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Modelling value of time for trip chains in daily schedules

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Abstract

The decision about spending time on an activity, switching to the next activity and transport mode used to travel to the next activity location depends on money value of time; opportunity cost of time at activity. Optimal condition of transition between two activities occurs when their marginal utility of time is equal. The presented framework in this paper models the marginal utility of activity to express the money benefit earned by spending each unit of time at the given activity. The proposed model is generalized for the schedule with any number of activities as contrast to previous studies, where such models were used for schedules with fixed number of activities. This framework can be used to calculate the loss in value of time due decreased activity participation resulting from travel delays.

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Keywords: Value of time; Opportunity cost of time;

1. Introduction

Money value of time of an individual varies according to the types of the activities at which it is spent. The decision about spending time on an activity, switching to the next activity and transport mode used to travel to the next activity location depends on money value of time; opportunity cost of time at activity[1]. For example, during early morning, an individual who has to be at work at 9 am will like to stay at home rather than starting work at 7 am. So, opportunity cost of work activity before/after the preferred start/end time will be minimum[2]. Net benefit earned by spending time on any activity is bound by the preferred start time of the activity and its duration. On the other hand,

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start time of the activity and activity duration also depends on travel mode; eventually travel duration. Where travel duration also depends on selected mode and respective travel delay associated with selected mode. Mode of travel can be selected out of available modes to the individual in order to keep travel duration minimum with available travel budget. Hence, activities in daily schedule are optimized to escalate the net benefit earned by time distribution in all activities and required travel by a trade-off between money and time spent on the travel. This is important, for example, for decision to pay an extra euro cent to avoid getting delayed for one-unit time depends upon the individual's urgency for being at destination.

In order to evaluate the benefit earned by spending time in activities and traveling, a model is presented in this paper. A marginal money value of time function is used to estimate the value of time of an individual coupled with type of activities. For the given activity, this model is used to calculate the net profit earned by spending time on this activity by the individual. The time spent on the activity is subject to the activity start time; in other words, in case of undesirable activity start time due to late/earlier arrival, net profit earned cannot be maximum as compared with optimal case. In such scenarios, this model is used to calculate the lost benefit which could be earned by starting the activity at preferred start time.

Any unwanted incident in transportation system can cause significant disruptions in transportation system which creates losses in capacity and efficiency of the system. Such situations may lead to travel time increase that propagate to the nearby transportation network through queues and congestions. Delay in travel duration can impair the expected activity participation; hence earned satisfaction cannot reach at expected level which can result in loss of value of time. Daily schedules consist of the chain of daily activities which are partially flexible which means that time lost during one trip can be compensated from all of the succeeding activities if there is no hard deadline. To compensate the lost time, activity start time and duration are recalculated for all of the succeeding activities after the time loss incident[3]. To capture the loss due to decreased participation in all activities, accumulated benefit is calculated by applying this model to all activities in the schedule for comparison between optimal and recalculated timings.

This paper is organized as follow: Section 2 provides the conceptual theory of presented framework. It describes the utility function is sum of marginal utilities of all activities in the schedule, then it describes the marginal utility function of an activity. Section 3 provides a procedure to calibrate the parameters used in marginal utility. Section 4 provides the conclusion drawn from this work.

2. Opportunity cost of time

The decision about allocation of available resources to different activities is made to maximize the satisfaction to fulfil the individual's needs. Time and money are vital resources which are used to accomplish the long and short-term goals. Time is a finite resource which neither can be acquired nor stored but can be distributed in daily activities such that it yields maximum satisfaction[4]. Time spent on different activities can be valued in term of foregone opportunity; opportunity cost of time of any activity in a daily schedule is the net benefit of the time spent in next best alternative activity[1].

2.1. Theoretical framework

The framework modelled in this work postulates that individuals take part in daily activities and make trips to travel between activities. There are fixed number of activities with a given sequence for each individual which construct the daily schedule of that individual. Each activity has a preferred start time, duration and the location. The initial daily schedules of whole population of study area are generated using activity-based model FEATHERS[5] and are considered optimal. Optimal schedule connotes that activity start time and duration are considered optimized and preferred by the individual which yields maximum satisfaction required by the individual by activity participation. It is the maximum benefit earned by the individual by spending time at different activities and trips during the day and it is represented by utility function U. Total utility of the schedule is sum of utility of all activities and disutility of all trips in the schedule. The utility gained by spending a unit time on any activity is expressed as marginal utility which is the function of start time and time of the day. Such models have formulated previously by Ettema and Timmermans[6], Zhang et al.[7] and Jenelius[8], however all previous models only formulate the fixed number of activities. In this work, the described framework is used to calculate the value of time for schedules created by an activity-based model. Suppose a schedule consists of n activities where $n-1$ trips are required to travel between n activities locations. Each activity i starts at t_i^s time of day and ends at trip departure time t_i^d to next activity location. Each trip is T_i duration long which starts from the departure time t_i^d of the activity i and ends at start time t_s^{i+1} of the succeeding activity $i+1$. Hence, the total utility U of such schedule is the sum of all utilities which is yielded by integrating the marginal utilities of all activities and travels where $u_i(t)$ is the marginal utility of the activity i and $v[T_i]$ is the marginal disutility of the travel T_i.

$$U(t) = \sum_{i=1}^{n} \int_{t_i^s}^{t_i^d} u_i(t)dt - \sum_{i=1}^{n-1} v\left[T_i\left(t_d^i, t_s^{i+1}\right)\right] \quad (1)$$

$$t_i^s = \begin{cases} 0 & if\ i = 1 \\ t_i^s & if\ i > 1 \end{cases}$$

$$t_i^d = \begin{cases} 1 & if\ i = n \\ t_i^d & if\ i < n \end{cases}$$

Fig. 1 illustrates the model described above where number of activities are four. Each activity has the maximum marginal utility with warm-up and cool-down periods. In this figure, x-axis displays the time of the day where y-axis shows the marginal utility. In this framework, money/hour is the unit used for marginal utility. Hence, when marginal utility is integrated with time, it gives the money benefit earned by spending time in different activities over the day and has the monetary units.

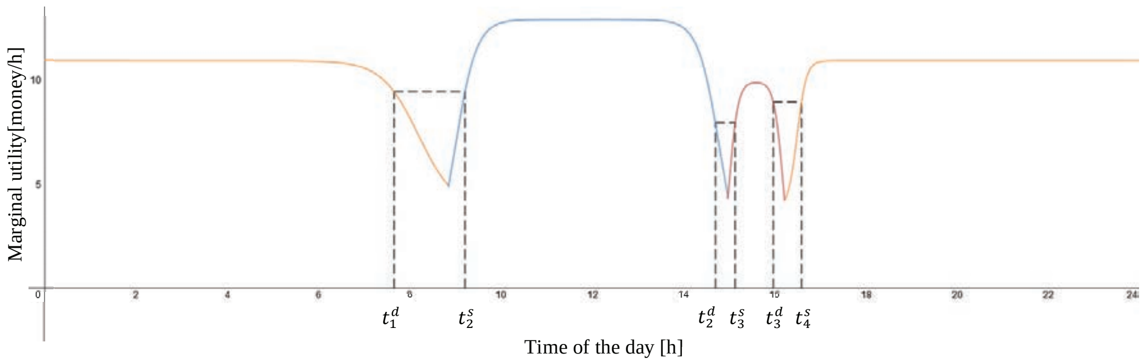

Fig. 1. Set of marginal utilities of a schedule with four activities. solid line shows the value of marginal utility for each activity. Each pair of dotted lines shows the trip departure and trip finish period.

2.2. Marginal Utility

Spending time either at home or at work in the morning depends upon their relative difference of value of time. Each activity has its preferred start time and duration which yields maximum benefit. If activity is started earlier or finished after the preferred time, the earned benefit will always be lower than the maximum value. Each activity has maximum and minimum marginal benefit earned by spending another minute on any activity. Maximum value shows the interest of spending a unit time on the activity and minimum value shows the disinterest. There is a warm-up period after the activity starts and a cool-down period before the activity ends. First activity, which is always a home activity, starts with start of the day with a maximum marginal value and only contains the cool-down period prior to the departure time. All activities, after the first activity and before the last activities $[2, n-1]$, start from a warm-up period and gain a maximum value. After a certain time, there happens a shift which leads to the cool-down period until departure time occurs. For last activity, which is again a home activity, there only warm-up period occurs which ends at a maximum marginal value at the end of the day.

$$u_1(t) = h_1 - \frac{h_1 - l_1}{1 + e^{\left(-p_1 * (t - t_1^d)\right)}} \quad 0 \le t \le t_1^d \tag{2}$$

$$u_i(t) = \begin{cases} h_i - \frac{h_i - l_i}{1 + e^{\left(p_i * (t - t_i^s)\right)}} & t_i^s \le t \le t_i^{shift} \\ h_i - \frac{h_i - l_i}{1 + e^{\left(-p_i * (t - t_i^s - t_i^d)\right)}} & t_i^{shift} \le t \le t_i^d \end{cases} \tag{3}$$

$$t_i^{shift} = \frac{t_i^s + t_i^d}{2} \tag{4}$$

$$u_n(t) = h_n - \frac{h_n - l_n}{1 + e^{\left(p_n * (t - t_n^s)\right)}} \quad t_n^s \le t \le 1 \tag{5}$$

Transition between the two activities depends on the following factors:

1. Transition between two activities should occur when their marginal values of time are equal. In Fig. 2, two sigmoid graphs $u_1(t)$ and $u_2(t)$ are illustrated for two consecutive activities. $u_1(t)$ and $u_2(t)$ represent the marginal value of time of being at activity 1 and activity 2 respectively. Value of both marginal functions are equal at t' at which a transition should occur from activity 1 to the activity 2. For the condition of optimal schedule following condition must hold:

$$u_{i-1}(t_{i-1}^d) = u_i(t_i^s) \tag{6}$$

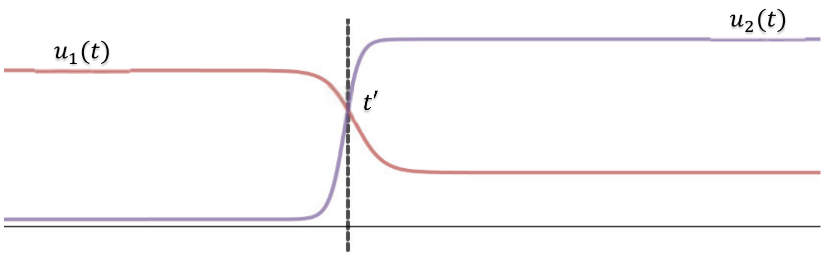

Fig. 2. Point of transition where condition of optimality holds

2. Preferred start time of the succeeding activity is a straightforward factor in selection of departure time from previous activity. To start the activity at the preferred time, one has to take into account the transport mode

dependent travel duration. For given trip length, each transport mode has a travel duration associated with a travel cost. Transport mode is selected by a trade-off between time as a resource and available money budget for the trip. For each selected mode, time-varying travel duration and travel cost are also important to include in selection of departure time, because they can be affected by external time-varying factors. For example, travel duration and travel cost depend upon the instantaneous traffic load (on-peak and off-peak travel durations or congestion costs). For instance, if t_i^s is the preferred start time of activity i, and T_{i-1}^{dur} is the travel duration from location of previous activity $(i-1)$ to the location of current activity (i), the departure time t_{i-1}^d from previous activity location is given below. Travel duration T_{i-1}^{dur} depends on the time of the day (t), the mode (m), and operational and non-operational costs associated with given mode. Operational cost of the mode depends on the distance to be travelled for the given trip while non-operational cost of the mode depends on the time of the day of the trip; i.e. congestion cost.

$$t_i^s = t_{i-1}^d + T_{i-1}^{dur}\left(t, m\,,\, c_m^{opr}(dis), c_m^{n_{opr}}(t)\right) \tag{7}$$

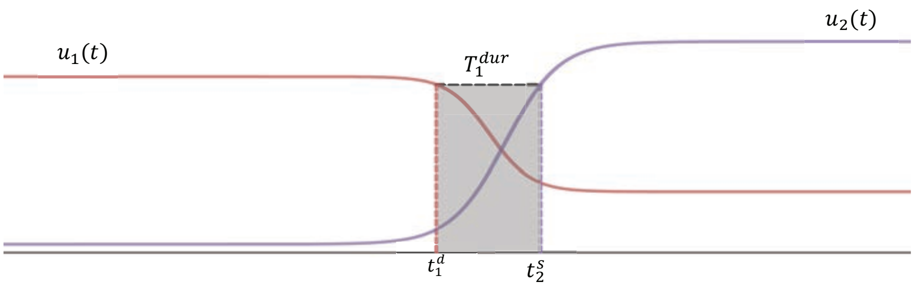

Fig. 3. Trip timings to travel from activity 1 to activity 2

As shown in Fig. 3, required travel T_1^{dur} lapses from departure time t_1^d during activity 1 to the preferred start time t_2^s of the activity 2. As described above, duration of the travel depends vitally on the selected mode, timing of the trip and money that a traveller is willing to spend to accomplish the trip.

3. Calibration of marginal utility function

Maximum and minimum values of marginal utility function depend on individual's socio-economic class (SEC) and type of the activity. All individuals in the study area are divided into three SEC categories having 30,000 Euro/annum, 60,000 Euro/annum and 90,000Euro/annum household income. There are 10 types of activities that exist in daily schedules of study population; home, work, bring/get, daily shopping, non-daily shopping, service, social visit, leisure, touring and other. p_i in marginal utility function is defined manually for each type of the activity, and values are shown in Table 1. maximum and minimum values of marginal utility varies for each individual and activity type. Assume there are k number of individuals in a house h which belongs to one SEC category as defined above. Daily share j_d for individual j from annual household income A is calculate as $A/(k*365)$. Now suppose that individual j has n activities in a schedule of a given day. Maximum value of marginal utility function for any activity i in daily schedule of individual j is calculated as shown in equation (8). Minimum value is selected 0 in this study for all types of activities for each individual. The units of maximum value of marginal utility h_i^j are [€/min] which will yield marginal utility in same units. As initial daily schedules used for the study are assumed optimal, hence marginal utility value per unit time calibrated using activity duration Dur_i. The marginal utility values calibrated using optimal schedule can further be used as reference while comparing the total utility of the schedule after any disturbance in activity timings.

$$h_i^j = \frac{j_d * \ p_i}{\sum_{a=1}^{n} p_a} \tag{8}$$

Table 1. Values of p per activity type

Type of the Activity (a)	p_a
Home	3
Work	9
Bring/Get	10
Daily Shopping	4
Non-Daily Shopping	4
Service	6
Social Visit	8
Leisure	4
Touring	4
Other	4

4. Conclusion

In this paper a conceptual framework is presented to model the marginal utility of activity participation time. The value of marginal utility reveals the benefit earned by the individual by spending one-unit time at the given activity. Total utility of schedule exhibits the benefit earned by activity participation using distributed time between activities and travels. Parameters in marginal utility function are calibrated using the optimal timing of the schedules. This framework can be used for calculation of cost of traveller's delay, as delayed travel decreases the activity participation.

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