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Travel and activity choices based on an individual accessibility model*

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Abstract. An individual's travel and activity behaviour is influenced by temporal and spatial constraints, travel and activity characteristics and individual attributes. This article formulates an individual accessibility model to measure the accessibility benefits of daily activities undertaken through a trip, a trip chain or at home. The model is extended further to analyse individuals' activity location choices, choices between activities at home and activities through travel, and activity timing and scheduling decisions, with the assumption that an individual chooses an activity/travel alternative with the maximum accessibility benefits. An individual's choice among different locations for participating in an activity is shown to depend on the time budget and the locations of activities scheduled before and after this decided activity. The substitution of an activity at home for an activity through travel is shown to depend on the relative magnitude of activity location attraction and activity duration between these two types of activities and preference parameters. Finally, the article illustrates how an individual schedules one or several continuous or discontinuous activities with time-dependent accessibility benefits so as to maximise benefits.

JEL classification: D11, R22, R40

Key words: Travel behaviour, accessibility, activity choices

1 Introduction

The travel and activity behaviour of an individual is complicated. This behaviour is affected by temporal and spatial constraints, travel and activity characteristics

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and personal attributes. Individuals value accessibility, but the accessibility-related measures are normally defined by means of an aggregate geographical approach (Allen et al. 1993; Pooler 1995). In this article we formulate an individual accessibility model to measure the accessibility benefits of daily activities undertaken by an individual, either through a trip, a trip chain or at home, and then analytically explore an individual's travel and activity choices based on this model.

Travel is a derived demand generated to enable an individual to participate in a variety of activities distributed in space. In recent years there has been a surge in activity-focused research. This type of research is derived principally from the early work of Hägerstrand (1970) in time-space geography, in which travel and activity participation are recorded as a passage through time and space (Recker 1995). Pas (1985) summarised several themes in these studies, such as analysis of the demand for activity participation, scheduling of activities in time and space, constraints on activity and travel choice, interventions between activity and travel decisions over the day, as well as the interactions between different individuals, structure of the household, and roles played by various household members. Recent research has further extended one or more of these themes by using more complicated discrete choice random utility models. For instance, Dunn and Wrigley (1985) have developed models for the choice of location of non-work activity participation. Kitamura and Kermanshah (1983), Golob (1986), and Nishii and Kondo (1992) focused on understanding the mechanism by which individual non-work activities are chosen for participation and sequencing. Bhat (1996) focused on developing a generalised hazard model for non-work activity duration during the return-to-home-from-work trip.

Recent research has also gradually evolved into an attempt to understand a complex dynamic process of decision-making that involves not only travel but also activities undertaken by household members at home or away from home. For instance, Ben-Akiva and Bowman (1998) formulated an integrated discrete choice model of a household's choice of residential location and its members' daily activity and travel choices. These authors measure residential accessibility by the maximum utility of household members' daily activity schedules. Supernak (1992) developed the concept of analysing the temporal utility profiles of activities accompanied by the associated effort such as travel. Small (1982) and Wilson (1989) attempted to explain and model the costs of arrival delay at work, or for arrival delay at the location of other activities, and linked such delay costs to travel time. Wang (1996) focused on the methodology for estimating the timing utility of individuals' daily activities and examined how such utility interacts with travel time.

These recent studies have modeled travel and activity behaviour by using rather complicated random utility models or mathematical programming models. Although these studies have provided much valuable insight into understanding individuals' travel and activity behaviour, they have usually focused on a limited number of issues. The variables considered and the modeling process in each contribution have evolved into a rather complicated and diversified paradigm. In a departure from the approach of these recent studies, our article attempts to identify only a few key variables that capture the essence underlying a variety of situations in travel and activity choice behaviour and to proceed to formulate a simple generalised individual accessibility model for analysing these choices. Using simple analytical models and charts rather than complex mathematical descriptions is beneficial for unveiling the basic relationships among the key variables of concern in a transparent manner and for extending this fundamental model to specific cases.

We formulate in Sect. 2 the individual accessibility model. The model is extended further to analyse an individual's travel and activity behaviour on the basis of the assumption that an individual chooses an activity/travel alternative with the maximum accessibility benefits. Further in Sect. 3 we describe individuals' activity centre choices and trip-linkages of rail commuters. We analyse in Sect. 4 individuals' choices between at-home and away-from-home activities and then proceed in Sect. 5 to illustrate how an individual schedules one or two activities with time-dependent accessibility benefit. Conclusions follow.

2 An individual accessibility model

In this section we develop an individual accessibility model to measure the accessibility benefits of daily activities, either at away-from-home locations through a trip or a trip chain, or alternatively at home. Although many variables affect an individual's accessibility benefit, only three key variables are defined here, in a manner analogous to the definitions of Weibull (1976) and Burns (1979). By assuming that individuals value a spatial opportunity relative to the amount of time they can spend pursuing this opportunity, the measure proposed here strives to capture accessibility's temporal dependence. The accessibility measure incorporates the utility an individual gains from attributes of an activity location, and the duration he or she can spend undertaking this activity, as well as the disutility associated with the travel required to reach the location.

Assume that the accessibility benefit Z_m of an activity undertaken by an individual m at a certain location is a function of an index of activity attributes a of the location, the time T the individual can devote to the activity at the location, and round-trip travel time t which the individual requires to access the location. Hence:

$$Z_m = Z_m(a, T, t) \,, \tag{1}$$

where T and t denote non-negative real numbers measured in time units, and a represents the index value of attributes characterising the location. These attributes could be levels of activity or facility capacities, e.g., square feet retail floor area, etc. Properties of Z_m include the following:

1. $\frac{\partial Z_m}{\partial a} \geq 0, \quad \frac{\partial Z_m}{\partial T} \geq 0, \quad \frac{\partial Z_m}{\partial t} \leq 0,$
2. $\lim_{t\to\infty} Z_m(a,T,t)=0, Z_m(0,T,t)=0, Z_m(a,0,t)=0$, and $Z_m(a,T,0) \neq 0$.

The variables a, T, and t are referred to as activity attributes, activity duration and travel time, respectively, in order to simplify the descriptions in the following discussions.

An individual not only participates in away-from-home activities, e.g., working, shopping and recreation, but also participates in at-home activities such as sleeping, eating, and personal care. In a broad sense, an individual acquires accessibility benefits from both types of activities. Let $t = 0$, then the accessibility benefit of an activity undertaken by an individual at home is:

$$Z_m = Z_m(a, T, 0) . \tag{2}$$

The gravity-type function has the form of a multiplicative function of location attraction combined with a negative exponential function of location access time. This hybrid form is commonly used in transportation and regional science literature, which implies that there is interaction between the effects of its variables. We define Z_m as a gravity-type function:

$$Z_m = Z_m(a, T, t) = a^\alpha T^\beta \exp(-\gamma t) \qquad \alpha, \beta, \gamma \geq 0 , \tag{3}$$

where α, β, and γ, represent the weights which an individual places on activity attributes, activity duration, and travel time, respectively. The values of these parameters vary, and depend on the disparities in tastes or perceptions of individuals with different socioeconomic backgrounds, and on the characteristics of different types of activities. Z_m is clearly an accessibility-benefit measure that satisfies the two properties given above.

Let d and v denote, respectively, the round-trip distance and average travel speed of the individual on the entire trip, including each travel segment, from home to the activity location. Thus, the round trip travel time, which determines an individual's travel decision, can be estimated by d/v. The value of v would vary over the day and result in time-dependent travel time. Consequently, individuals may schedule their daily activities to avoid congestion. This issue will be further explored in Sect. 5. Given the round trip travel time d/v, the accessibility-benefit measure for an activity at an away-from-home location through a trip is:

$$Z_m = a^\alpha T^\beta \exp(-\gamma d/v) , \tag{4}$$

and that for an activity at home is:

$$Z_m = a^\alpha T^\beta . \tag{5}$$

Hence Equations (4) and (5) show that, using a gravity-type function, Z_m can represent the accessibility-benefit measure not only for an activity at an away-from-home location but also for an activity at home. Individuals usually confront temporal constraints that limit their accessibility. The accessibility-benefit is related to the amount of time an individual can devote to undertaking an activity. Let τ denote the time budget of an individual m for an activity at an away-from-home location through a trip. We see that the maximum activity duration, T, is constrained by the individual's time budget, τ, and $T = \tau - d/v$ for $\tau > d/v$ and $T = 0$ for $\tau \leq d/v$, that is, $Z_m = 0$ when $\tau \leq d/v$. By taking the time budget τ into account, Equation (4) generates a constrained spatial interaction model. In addition to the time budget constraint, the accessibility benefit is also affected by spatial constraints, i.e., origin and destination locations at which an individual is located before and after the decided activity is undertaken. This will be further explored in Sect. 3.

Individuals normally combine trips into a home-based "chain" in which more than one destination may be visited. The importance of incorporating this aspect of travel behaviour into the analysis becomes evident when one considers how spatial and temporal distributions of trips will vary depending on the ways in which individuals organise their daily activities, develop itineraries, and make chain trips.[1] Similar to the definition of Z_m in Equation (1), the accessibility benefits of N activities undertaken by an individual m, through a trip chain with N destinations, f_m, can be expressed as:

$$f_m = f_m(\mathbf{a}_\mathrm{N}, \mathbf{T}_\mathrm{N}, \mathbf{t}_\mathrm{N}^*) \quad (6)$$

where $\mathbf{a}_\mathrm{N} = (a_1, a_2, ..., a_n, ..., a_\mathrm{N})$ and $\mathbf{T}_\mathrm{N} = (T_1, T_2, ..., T_n, ..., T_\mathrm{N})$ denote two vectors that, respectively, comprise activity attributes and activity duration at destination location $n, n = 1, ..., N$, visited by individual m via a trip chain. Furthermore, $\mathbf{t}_\mathrm{N}^* = (t_1^*, t_2^*, ..., t_n^*, ..., t_\mathrm{N}^*)$ denotes the set comprising the differences in travel times between visiting N destination locations and visiting $N-1$ destination locations in a trip chain, where t_1^*, i.e., $N = 1$, stands for the round-trip travel time to visit one destination location.

Furthermore, when $N{=}1, f_m(a_1, T_1, t_1^*){=}Z_m(a_1, T_1, t_1){=}a_1^\alpha T_1^\beta \exp(-\gamma t_1)$. Here f_m is equivalent to Z_m, representing the accessibility benefit of an activity undertaken by an individual at an away-from-home location through a single trip. Accordingly, when $N = 1$, and $t = 0$, $f_m(a_1, T_1, 0) = Z_m(a_1, T_1, 0) = a_1^\alpha T_1^\beta$, and f_m stands in this case for the accessibility benefit of an activity undertaken by an individual at home. Therefore, f_m is a generalised individual accessibility model for measuring the accessibility benefits of activities undertaken by an individual, either through a trip, a trip chain or at home.

Previous empirical studies have shown that busier individuals are more likely to combine trips into a trip chain in which more than one destination location may be visited. This implies that if $N \geq 2$, the accessibility benefits of N activities undertaken by an individual through a trip chain must be higher than those of N activities undertaken by the same individual through N separate trips. That is:

$$f_m(\mathbf{a}_\mathrm{N}, \mathbf{T}_\mathrm{N}, \mathbf{t}_\mathrm{N}^*) \geq \sum_{n=1}^{N} Z_m(a_n, T_n, t_n) \, . \quad (7)$$

Assume that one more activity destination n is added to a trip chain. The accessibility benefits of activities through this trip chain increases by an accessibility benefit of $a_n^\alpha T_n^\beta \exp(-\gamma t_n^*)$. Hence when $N = 2$,

$$f_m = a_1^\alpha T_1^\beta \exp(-\gamma t_1^*) + a_2^\alpha T_2^\beta \exp(-\gamma t_2^*) \, . \quad (8)$$

Accordingly, when $N > 2$,

$$f_m = \sum_{n=1}^{N} (a_n^\alpha T_n^\beta \exp(-\gamma t_n^*)) \, . \quad (9)$$

[1] For further discussion on this issue, see e.g., Oster (1978), Alder and Ben-Akiva (1979), Kitamura (1984), and Koppelman and Pas (1985).

Equation (9) satisfies Equation (7). This statement can be easily proved as follows. Since when there is one more destination location n added to a trip train, the increased travel time due to the added destination can not be larger than the travel time for solely visiting this destination n, that is, $t_n^* \leq t_n$. Moreover, since $\gamma > 0$, then $\exp(-\gamma t_n^*) \geq \exp(-\gamma t_n)$. Therefore, $a_n^\alpha T_n^\beta \exp(-\gamma t_n^*) \geq a_n^\alpha T_n^\beta \exp(-\gamma t_n)$, and $\sum_{n=1}^N (a_n^\alpha T_n^\beta \exp(-\gamma t_n^*)) \geq \sum_{n=1}^N (a_n^\alpha T_n^\beta \exp(-\gamma t_n))$. Consequently, $f_m(\mathbf{a}_\mathrm{N}, \mathbf{T}_\mathrm{N}, \mathbf{t}_\mathrm{N}^*) \geq \sum_{n=1}^N (a_n^\alpha T_n^\beta \exp(-\gamma t_n^*))$ must hold.

Hägerstrand (1970) developed a space-time representation of human activity. An individual's daily activities can be represented by an unbroken trajectory through space and time. This trajectory describes how an individual organises daily activities, and develops itineraries and chain trips. Assume, in one day, that an individual undertakes I at-home activities and J trips, each with N_j ($j = 1, ..., J$) activities. Let the total accessibility benefit of activities in a day be the sum of accessibility benefit of these respective activities. Then, the accessibility benefit of daily activities undertaken by individual m, A_m, can be obtained from Equations (5) and (9), and expressed as:

$$A_m = \sum_{i=1}^{I} (a_i^\alpha T_i^\beta) + \sum_{j=1}^{J} \sum_{n=1}^{N_j} (a_{nj}^\alpha T_{nj}^\beta \exp(-\gamma t_{nj}^*)) . \quad (10)$$

Equation (10) is a standard formula of the accessibility benefit measure, which comprises the accessibility benefit of activities undertaken by an individual, either through a trip, a trip chain, or at home in a day (or similarly for any other period of time). Using this equation we can analyse the influences of temporal and spatial constraints on an individual's travel and activity choices. The accessibility benefit measure above is further extended to analyse individuals' activity location choices, choices between activities at home and activities that require travel, and activity timing and scheduling decisions. Such travel and activity decisions are analysed on the basis of the assumption that an individual chooses an activity/travel alternative with the maximum accessibility benefit subject to temporal and/or spatial constraints.

3 Activity location choices

Conventional destination choice models such as the gravity model and the intervening opportunity model normally assume that individuals select their activity locations based on location attractions and travel time. However, temporal and spatial constraints, such as an individual's time budget and origin and destination locations at which an individual is located before and after the decided activity is undertaken, may influence the individual's location choice for that activity.

Here, we analyse location choices based on the individual accessibility model developed in Sect. 2 by incorporating these considerations. Furthermore, we provide theoretical insights that elucidate the empirical findings of Nishii and Kondo (1992), who investigated the activity location choices and trip linkages of urban railway commuters.

3.1 Choices of activity locations in a hierarchy

Many observers of urban form have pointed out that the bulk of urban activities occur in ordered hierarchies. Assume that there are two levels of activity centres. The lower level consists of regional activity centres, which could be suburban shopping centres, centres of small neighbourhood cities, etc., and the higher level is a central activity centre, which could be the central business district (CBD) or the metropolitan core. The activity attributes of the central activity center, a_c, are normally higher than those of a regional activity centre, a_r, i.e., $a_c > a_r$; and the average travel distance from the individual's home to the central activity centre, d_c, is also usually higher than that to the regional activity centre, d_r, i.e., $d_c > d_r$.

Assume that an individual decides to undertake an activity at one of these two activity centres from home and then return back to home, i.e., by a trip starting at home, going to the activity centre and then returning back home. Denote the average travel speed and time budget of individual, m, for this activity/travel by v and τ. Then the accessibility benefit of an activity undertaken by individual, m, at the central activity centre and at the regional activity centre, A_{mc} and A_{mr}, are, respectively, as follows:

$$A_{mc} = a_c^{\alpha}(\tau - 2d_c/v)^{\beta}\exp(-\gamma(2d_c/v)), \tau > 2d_c/v \ . \tag{11}$$

$$A_{mr} = a_r^{\alpha}(\tau - 2d_r/v)^{\beta}\exp(-\gamma(2d_r/v)), \tau > 2d_r/v \ . \tag{12}$$

Following the theory of utility maximisation, the individual selects the activity centre that yields the highest accessibility benefit within his or her time budget. Figure 1 depicts variations in the accessibility benefit as an individual's time budget, τ, changes. As the individual's time budget τ increases, his or her accessibility benefit for undertaking the activity at either of the two activity centres increases in both cases; however, the optimal choice shifts at some stage from one to the other. Region I in Fig. 1 represents the case in which $\tau \leq 2d_r/v$ and the individual does not have sufficient time to undertake the activity at either activity centre. His or her accessibility benefit is then zero. As τ increases and $2d_r/v < \tau \leq 2d_c/v$, the individual may choose to travel to regional activity centre as shown by Region II, where $A_{mr} > A_{mc}$. However, as τ further increases and $\tau > 2d_c/v$, he or she may then choose central activity centre due to $A_{mc} > A_{mr}$ (region III). Figure 1 shows the case for $\beta = 1$, and there will be similar results for $\beta > 1$ and $\beta < 1$. Let A_m represent the maximum accessibility benefit of the activity undertaken by individual m at the chosen activity centre, then:

$$A_m = \begin{cases} 0, & \tau \leq 2d_r/v \\ A_{mr}, & 2d_r/v < \tau \leq 2d_c/v \\ \max\{A_{mc}, A_{mr}\}, & \tau > 2d_c/v \ . \end{cases} \tag{13}$$

Assume that an individual intends to select an additional activity during a home to central activity centre trip, i.e., individual departs from home and is constrained to go to the central activity centre after undertaking this additional activity. Let d_{cr} represent the average travel distance between the central activity centre and the regional activity centre. Since $d_r + d_{cr} \geq d_c$ and $a_c > a_r$, it can be easily shown that the individual should always undertake the additional activity at the central activity centre – even when the regional activity centre is on the shortest path connecting his or her home and the central activity centre, i.e., when $d_r + d_{cr} = d_c$.

On the other hand, assume that an individual intends to select an activity centre for an additional activity during a home to regional activity centre trip. Then, when the individual's time budget is insufficient to go to the central activity centre, the person will undertake the activity right at the regional activity centre. However, when the individual's time budget is sufficiently large, the person will select the one with the higher accessibility benefit. That is:

$$A_m = \begin{cases} A_{mr}, & d_r/v \leq \tau \leq (d_r + d_{cr})/v \\ \max(A_{mc}, A_{mr}), & \tau \geq (d_r + d_{cr})/v \ , \end{cases} \tag{14}$$

where $A_{mc} = a_c^{\alpha}(\tau - (d_{cr} + d_c)/v)^{\beta}\exp(-\gamma(d_{cr} + d_c)/v))$ and $A_{mr} = a_r^{\alpha}(\tau - d_r/v)^{\beta}\exp(-\gamma d_r/v)$.

3.2 Trip linkages of urban rail commuters

Nishii and Kondo (1992) investigated trip linkages of urban railway commuters under time-space constraints. Their empirical observations indicated that rail commuters concentrate their non-work activities around rail terminals and workplaces when they plan to undertake non-home trips in addition to their regular work trips. Specifically, rail commuters without a transfer tend to remain around their workplaces for non-home activities, while those with a transfer tend to undertake non-home activities around transfer terminals.

The above trip linkage finding can be investigated by the accessibility-benefit measure for activities undertaken by an individual through a trip chain during the home-to-work or work-to-home commute. The accessibility benefit for one work activity plus one non-home based non-work activity undertaken by an individual

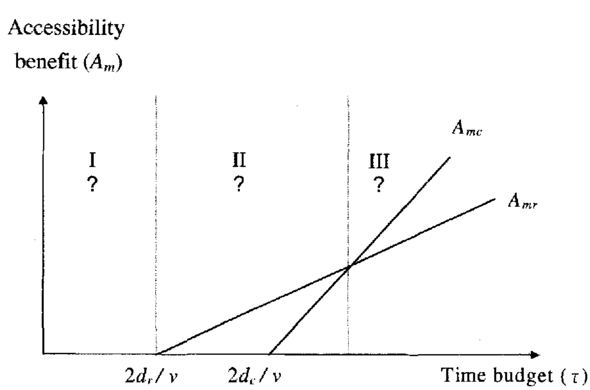

Fig. 1. Accessibility benefit versus time budget for activity centre choices for $\beta = 1$

through a trip chain can be formulated by Equation (9) in Sect. 2 as:

$$a_w^\alpha T_w^\beta \exp(-\gamma t_w) + a_n^\alpha T_n^\beta \exp(-\gamma t_n) , \quad (15)$$

where a_w, T_w, and t_w represent the activity attributes, activity duration, and round-trip travel time from home to the workplace for the work activity, respectively, and a_n, T_n, and t_n represent the activity attributes, activity duration and the additional travel time, respectively, for the non-work activity. Since the work activity is mandatory, therefore, the first term of Equation (15) does not vary with changes in the individual's choice on the activity location for the non-home non-work activity. We only need to compare the changes in the second term of Equation (15) to analyse variations in accessibility benefits when the individual changes activity location for another non-work activity.

Assume that activity attributes and activity duration are independent of activity location, i.e., a_n and T_n do not differ among alternative activity locations. Also, $t_n = 0$, i.e., no additional travel time for another non-work activity is required when rail commuters undertake the non-work activity around rail terminals or workplaces. In contrast, $t_n > 0$, when they undertake the non-work activity at locations other than rail terminals and workplaces. Since $\gamma > 0$ and hence $\exp(-\gamma t_n) < 1$, it is clear that:

$$a_n^\alpha T_n^\beta > a_n^\alpha T_n^\beta \exp(-\gamma t_n) . \quad (16)$$

Hence the accessibility benefits of undertaking the non-work activity around workplaces and rail terminals are higher than those at other locations if activity attributes and duration do not vary with changes in locations. This is consistent with the findings of Nishii and Kondo (1992).

Furthermore, activity attributes at a location can be reasonably assumed to be higher at locations with larger passenger flows. For instance, high-density, and multi-family apartment buildings are usually built around urban rail transit terminals, and induce high passenger flows in these terminals. Activity attributes at rail transit terminals are therefore usually high. Assume that the index of activity attributes at one location is positively related to the daily passenger flow, p, that is $a = cp$, where c is a constant. Let the average daily passenger flow at activity locations other than the rail transit terminal be p_1 and at the rail transit terminal be p_2. Accordingly, $p_2 > p_1$. Let $p_2 = k_1 p_1, k_1 > 1$. Since rail transit terminals usually have many transit passengers, these terminals therefore have a higher daily passenger flow, p_3, than non-transit terminals, i.e., $p_3 > p_2$. Let $p_3 = k_2 p_2, k_2 > 1$. Since $a = cp$, we have $a_1 = cp_1, a_2 = k_1 a_1$, and $a_3 = k_2 k_1 a_1$.

From Equation (16) the accessibility benefits for undertaking non-work activity at locations which are transit rail terminals, non-transit rail terminals, and other locations are, respectively, $(k_2 k_1 a_1)^\alpha T_n^\beta$, $(k_1 a_1)^\alpha T_n^\beta$, and $a_1^\alpha T_n^\beta \exp(-\gamma t_n)$. Since $k_3, k_2 > 1$ and $k_2 k_1 a_1 > k_1 a_1 > a_1$, we find that:

$$(k_2 k_1 a_1)^\alpha T_n^\beta > (k_1 a_1)^\alpha T_n^\beta > a_1^\alpha T_n^\beta \exp(-\gamma t_n) . \quad (17)$$

Equation (17) indicates that undertaking additional non-work activity at rail transit terminals results in the highest accessibility benefit, while activity away from rail terminals results in the lowest accessibility benefit. This relatively simple theoretical derivation underpins the empirical observations by Nishii and Kondo (1992), and demonstrates that rail commuters with transfers tend to concentrate their non-work activities at transfer terminals.

4 At-home activities versus away-from-home activities

Assume that an individual intends to undertake an activity within time budget τ. This activity can be undertaken either at home or at an away-from-home location that requires a trip. Recent telecommunication technology advances offer individuals a variety of new services that enable a range of activities to be undertaken at home. For instance, an individual may choose between store shopping and teleshopping, or between commuting to a workplace and telecommuting at home, or between seeing a movie in a cinema and watching a movie on cable TV at home. For a detailed discussion of the relationship between telecommunication and travel, see e.g., Mokhtarian (1990), Salomon and Koppelman (1988), Salomon and Schofer (1988) and Koppelman et al. (1991).

Let $A_{m,in}$ and $A_{m,out}$ represent, respectively, accessibility benefits of an activity undertaken by individual m at home and at an away-from-home location through a trip within time budget τ, then from Equations (3) and (5), $A_{m,in}$ and $A_{m,out}$ are as follows:

$$A_{m,in} = a_i^{\alpha}\tau^{\beta} \,, \tag{18}$$

$$A_{m,out} = a_o^{\alpha}(\tau - t)^{\beta}\exp(-\gamma t) \,, \tag{19}$$

where a_i and a_o, denote at-home and away-from-home activity attributes, respectively. The individual can either spend the total time budget, τ, to undertake the activity at home or can spend $\tau - t$ to undertake the activity at an away-from-home location via a trip with travel time t.

Assume that the individual aims to maximise accessibility benefits when choosing between at-home activities and away-from-home activities. Then, when $a_i \geq a_o$, then $a_i^{\alpha}\tau^{\beta} > a_o^{\alpha}(\tau - t)^{\beta}\exp(-\gamma t)$, and $A_{m,in} > A_{m,out}$, the individual always selects the at-home activity. However, when $a_i < a_o$, the magnitudes of $A_{m,in}$ and $A_{m,out}$ depend on activity attributes a_i and a_o, the time budget τ, the travel time t, and the parameters α, β, and γ. Furthermore, when the time budget $\tau$is less than the travel time t, i.e., $\tau \leq t$, the individual does not have enough time to spend traveling to undertake an away-from-home activity, then he or she will always choose the at-home activity. Conversely, when $\tau > t$, he or she selects the one with the higher accessibility benefit. Let A_m represent the optimal accessibility benefits for the chosen activity for the case of $a_i < a_o$, then:

$$A_m = \begin{cases} A_{m,in}, & \tau \leq t \\ \text{Max}(A_{m,in}, A_{m,out}), & \tau > t \,. \end{cases} \tag{20}$$

Figures 2a and 2b depict how an individual should select between at-home activity and away-from-home activity as the time budget τ increases, for $\beta = 1$. Figure 2a

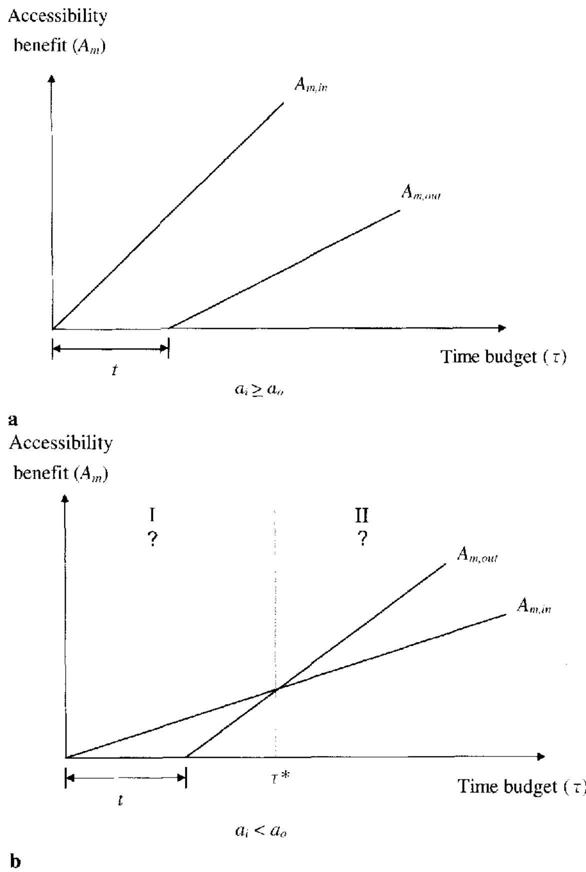

Fig. 2a,b. Choices between at-home activity and away-from-home activity when $\beta = 1$

shows that when $a_i \geq a_o$, the accessibility benefit of the at-home activity is always larger than that of the away-from-home activity, then the individual should always choose the at-home activity. On the other hand, Fig. 2b illustrates that when $a_i < a_o$, there exists a critical time budget, τ^*, which compels the identity $A_{m,in} = A_{m,out}$ to hold. Therefore, when an individual's time budget $\tau < \tau^*$, the accessibility benefit of at-home activity is higher than that of away-from-home activity, he or she should choose the at-home activity; whereas when an individual's time budget $\tau > \tau^*$, he or she should select an away-from-home activity. Regions I and II in Fig. 2b show these two conditions.

The critical time budget is introduced as a means of determining the optimal choice between at-home and away-from-home activities as the individual's time budget varies. Similarly, we can observe the effects of variations in other variables and parameters on the individual's optimal choice by letting $A_{m,in} = A_{m,out}$. That is:

$$a_i^\alpha \tau^\beta = a_o^\alpha (\tau - t)^\beta \exp(-\gamma t) \ . \qquad (21)$$

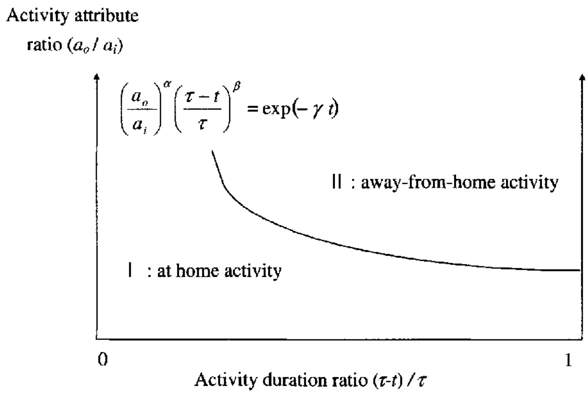

Fig. 3. Choices between at-home activity and away-from-home activity with variations in a_o/a_i and $(\tau - t)/\tau$

The above equation can be rewritten as:

$$\left(\frac{a_o}{a_i}\right)^\alpha \left(\frac{\tau - t}{\tau}\right)^\beta = e^{-\gamma t} \tag{22}$$

where a_o/a_i denotes the ratio of away-from-home and at-home activity attributes (with $a_o/a_i > 1$) and $(\tau - t)/\tau$ represents the ratio of away-from-home and at-home activity duration. Using $(\tau - t)/\tau$ as X axis, and a_o/a_i as Y axis, we can plot the boundary curve $(a_o/a_i)^\alpha((\tau - t)/\tau)^\beta = e^{-\gamma t}$, indicating how an individual should choose between at-home and away-from-home activities when confronted with a variety of scenarios with different away-from-home and at-home activity attribute and duration ratios. As Fig. 3 reveals, the lower left side of the boundary curve, i.e., region I, represents $(a_o/a_i)^\alpha((\tau - t)/\tau)^\beta < e^{-\gamma t}$, that is, $a_i^\alpha \tau^\beta > a_o^\alpha(\tau - t)^\beta \exp(-\gamma t), A_{m,in} > A_{m,out}$, so the individual should choose at-home activity, whereas the upper right side of the boundary curve, i.e., region II, represents $(a_o/a_i)^\alpha((\tau - t)/\tau)^\beta > e^{-\gamma t}$, $A_{m,in} < A_{m,out}$, so the individual should choose away-from-home activities. Furthermore, as a_o/a_i increases, region II expands while region I shrinks, as shown in Fig. 3. That is, when the attributes of an away-from-home activity are relatively higher than attributes of competing at-home activity, the individual is more likely to participate in this away-from-home activity. Similarly, as $(\tau - t)/\tau$ increases, region I also shrinks and indicates that as travel time to an away-from-home activity decreases, the individual is, as expected, also more likely to participate in this away-from-home activity.

As shown in Equation (22), parameters α, β, and γ also affect the position and the shape of the boundary in Fig. 3, when $a_o > a_i$. An individual is more likely to select an at-home activity when placing more weight on activity duration and travel time than on activity attributes, i.e., β and γ are larger while α is smaller. Conversely, an individual is more likely to select an away-from-home activity through a trip when valuing activity attributes higher than activity duration and travel time, i.e., α is larger while β and γ are smaller.

Thus far we have assumed that an individual consumes a total time budget for away-from-home or at-home activities whereby the two activities have different activity duration. However, the same amount of time may be necessary for an activity wherever an individual undertakes this activity. For instance, employers may regulate employees' daily working hours to be the same, regardless of whether they select commuting to the workplace or telecommuting at home. Assume that both at-home and away-from-home activities have the same time duration T, and total time budget τ is not less than the sum of the away-from-home activity duration and its travel time, i.e., $\tau \geq T + t$. In this situation we should use the total time of $T + t$ as a basis for exploring the individual's choice between at-home and away-from-home activities. An individual may have "saved" travel time of t for other activities when choosing to undertake the activity at home. Assume that the accessibility benefit of other activities undertaken by the individual m using this saved travel time t is A'_m, $A'_m \geq 0$, then $A_{m,out}$ and $A_{m,in}$ for the time interval of $T + t$ are, respectively, as follows:

$$\begin{aligned} A_{m,out} &= a_o^{\alpha} T^{\beta} \exp(-\gamma t) \ , \\ A_{m,in} &= a_i^{\alpha} T^{\beta} + A'_m \ , \end{aligned} \tag{23}$$

where $A'_m = a_i^{\alpha} T^{\beta}$. When $a_I > a_o$, then $a_i^{\alpha} T^{\beta} > a_o^{\alpha} T^{\beta} \exp(-\gamma t)$ and $A_{m,in} > A_{m,out}$, thus the individual chooses to undertake at-home activity. When $a_i < a_o$, the choice between at-home and away-from-home activity varies as travel time t or $\tau - T$ increases. Figure 4 reveals that a critical travel time, t^*, exists, causing $A_{m,in} = A_{m,out}$. When $t < t^*$, $A_{m,out} > A_{m,in}$, the individual will choose an away-from-home activity through a trip, while when $t > t^*$, the individual will choose an at-home activity. Moreover, the accessibility benefit of other activities undertaken by the individual using his or her saved travel time t, A'_m, will also affect the position of t^*. When A'_m is larger, t^* is smaller, and the individual is more likely to choose at-home activity. This accessibility benefit of undertaking another activity at home by utilising the "saved" travel time, A'_m, relies not only on the value of travel time, t, but also on where the saved time slot is located and the increasing utility due to the rescheduling of other activities to utilise this time slot. Estimating such accessibility benefits requires a further investigation to portray time-dependent accessibility benefits of daily activities and timing choices of these activities.

5 Activity timing and scheduling

The accessibility benefit of an away-from-home activity undertaken by an individual through travel may depend on "when" the activity is to be undertaken. For instance, an individual may gain the accessibility benefit of the activity of shopping in a store only when visiting the store during open hours. The price and attributes of a department store or a restaurant may vary according to different time slots of a day. Many people tend to adapt their daily schedules to avoid peak congestion. These empirical observations imply that both activity attributes and travel time used for undertaking an activity at an away-from-home location are time-dependent.

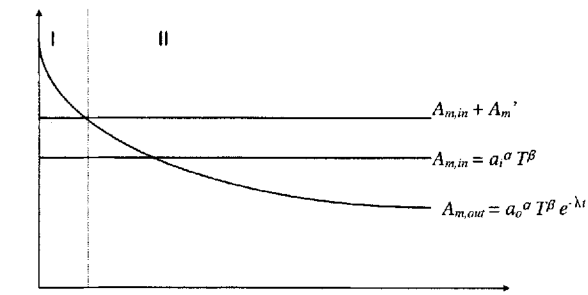

Fig. 4. Choices between at-home activity and away-from-home activity with the same activity duration

Although the individual accessibility model developed in Sect. 2 is simple, it can easily be extended to explore the activity timing and scheduling problems above.

5.1 Single activity timing

When one activity can be undertaken at a time slot independent of other time slots for other activities, its scheduling problem does not exist, and only the timing problem requires consideration.

1. Both activity attributes and travel time are independent of time. Then a and t are constants and the accessibility benefit does not change as time varies. Therefore, the individual may undertake this activity whenever he or she would like to do so. One example is to shop at a 24-hour convenience store via a short walk.
2. Activity attributes are time-dependent while travel time is independent of time. An example is eating out at a restaurant without traffic congestion, but with different prices and services for snacks, lunch, and dinner. Assume that activity attributes exist only during time interval (c_1, c_2),and their values depend on the start time of the activity,c. Denote the time-dependent activity attribute by $a(c)$, then $a(c)$can be expressed as:

$$a(c) = \begin{cases} a(c), c \in (c_1, c_2) \\ 0, \text{otherwise} \end{cases} , \tag{24}$$

and the accessibility benefit of the activity also depends on c. Let $A_m(c)$ stand for accessibility benefit of an activity with time-dependent attributes, then:

$$A_m(c) = \begin{cases} a(c)^{\alpha} T^{\beta} \exp(-\gamma t), c \in (c_1, c_2) \\ 0, \text{otherwise} . \end{cases} \tag{25}$$

The individual selects the optimal start time, $c^*, c^* \in (c_1, c_2)$, thereby maximising his or her accessibility benefit to undertake this activity.

3. Both activity attributes and travel time are time dependent. Assume that travel time for the activity is a function of departure time for traveling to undertake the activity at an away-from-home location. Then from Equation (25), the accessibility benefit of the activities with time-dependent activity attributes and travel time, $A'_m(c)$ is

$$A'_m(c) = \begin{cases} a(t(c') + c')^\alpha T^\beta \exp(-\gamma t(c')), \; t(c') + c' \in (c_1, c_2) \\ 0, \qquad \text{otherwise} \; , \end{cases} \tag{26}$$

where $t(c')$ denotes time-dependent travel time, which is a function of departure time, c'. The individual ought to depart at c' so as to arrive at the away-from-home location to start the activity at $t(c') + c'$, which is within time interval (c_1, c_2).

Figure 5a presents the timing of a single activity with time-dependent accessibility benefit. The maximum accessibility benefit is shown in the figure to occur at time c^* during time interval (c_1, c_2). An individual chooses time c^* to undertake the activity if he or she is free to do so at any time. However, most individuals are confronted with various degrees of time constraints. Assume that an individual is free to start traveling to undertake this away-from-home activity only during the time interval (c_3, c_4) and travel time is time dependent. Then, as shown in Fig. 5a, he or she should depart at c', arrive at the away-from-home location at $c' + t(c')$ so as to realise the activity with the maximum accessibility benefit that can possibly be obtained, A'_m, during time interval (c_3, c_4), where $c' > c_3$, and $c' + t(c') + T < c_4$ are assumed to hold.

5.2 Scheduling of two activities

An individual selects the optimal timing and sequencing of two activities so as to ensure that the cumulative accessibility benefit of undertaking the two activities reaches a maximum, when he or she simultaneously considers both of these. If the optimal undertaking times for the two activities do not overlap, the individual can undertake each at their corresponding optimal times. Thus, the optimal accessibility benefit of undertaking two activities is the same as the sum of two optimal accessibility benefits by undertaking these one by one. Conversely, if they overlap, one of the two activities can not be undertaken at its optimal time. In that case, the cumulative accessibility benefit of the two activities is less than that which can be obtained when they are not overlapping.

Assume that time durations for two activities are T_1 and T_2, respectively, and independent of time, while the activity attributes and travel time depend on actual clock time c. Denote time-varying activity attributes and travel time by $a_i(c)$ and $t_i(c)$, $(i = 1, 2)$, respectively, then the accessibility benefits of the two activities are also time dependent. Denote these by $A_{mi}(c), i = 1, 2$, and:

$$A_{mi}(c) = a_i(c)^\alpha T_i^\beta \exp(-\gamma t_i(c)), i = 1, 2 \; . \tag{27}$$

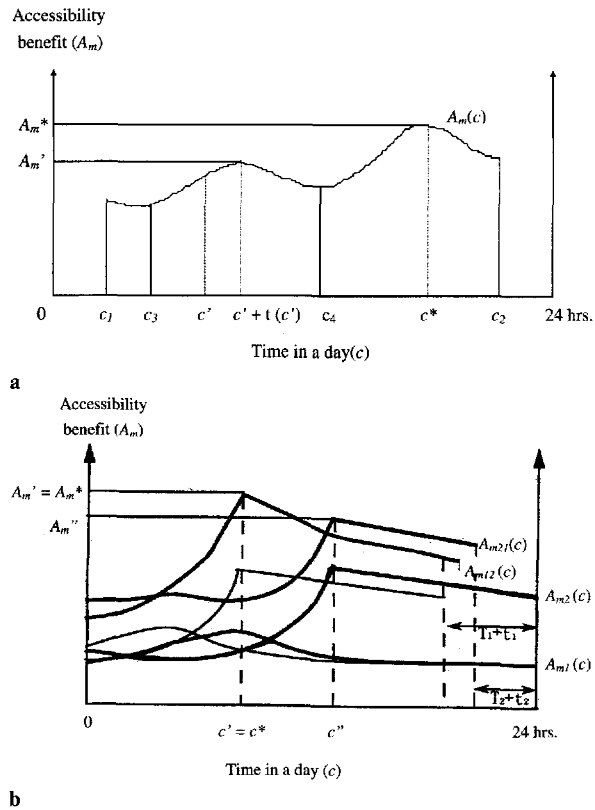

Fig. 5a,b. Timing and scheduling of activities with time-dependent accessibility benefits. **a** Single activity; **b** two activities

Analysing the timing of two activities is more complicated than the analysis of a single activity. However, the problem becomes easier if the two activities are sequentially undertaken continuously. Here we first analyse two continuous activities.

5.2.1 Two continuous activities

Assume that an individual begins to undertake activity 1 at time c, and then undertakes activity 2 at time $c + T_1 + t_1$, after he or she spends travel time t_1 and activity duration time T_1 on activity 1. Let $A_{m12}(c)$ represent the accessibility benefit of undertaking two continuous activities with activity 1 undertaken firstly and activity 2 undertaken thereafter, then:

$$A_{m12}(c) = A_{m1}(c) + A_{m2}(c + T_1 + t_1) \ . \tag{28}$$

On the other hand, if $A_{m21}(c)$ represents the accessibility benefit of undertaking two continuous activities with activity 2 undertaken first and activity 1 undertaken thereafter, then:

$$A_{m21}(c) = A_{m2}(c) + A_{m1}(c + T_2 + t_2) \ . \tag{29}$$

The optimal start times for the two activities scheduled above are, respectively, c', and c'', which maximise $A_{m12}(c)$ and $A_{m21}(c)$, that is, $A_{m12}(c') = \max\{A_{m12}(c)\}$ and $A_{m21}(c'') = \max\{A_{m21}(c)\}$. If an individual is free to schedule two activities in either manner, then he or she will choose the optimal start time, c^*,

$$c^* = \begin{cases} c & if \quad A_{m12}(c) > A_{m21}(c'') \\ c'' & if \quad A_{m12}(c) < A_{m21}(c'') \end{cases} \tag{30}$$

and acquire the accessibility benefit A_m^*, where $A_m^* = \max\{A_{m12}(c'), A_{m21}(c'')\}$.

The problem above and its solution can be illustrated by the example in Fig. 5b. In this figure, the $A_{m1}(c)$ and$A_{m2}(c)$ curves represent time-dependent accessibility benefits of activity 1 and 2, respectively. The curve of $A_{m12}(c)$ is obtained by shifting the $A_{m2}(c)$ curve horizontally to the left by time $T_1 + t$ and adding the resulting curve vertically to the $A_{m1}(c)$ curve. The highest point of the $A_{m12}(c)$ curve, i.e.,$A_{m12}(c')$, and its corresponding time c' depict the maximum accessibility benefit and the optimal starting time of scheduling activity 1 first and activity 2 second. Similarly, the curve of $A_{m21}(c)$ can be obtained by shifting the $A_{m1}(c)$ curve horizontally to the left by time $T_2 + t$ and adding the resulting curve vertically to the $A_{m2}(c)$ curve. The highest point of the $A_{m21}(c)$ curve, i.e., $A_{m21}(c'')$, and its corresponding time c'' are the maximum accessibility benefit and the optimal starting time of scheduling activity 2 first and activity 1 second. In Fig. 5b, $A_{m12}(c') > A_{m21}(c'')$, so that the optimal starting time for these two activities is $c^*, c^* = c'$, and the maximum accessibility benefit is A_m^*, $A_m^* = A_{m12}(c')$. The individual should start activity 1 at c^* and then activity 2 right after finishing activity 1 in order to obtain the maximum accessibility benefit.

5.2.2 Two discontinuous activities

Two activities are discontinuous in time if a slack time occurs between the finishing time of the first activity and the starting time of the second activity. Let $A_{m12}(c_1, c_2)$ represent the accessibility benefit of starting activity 1 at c_1 and starting activity 2 at c_2, and $A_{m21}(c_1, c_2)$ represent that of starting activity 2 at c_1 and starting activity 1 at c_2, then:

$$A_{m12}(c_1, c_2) = A_{m1}(c_1) + A_{m2}(c_2) \tag{31}$$

$$A_{m21}(c_1, c_2) = A_{m2}(c_1) + A_{m1}(c_2) \ . \tag{32}$$

Assume that there are two sets of optimal starting times, i.e., (c_1', c_2') and (c_1'', c_2''), which satisfy, respectively, $A_{m12}(c_1', c_2') = \max A_{m12}(c_1, c_2)$ and $A_{m21}(c_1'', c_2'') = \max A_{m21}(c_1, c_2)$. Then, if an individual is restricted to undertake activity 1 first and activity 2 second, he or she ought to start to undertake these at time c_1' and c_2', respectively, in order to obtain the maximum accessibility benefit

$A_{m12}(c_1', c_2')$. On the other hand, c_1'' and c_2'' are the optimal starting times for activity 2 and activity 1 if the individual is restricted to undertake the two activities in reverse order. However, if the individual is free to schedule the two activities in either order, he or she should select the optimal times, c_1^* and c_2^*, which are:

$$(c_1^*, c_2^*) = \begin{cases} (c_1, c_2) & if \quad A_{m12}(c_1, c_2) > A_{m21}(c_1'', c_2'') \\ (c_1'', c_2'') & if \quad A_{m12}(c_1, c_2) < A_{m21}(c_1'', c_2'') \end{cases}, \tag{33}$$

in order to obtain the maximum accessibility benefit A_m^*, where $A_m^* = \max \{A_{m12}(c_1', c_2'), A_{m21}(c_1'', c_2'')\}$.

The growing popularity of flexible working hours increasingly enables individuals to alter their departure times for commuting to the workplace and work starting time. The decision regarding this issue can be portrayed by Equation (26). The decision on the optimal timing of commuting to work not only depends on the time-varying travel time, $t(c')$, and the time-varying work attributes, $a(t(c') + c_1')$, but also on parameters representing perceptions of an individual towards these, i.e., α and β. We note that the variables and parameters will vary across different individuals in accordance with socioeconomic background and occupation.

6 Conclusion

This article has formulated an individual accessibility model to measure the accessibility benefits of daily activities undertaken by an individual either through a trip, a trip chain, or at home. Instead of utilising the rather complicated models of the recent literature, this article has focused on a description of an individual's accessibility benefits in a way that captures the essence of his or her complicated travel and activity behaviour by considering only a few key variables within a simple analytical model. The model is then extended to analyse individuals' non-work activity location choices, choices between at-home activities and away-from-home activities, and activity timing and scheduling. These travel and activity choices are made on the basis of the assumption that individuals select the optimal activity and travel pattern to maximise accessibility benefits subject to temporal and spatial constraints.

An individual's choice between a regional activity centre and a central activity centre depends on his or her coupling constraints, that is, the time budget and origin and destination locations of activities scheduled before and after the determined activity. Applying the individual's accessibility model for a trip chain has provided theoretical insights into the empirical observations made by Nishii and Kondo (1992), who showed that urban railway commuters' non-work activity locations are concentrated either at rail terminals or work sites. The substitution of an activity at home for an activity at another location through travel is shown to depend on the ratios of activity attributes and activity duration between two types of activities, and on parameters representing his or her own preferences. Finally, this article has illustrated how an individual should select the optimal timing for a single activity or schedule two continuous or discontinuous activities with time-dependent accessibility benefits in order to maximise one's total accessibility benefits.

This article has developed a relatively simple approach to measure the accessibility benefits of daily activities undertaken by an individual in order to understand and describe travel and activity choice behaviour. Recent work by Miller (1999) has developed realistic and easily computable techniques for measuring the individual accessibility developed in this article within network structures. Future research should be conducted to better understand the stochastic properties of choice behaviour among individuals, and to estimate the statistical distribution of key parameters in order to aggregate individual choices into market demand for different types of activities and travels.

The definitions and measurements of the key variables should be specified further for specific cases. For example, in retailing, large facilities usually allow both comparison and convenience shopping. Thus, the "attractiveness" of the central versus the regional facility should be defined as a composite of the different types of activities present, potentially allowing travel time savings for individuals performing multi-purpose shopping. Also, in examining the competition between smaller and larger facilities, the activities are usually more widely dispersed and parking is more difficult in the larger facilities. This can reduce the net effect of the travel time savings when carrying out all activities at the one facility.

Finally, activity timing and scheduling were analysed, for example, in Sect. 5 in the context of the trade-off between congestion and time-dependent activity benefits, from the individual's perspective. Future research should combine individuals into households and recognise the many interdependencies among household members. A stochastic approach is probably necessary to accomplish this endeavour.

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