54	8.75
TRAVEL RATIO														
Basic Need	-0.44	-4.36	-0.70	-6.98	-0.88	-9.86	-0.29	-6.29	-0.40	-5.81	-0.54	-8.75	-0.48	-25.62
Work / School	-0.71	-2.93	-4.09	-11.96	-3.16	-8.12	-4.03	-7.97	-1.09	-7.98	-1.44	-7.19	-1.58	-27.88
Drop off Pick Up	-0.76	-14.89	-0.67	-13.11	-0.48	-15.73	-0.67	-11.08	-0.25	-9.09	-0.51	-13.50	-0.50	-40.18
Shopping	-1.01	-7.99	-1.17	-8.55	-0.98	-10.47	-1.19	-7.66	-0.69	-7.35	-0.37	-4.94	-0.87	-23.49
Services / Private Business	-0.56	-7.28	-0.85	-11.72	-0.41	-7.72	-0.58	-5.33	-0.54	-13.77	-0.32	-6.40	-0.51	-27.22
Recreation	-1.34	-1.66	-0.45	-0.88	-0.01	-0.05	-0.30	-0.49	-0.03	-0.08	0.00	0.02	0.00	0.06
Social	-1.30	-3.37	-0.51	-2.11	-1.54	-2.80	-0.32	-0.88	-0.15	-1.05	-0.52	-1.33	-0.28	-10.14
Others	-1.43	-0.42	-0.86	-0.80	-1.18	-1.00	-0.96	-2.69	-1.55	-1.42	-1.38	-0.25	-0.91	-5.26

Table 1 Continued.....

<i>NUMBER OF PEOPLE INVOLVED</i>														
Basic Need	0.14	7.18	0.13	5.53	0.18	7.01	0.12	4.93	0.13	5.58	0.12	5.44	0.14	16.97
Work / School	0.46	6.48	0.32	4.09	0.25	2.70	0.51	6.39	0.51	5.58	0.55	7.54	0.50	16.59
Drop off Pick Up	0.11	1.77	0.27	5.03	0.32	5.21	0.57	6.31	0.42	5.60	0.28	4.08	0.31	14.00
Shopping	0.20	7.11	0.16	5.55	0.16	4.52	0.09	2.99	0.24	7.87	0.13	3.93	0.16	14.81
Services / Private Business	0.39	8.31	0.24	6.74	0.28	7.35	0.30	7.65	0.25	6.05	0.32	7.52	0.30	20.35
Recreation	0.19	1.97	0.29	2.73	0.14	1.64	0.16	2.34	0.17	1.50	0.28	1.94	0.21	6.33
Social	0.20	4.88	0.23	4.27	0.24	4.93	0.19	4.84	0.21	3.84	0.17	4.40	0.21	12.59
Others	-0.05	-0.08	0.25	0.29	-0.19	-0.19	0.39	0.75	1.42	2.00	0.46	0.37	0.15	1.01
<i>Satiation Parameter of Composite Activity, ρ</i>														
Variable	Par	't'	Par	't'	Par	't'	Par	't'	Par	't'	Par	't'	Par	't'
CONSTANT	-1.32	-28.38	-1.44	-31.82	-1.03	-22.11	-1.14	-31.85	-1.41	-33.89	-1.33	-30.73	-1.21	-103.87
MARRIED (Dummy)	0.00	-0.10	0.01	0.67	0.00	-0.07	0.00	0.07	0.01	0.73	0.01	0.42	0.00	0.66
LN(No. of Household Members)	0.03	1.89	-0.02	-1.20	-0.04	-2.17	-0.02	-1.19	-0.01	-0.66	-0.02	-1.03	-0.01	-1.84
HOUSEHOLD VEHICLE (≥ 2)	0.04	1.63	0.01	0.66	0.02	0.61	-0.01	-0.50	0.03	1.56	0.01	0.35	0.02	2.07