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Space-time accessibility measures: A geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration

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Abstract. Space-time accessibility measures have received much attention in recent years due to their sensitivity to differences in individual ability to participate in activities in space and time. Despite the conceptual attractiveness and robustness of space-time measures, only few attempts have been made to operationalize them to date. Research that seeks to improve space-time accessibility measures is still sorely needed. This study seeks to enhance space-time accessibility measures through developing a new operational method and GIS-based algorithm that better represents the space-time characteristics of urban opportunities (e.g. their geographical distribution and opening hours) and human activity-travel behavior (e.g. delay times, minimum activity participation time, and maximum travel time threshold). The proposed method not only takes into account the number and size of opportunities, but also the possible activity duration at each activity location given its opening hours and the effect of transport network topology (e.g. one-way streets, turn restrictions and over-pass). Incorporating these elements into space-time measures helps overcome several shortcomings of previous approaches to evaluating space-time accessibility.

Key words: Individual accessibility, space-time accessibility measures, space-time constraint, space-time prism, GIS

JEL classification: C60, R40

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1 Introduction

Space-time accessibility measures have received much attention in recent years due to their sensitivity to differences in individual ability to participate in activities in space and time (Kwan 1998; Weber and Kwan 2003). Despite the conceptual attractiveness and robustness of space-time measures, only few attempts have been made to operationalize them to date. This is mainly due to the difficulties of incorporating real world complexities into GIS-based algorithms. Research that seeks to improve space-time accessibility measures is still sorely needed. More specifically, various improvements can be conceived with regard to the representation of the spatial and temporal availability of urban opportunities, and to the effect of the directionality of the transport network and travel speed.

This paper proposes several enhancements through which space-time accessibility measures can be rendered more realistic. First, space-time accessibility is extended as a measure of not only the number of accessible opportunities, but also the duration for which these facilities can be enjoyed given the space-time constraint of an individual and facility opening hours. Second, more realistic travel times are incorporated through better representation of the transportation network, such as one-way streets in downtown areas and turn prohibition – besides incorporating the effect of congestion and location- and segment-specific travel speeds. Third, ways are developed to better incorporate other factors such as facility opening hours, minimum activity participation time, maximum travel time threshold, and delay times. By doing so, this research seeks to enhance space-time accessibility measures with more rigorous representation of the temporal and spatial characteristics of opportunities and human activity-travel behavior.

The paper begins with a discussion of the limitations of previous space-time accessibility measures. Then a new series of space-time accessibility measures is formulated and the GIS procedures for operationalizing it will be described. The geocomputational algorithm proposed is described in Sect. 4 and 5 before an example is discussed in Sect. 6.

2 Limitations of previous space-time accessibility measures

Space-time accessibility measures are based on the construct of the space-time prism proposed by Hägerstrand (1970) and elaborated by Lenntorp (1976). The projection of the three-dimensional space-time prism onto two-dimensional geographical space is called the potential path area (PPA). It delimits the area within reach given an individual's space-time constraint. Space-time accessibility measures evaluate individual accessibility by delimiting the space-time prism, which is determined by the locations of activities, the distances between relevant locations, the amount of time available for travel and activity participation, as well as travel speeds (Burns 1979). The space-time prism delimits the feasible opportunity set (FOS) for travel and activity participation in a bounded region in space-time (Kwan 1998, 1999; Weber and Kwan 2002, 2003; Dijst and Vidakovic 2000; Dijst et al. 2002). Previous space-time accessibility measures need enhancements due to the limitations in their representation of the space-time properties of urban opportunities, the temporal characteristics of human activity-travel behavior, and the transport network. These limitations are discussed as follows.

2.1 Representation of the space-time properties of opportunities

Representation of certain spatial and temporal properties of urban opportunities by previous space-time accessibility measures still calls for improvement. These properties include the volume of the space-time prism, the spatial distribution of opportunities, the maximum activity participation time at each opportunity within the prism, and the temporal availability of each opportunity. To illustrate these limitations more concretely, Fig. 1 identifies six possible types of space-time accessibility measures. Figures 1a–e

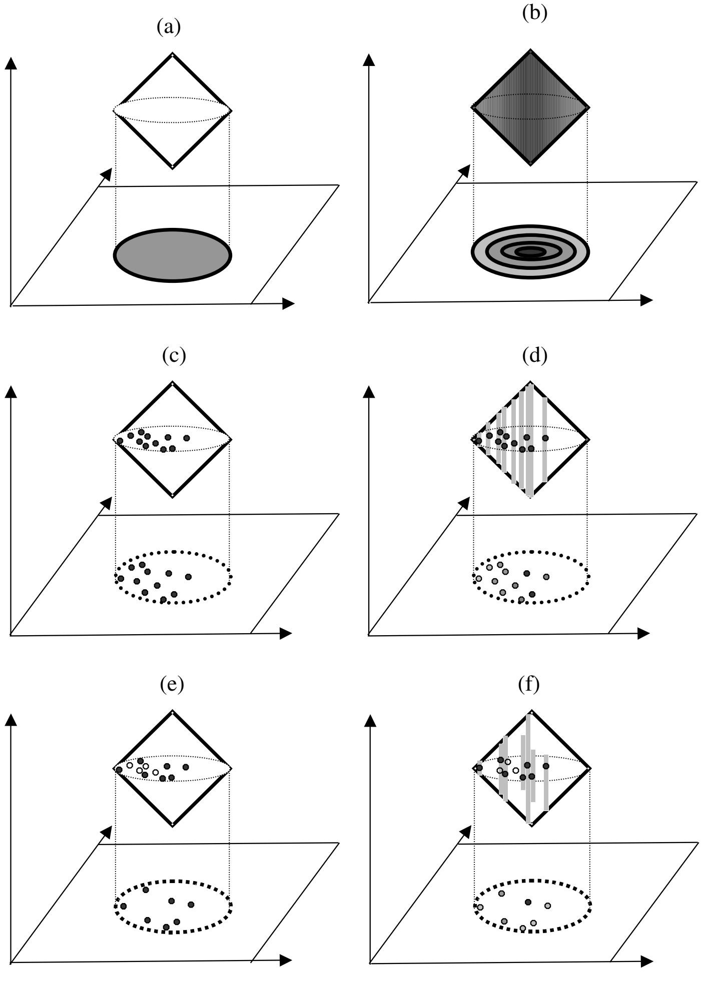

Fig. 1. Different approaches to evaluating space-time accessibility of individuals

show different methods of evaluating accessibility used in previous space-time accessibility measures. Figure 1f provides a preliminary conceptual framework proposed in this paper that retains more detailed temporal properties of the space-time prism for the evaluation of individual accessibility. This framework will be discussed in greater detail in Sect. 3 below.

The first type of accessibility measures (Fig. 1a, b) is geometric or mathematical calculation of accessibility (see Lenntorp 1976; Burns 1979; Villoria 1989; Newsome et al. 1998; Nishii and Kondo 1992). For example, Lenntorp (1976) and Burns (1979) used the volume of the space-time prism and/or the area delimited by the potential path area (PPA) formed by the prism's projection onto geographical space as an accessibility indicator. By simply measuring the spatial extent of the reachable area given the space-time constraint of an individual, this type of formulation, as shown in Fig. 1a, does not take into account of any of the space-time properties of the prism (e.g. the geographical distribution and temporal availability of opportunities). Measuring the volume of the prism as shown in Fig. 1b is another type of geometric method that is based upon the Euclidean distance between two fixed activities. The space-time prism takes the form of two equal-sized cones with a common base, and the PPA takes the shape of an ellipse (Burns 1979). This formulation of the prism and the PPA (Fig. 1a, b), however, does not represent the space-time properties of opportunities and the urban space realistically. It ignores the uneven spatial distribution of opportunities, the restricted mobility due to the geometry of the transport network, variable travel speeds throughout the urban environment, and the temporal availability of opportunities associated with limited opening hours.

Recently, GIS methods have been used to overcome the limitations of geometric methods. For instance, instead of assuming an even distribution of opportunities, uniform and constant travel speed, or using Euclidean distance, Kwan (1998, 1999), Kwan and Hong (1998), Miller (1999), Miller and Wu (2000), Weber (2003), Weber and Kwan (2002) developed various operational methods for deriving a network-based space-time prism that takes the spatial distribution of urban opportunities into account.

Figure 1c describes a GIS-based method that sums up the number or area of the opportunities within a PPA (PPAs with irregular shapes are schematically represented as ellipses in Fig. 1c–f) (e.g. Kwan 1998, 1999). This method considers the uneven distribution of opportunities, varying mobility due to the transportation configuration and speeds over space. The method, however, does not consider the geographical distribution of opportunities within the PPA by focusing mainly on creating bounded space and identifying the feasible opportunity set (FOS) within there. It therefore ignores the activity participation time possible at a particular opportunity location and the temporal availability of the opportunities in the PPA.

Another type of GIS-based methods takes the effect of the spatial distribution of opportunities within a PPA into account (Fig. 1d) (e.g. Miller 1999; Miller and Wu 2000). This type of measures considers the maximum activity participation time possible at each opportunity and thus allows the researcher to differentiate the contribution of different opportunities within a PPA to individual accessibility. The effect of facility opening hours, however, is still ignored in this type of formulations.

The temporal availability of opportunities within a PPA is taken into account by the method implemented in Weber and Kwan (2002, 2003) (Fig. 1e). This method, however, paid no attention to the effect of the geographical distribution of opportunities inside the PPA and the possible activity participation time on individual space-time accessibility, as all opportunities reachable during their opening hours are equally weighted. Beyond the simple consideration of the absence/presence of each opportunity with respect to its opening hours, the measure as proposed in Fig. 1f should be able to explicitly consider the reduction in activity duration and the exclusion of some opportunities even within their opening hours due to the temporal mismatch between the timing of possible activity participation and the opening hours of each opportunity.

The method proposed in this paper therefore seeks to contribute to research on individual accessibility in space-time through evaluating whether activities can be performed at particular locations and incorporating the possible duration of activities (given the opening hours of facilities) into the measure. It shows that space and time are closely linked, in that the location of an opportunity will affect the duration of its availability. The paper therefore goes beyond the two-dimensional geospatial representation of opportunities in previous research through a representation that also takes the temporal dimension into account.

2.2 Representation of the temporal characteristics of human activity-travel behavior

Besides the effect of the geographical distribution of opportunities and facility opening hours, this paper attempts to further improve space-time accessibility measures by incorporating several temporal characteristics of human activity-travel behavior that were not fully recognized in previous measures. These include the minimum time required for meaningful participation in particular activities, various types of delay times, and the maximum travel time threshold. Because of the difficulty in developing an appropriate geocomputational algorithm, no previous measures have integrated all of these elements into a single coherent framework when operationalizing space-time accessibility measures.

Based on the recognition that travel is a derived demand (see Damm 1983; Jones 1983; Kitamura 1988; Jones et al. 1990; Axhausen and Gärling 1992), the accessibility measure proposed in this paper incorporates the effect of the minimum activity participation time at each opportunity and the maximum travel time threshold. Since people usually do not travel for a long distance for undertaking an activity for just one or two minutes, certain amount of activity participation time is necessary to make travel worthwhile and also to make the measure more realistic. Further, travel times to activity locations need to be limited to an acceptable amount to most individuals. Consider, for instance, an individual who has a 5-h time budget for flexible activities between two fixed activities. The resulting maximum travel time (2.5 h) will generate a PPA that covers an area much larger than what a person would normally travel for ordinary discretionary activities in any particular day (Fig. 2a). It is unreasonable to assume that people will travel for 2.5 h in order to participate in a discretionary activity

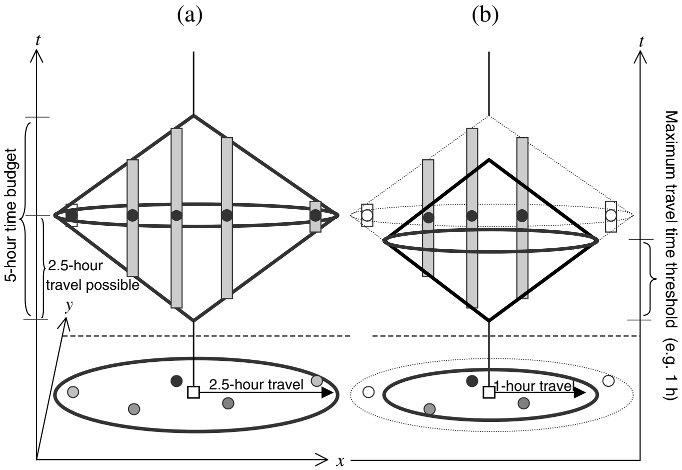

Fig. 2. The effect of the maximum travel time threshold on the space-time prism and potential path area (PPA)

for just one minute. Rather, people would likely spend time on participating activities within certain acceptable travel distances as shown in Fig. 2b. Studies that ignore this behavioral attribute may render extremely large and unrealistic PPAs possible. It is therefore necessary to implement some reasonable thresholds on activity participation time and travel time in order to identify a meaningful opportunity set when evaluating space-time accessibility.

Further, there are several types of delay times that need to be included into the algorithms of space-time accessibility measures since the arrival and departure times at activity locations are subject to random variation (Villoria 1989). They stem mainly from two sources: (1) *static delay time* required for looking for a parking space, walking from/to opportunities before/after parking, or waiting for buses; and (2) *dynamic delay time* spent during travel associated with traffic lights, turns, and traffic accidents. In this study, the former type of delay times is combined together with the minimum activity duration as the *extended minimum activity time* required. The latter type of delay times is combined with the travel time between two locations as the *extended travel time* (*Shrt_T*). The inclusion of delay times in the proposed method takes into account the fuzzy boundary of a PPA or FOS (as suggested by Villoria 1989).

2.3 Representation of travel times and speeds on the transport network

Space-time accessibility measures can also be enhanced through more realistic estimation of travel speeds and times on the transport network. Although some recent operational methods of space-time measures attempt to incorporate this dimension into the geocomputational algorithm (e.g. Kwan 1998; Miller 1999), and different travel speeds for different types of road segments are used, there is still room for further enhancement as travel speeds may be different among different road segments of the same type. As Weber and Kwan (2003) demonstrated, travel velocities are both spatially and temporally uneven as well as segment-dependent. Travel speeds may vary depending on the location of the streets (e.g. CBD versus rural areas) or on the time of day (e.g. peak versus off-peak period). The fact that congestion does not uniformly and equally affect all areas of a city should be taken into account by space-time measures (Weber and Kwan 2002).

Further, previous approaches are often based upon unrealistic assumptions about the directionality and topology of the transport network that ignore the unequal travel speeds along different directions of the same network segment and the effect of turn prohibitions. They therefore ignore the existence of many one-way streets and cross-sections with turn restrictions in the urban environment. In this light, it can be argued that previous space-time measures tend to overestimate individual accessibility as considerable amount of urban opportunities are found in CBD, where congestion can be a chronic problem and the existence of many one-way streets cannot be ignored. In this paper, the effect of one-way streets is explicitly taken into account through using a field named "ONEWAY" in the digital street data. Based upon the directional arrows of the one-way streets shown on a large-scale map of the study area, this field contains a value that indicates the direction of permitted traffic (e.g. "TF" indicates that travel is permitted from the start to the end of the line only; "FT" indicates that travel is permitted from the end of the line to the start of the line only; "N" means that travel is not permitted in either direction).

Lastly, most of previous space-time measures use the street network data with a planar structure and assume that turns can be made from any link to any link. However, as turns cannot be made when the cross-section actually represents an overpass or underpass – which will lead to different shortest paths and affect travel times considerably – their effects need to be taken into consideration when evaluating individual accessibility using space-time measures. This paper follows Weber and Kwan (2002, 2003) study, in which the effect of turn prohibitions from/to freeways is incorporated through creating a turntable with the node numbers where turns can potentially be made and linking it to the street network data.

3 Conceptual framework

This research seeks to enhance space-time accessibility measures with more rigorous representation of the temporal and spatial characteristics of opportunities and human activity-travel behavior. Figure 3 describes the method proposed in this study which takes into account both the possible activity participation time based on the spatial distribution and the temporal availability of opportunities. Using this framework, this study evaluates space-time accessibility based not only on the number of accessible opportunities but also on the duration for which an individual can enjoy these facilities given the space-time constraint. As shown in Fig. 3, the size of the space-time prism used in this paper is smaller than those specified in previous approaches due to the inclusion of static and dynamic delay times, minimum activity duration, and maximum travel time threshold (compare the boundary of the prism delimited by the solid line with those delimited by

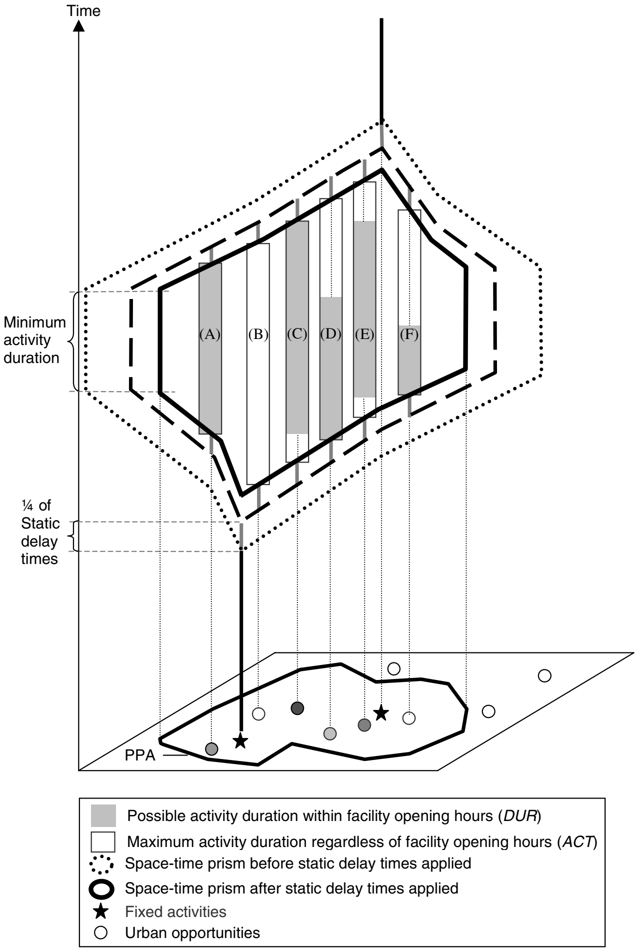

Fig. 3. The proposed conceptual framework

dashed or dotted lines). Further, the number of feasible opportunities within the space-time prism and the possible activity duration at each opportunity are reduced due to the effect of facility opening hours. At each opportunity within the space-time prism, the size of two types of bars indicates the possible difference between the maximum activity participation time (*ACT*) and the possible duration due to the effect of its temporal availability (*DUR*). The opportunities within the potential path area (PPA) can be excluded according to their temporal availability (i.e. $T = 1$ if available, otherwise $T = 0$) or are weighted according to the possible activity duration (*DUR*).

Six cases are included in Fig. 3 to illustrate the effect of these factors on the space-time prism. Opportunity A is available to the individual throughout the entire duration within the prism given its opening hours (i.e. $ACT = DUR$). In contrast, opportunity B can be reached but is not available because it is closed throughout the entire duration within the prism (i.e. $ACT \neq DUR$). This opportunity should therefore be excluded from the feasible opportunity set. Opportunity C should be included only if the individual is willing to wait for its opening. In this situation, some amount of the possible activity time will be lost due to the time spent in waiting. For opportunity D, the individual needs to arrive early enough in order to be able to undertake that activity with a duration that exceeds the minimum activity duration. Since activity at the opportunity location is impossible after the closing hour, some portion of the possible activity participation time would be lost. Opportunity E can be enjoyed only during its opening hours even as more time is available for the activity. Therefore, the activity time budget before and after the opening hours will be lost. Lastly, opportunity F, although reachable within the space-time prism, has possible activity duration smaller than the minimum activity participation time. It should therefore be excluded from the feasible opportunity set when evaluating individual accessibility. Operational space-time measures should differentiate between these possibilities and should exclude and weight opportunities with possible activity duration accordingly.

4 Operational procedures and geocomputational algorithm

To implement the conceptual framework outlined above, this section proposes a new GIS-based geocompuational algorithm for deriving the space-time prism and for evaluating individual accessibility. The method is based partly on Kwan (1998) and partly on Weber (2001), in which the segment-, location- and time-specific travel velocity on the transport network and the weighting scheme for urban opportunities are incorporated. In this new framework, the attractiveness of an opportunity is defined in terms of its weighted area (*WArea*). Individual accessibility measures proposed in this research are derived by summing up the weighted areas of opportunities (*WArea*) multiplied by the possible activity participation time (*Dur*) for all PPAs of an individual for a particular day (daily PPA). The GIS procedures for deriving the potential path area (PPA) and for calculating space-time accessibility are implemented using Avenue, the object-oriented programming language in ArcView GIS.

The key idea of the geocomputational algorithm is to efficiently identify all of the feasible opportunities within the space-time prism using several "*Find Service Area*" operations in ArcView GIS, while limiting the spatial search boundary with information about the travel and activity participation time available between two fixed activities. This algorithm was developed based upon numerous tests of the computational efficiency of different methods and a series of experiments using a large activity-travel diary data set and a digital street network.

Figure 4 describes the concept behind the proposed algorithm (where the network-based service areas are represented schematically by circles and the potential path area (PPA) by an ellipse for simplicity purpose). Conceptually the feasible opportunities within a PPA comprise a set of activity locations where the total amount of the travel times from the origin and to the destination fixed activity are less than or equal to the total time budget (in this case, *Total_T*) beyond the minimum activity time. The shaded area delimited by the boundary in bold indicates where the spatial search for feasible opportunities will initially take place (Step 1). Since there is no

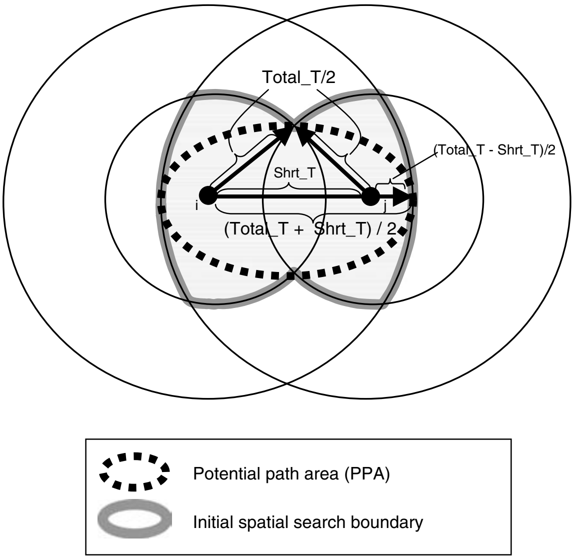

Fig. 4. Procedures implemented by the geocomputational algorithm

simple and direct method to delimit the boundary of the PPA, this research draws on the initial spatial search area as small and close as possible to the PPA boundary for the efficiency purpose. The spatial search boundary is defined by half of the total time budget ($Total\_T/2$) and the shortest-path travel time ($Shrt\_T$) between the two fixed activities in the manner shown in Fig. 4. The resulting feasible opportunity candidate set (FOSc) within the spatial search boundary is identified in Step 1. After this step, some opportunities outside the potential path area will be removed from the FOSc. In other words, travel times from the first fixed activity to each urban opportunity in the search area and from each opportunity to the next fixed activity are computed in order to choose opportunities only within the PPA (*FOS*) out of the FOSc. If the sum of these two travel times is greater than the time budget ($Total\_T$), the opportunity is eliminated from the feasible opportunity candidate set (*FOSc*). In Step 3, each opportunity in the FOS generated in Step 2 is screened with respect to whether and how long it is available given its opening hours and the arrival and departure time. After identifying the FOS within the PPA, the level of accessibility is evaluated in terms of the attractiveness of opportunities and the possible activity duration at each opportunity given its temporal availability. Simplified pseudo code of the geocomputational algorithm is as follows:

Step 0. Initialize

Step 0.1. For each individual, set up variables.
Step 0.2. For each fixed activity of an individual, calculate time budget between *i* and *j* ($Total\_T$).

$$\text{StartTime} = \text{departure time at first fixed location}, i$$

$$\text{EndTime} = \text{arrival time at next fixed location}, j$$

$$\text{ExtMinAct} = \text{the extended minimum activity time}$$

$$\text{Total\_F} = \text{EndTime} - \text{StartTime}$$

$$\text{Total\_T} = \text{Total\_F} - \text{ExtMinAct}$$

Step 0.3. Set up the network cost field for Step 0.4 (*NetCost1*). Depending on the time of day for travel, either the peak period (*CongFlow*) or off-peak period travel speed (*FreeFlow*) is assigned.
Step 0.4. Calculate the shortest path travel time from i to j (*Shrt_T*) with *NetCost1*.
Step 0.5. Check if space-time prism can be made ($Total\_T \geq Shrt\_T$). If not, go to step 0.2 to work with the next set of activities.

Step 1. Delimit the initial search areas for feasible opportunity sets using Service Area functions and find the opportunity candidates within the search area

Step 1.1. Calculate the service area radii for both i and j.

$$\text{Serv\_Tbig} = \text{Shrt\_T} + (\text{Total\_T} - \text{Shrt\_T})/2$$

$$\text{Serv\_Tsm} = \text{Total T}/2$$

Step 1.2. Check if the maximum travel time threshold (MAX) needs to be set. If any of resulting service radii from Step1.1 is greater than the maximum travel time threshold (MAX), then set the service radius to be MAX.
Step 1.3. Set up network cost field for service areas (*NetCost2*).
Step 1.4. Create network-based service areas from i to k (*Serv1*) and from k to j *(Serv2)* with travel time *Serv_Tbig* with *NetCost2*.
Step 1.5. Create network-based service areas from i to k (*Serv3*) and from k to j *(Serv4)* with travel time *Serv_Tsm* with *NetCost2*.
Step 1.6. Delimit the initial search area from the four service areas where (Serv1 $\cap$Serv2) $\cap$ (Serv3 $\cup$ Serv4).
Step 1.7. Find the opportunity candidates (FOSc) within the initial search area.

Step 2. Identify opportunities within the potential path area and calculate the maximum activity duration possible at each opportunity location.

Step 2.1. For each k in FOSc, calculate travel times from i to k (*OPCost*) and from k to j (*PDCost*).
Step 2.2. Calculate total travel times from i to j through k ($OPDCost = OPCost + PDCost$).
Step 2.3. Calculate the maximum activity participation time available at k (*ACT*).
Step 2.4. Check if the opportunity candidate at k is feasible. If the activity duration at k (*ACT*) is smaller than minimum activity duration specified, then remove k from FOSc.
Step 2.5. Go to Step 2.1 and repeat the steps until the end of records k

Step 3. Identify the final FOS given the effect of facility opening hours and calculate accessibility of an individual

Step 3.1. For each opportunity k in FOS, get the weighted area values from k.
Step 3.2. Check if the activity time at feasible opportunity candidate k falls into its opening hours. If outside, remove k from the FOS.
Step 3.3. Calculate the possible activity duration (DUR) at k regarding its opening hours.
Step 3.4. Multiply the possible activity duration (DUR) by the weighted area ($WArea$) at k ($WAreaDur$).
Step 3.5. Sum up the accessibility values ($WAreaDur$) for all the opportunities within a PPA
Step 3.6. Go to Step 3.1 and repeat the steps until the end of records k.
Step 3.7. Sum up the accessibility values of all PPAs during a day.
Step 3.8. Go to Step 0.2 and repeat the steps until the end of fixed activity records for the individual
Step 3.9. Go to Step 0.1 and repeat the steps until the end of records for all the individuals

5 Data preparation

The GIS procedures and geocomputational algorithm outlined above is implemented using the data of an individual selected from a large activity-diary data set, which was collected in the Activity and Travel Survey in Portland Metropolitan Area in Oregon in 1994 and 1995. The data set provides information about 128,188 activities performed by 10,084 individuals from 4,451 households. Several obligatory activities in the activity-travel diary data set are treated as *fixed activities* in this study. These include work, household obligations, pickup or drop-off passengers, medical or professional business, and school activities. Discretionary activities such as shopping, entertaining, relaxation and so on are defined as *flexible activities*.

The geographic data sets used in this research are the digital transport network with 130,141 arcs and 104,048 nodes and the centroids of all of the 27,749 commercial and industrial land parcels (as urban opportunities) of the study area. These digital geographic data are provided by Metro (the regional government of Portland Metropolitan Region, Oregon). Additional data incorporated into the database includes time-specific and location-specific travel speeds, dynamic delay times along the streets, turn prohibition from/to highways, weighted areas of opportunities and business hours. These data were constructed and provided by Weber (2001) (see also Weber and Kwan 2002, 2003).

In addition to these data on street network, urban opportunities and facility opening hours already specified by Weber, other elements are added and incorporated into the database in order to allow for a more realistic and rigorous estimation of travel times and individual space-time accessibility. For example, the effect of the morning peak-period (7 AM $\sim$ 9 AM) on travel speeds is incorporated in the operational procedure. Besides such dynamic delay times, static delay times are also assigned for delays that happen before or after arriving at or leaving activity locations (see the next section for their assignment). Further, the effect of one-way streets, minimum activity duration, and maximum travel time threshold on the space-time prism is taken into account.

6 An empirical example

The activity program of the selected person is shown in Table 1. The person is a married, female full-time worker, who commuted by a car and undertook 9 activities in the sample day. Activities are classified as either fixed or flexible depending on the nature of the activity in question. The last activity is considered fixed since the person has to return home in the evening – even though the activity was reported as amusement at home. Therefore the person undertook 6 fixed activities and 3 flexible activities in the sample day. There are 3 time windows for deriving the space-time prism (i.e. Activity ID 2∼4, 5∼7, and 7∼9).

As described in Table 2, the time budget for travel and activity (*Total_T*) is first identified by subtracting the minimum activity duration and static delay times from the total time budget (*Total_F)* between two consecutive fixed activities. The travel time between these two fixed activities (*Shrt_T*) is then computed using the appropriate travel speed.

Following Kwan and Hong (1998) and Weber and Kwan (2002), who based their estimation upon field observations in Portland, Oregon, travel times are adjusted upward by 25% to take into account dynamic delays. Regarding travel speeds to be applied, if the midpoint (*MidTime*) of travel start time and travel end time falls within the traffic peak periods, then congested speeds (*CongFlow*) are used in the computation; otherwise, free flow speeds (*FreeFlow*) are used. A comparison of the shortest-path travel time (*Shrt_T*) with the available time budget (*Total_T*) determines whether the procedure will continue or not. If the time budget (*Total_T*) is smaller than the shortest-path travel time for two consecutive fixed activities (*Shrt_T*), no discretionary flexible activity can be undertaken and the procedure will proceed to the next step without specifying a space-time prism. A minimum duration is required for the meaningful participation in any discretionary

Table 1. The activity schedule of the person selected from the sample

Activity ID	Activity type	Activity location	Activity start time	Activity end time	Activity fixity
1	drop-off	residence	7:20 AM	7:21 AM	fixed
2	work	workplace	8:00 AM	2:00 PM	fixed
3	meal	at work	2:00 PM	2:30 PM	flexible
4	work	workplace	2:30 PM	5:00 PM	fixed
5	pick-up	residence	5:20 PM	5:21 PM	fixed
6	amusements	home	5:45 PM	6:30 PM	flexible
7	household obligation	kid's school	6:40 PM	8:30 PM	fixed
8	visiting	home	8:40 PM	9:15 PM	flexible
9	amusement	home	9:15 PM	11:00 PM	fixed

Table 2. Various temporal parameters used in the computation

	Fixed activity		Trip (min)			Time Budget (min)		Travel Cost (min)		Search Area Radius (min)	
	Type	Location	Start time	End time	Mid time	Total_F	Total_T*	Shrt_T	NetCost	Serv_Tbig**	Serv_Tsm***
1	drop-off	residence									
2	work	workplace	840	870	855	30	0	0	FreeFlow	0	0
4	work	workplace									
5	pick-up	residence	1,041	1,120	1,081	79	49	9.410	FreeFlow	29.205	24.5
7	household obligation	kid's school	1,230	1,275	1,253	45	15	2.560	CongFlow	8.780	7.5
9	amusement	home									

Note: * Total_T = Total_F – (Minimum activity duration + Static delay times) = Total_F – (10 + 20)
** Serv_Tbig = (Total_T + Shrt_T)/2
*** Serv_Tsm = Total_T/2

activity and the static delay time takes into account the stochastic travel behavior. In this paper, the minimum activity duration is assumed to be 10 min and the static delay times before and after each activity location are assumed to be 5 min each.

No space-time prism is constructed for the first pair of fixed activities because the available time budget (*Total_T*) does not allow the person to travel and participate in any discretionary activity. This explains why the person stayed at the workplace instead of going out for lunch as shown in Table 1. The second time window between fixed activities (activity 5~7) – from the passenger pick-up to the kid's school – allowed 49 min for discretionary activities beyond the minimum activity duration and delay times. A space-time prism can be constructed with the 49-min time budget (*Total_T*) and 9.41-min travel time between the two fixed activities (*Shrt_T*).

The boundary of the initial spatial search in Step 1 of the algorithm (see Fig. 4) is delimited by using four service areas at the origin and destination with two different radii. The radius of the small service area (in terms of travel time) from i or to j is half of the possible time budget (i.e. $Serv\_Tsm = Total\_T/2 = 49/2 = 24.5$ min) and that of the big service area is half of the possible activity duration and the shortest travel time (i.e. $Serv\_Tbig = (Total\_T + Shrt\_T)/2 = (49 + 9.410)/2 = 29.205$ min). Since none of these two radii exceeds the maximum travel time threshold, they are used for delimiting the initial spatial search boundary. If either of these two radii exceeds the threshold, the maximum travel threshold will be used instead of the computed *Serv_Tbig*. The initial spatial search boundary delimited by this procedure is shown in Fig. 5. It contains 10,223 opportunities.

In Step 2, opportunities in this set that do not meet the time budget constraint are eliminated (i.e. those locations where the sum of the travel times is greater than the time budget are removed from the set). This step delimits the potential path area as indicated in Fig. 4 by the dotted ellipse.

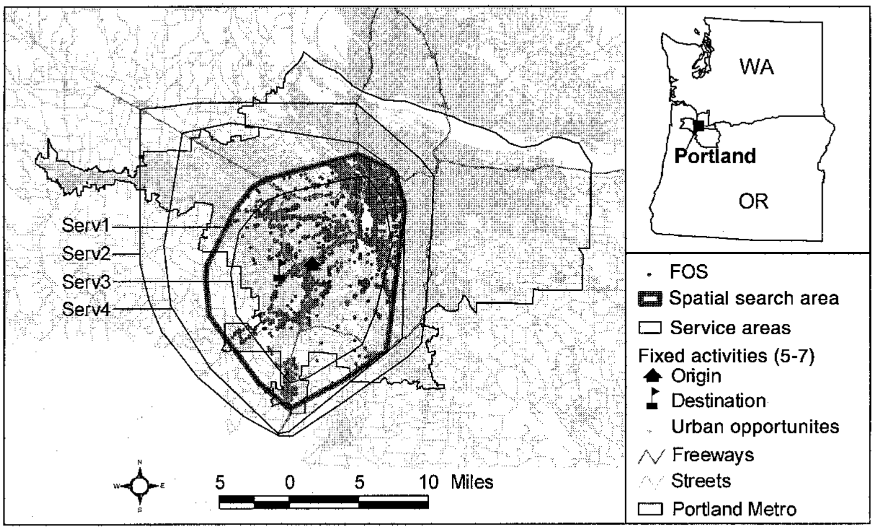

Fig. 5. The opportunity set delimited in Step 1

The number of opportunities (*Num*) is reduced to 9,847 after this step, as some opportunities in the eastern peripheral areas within the search boundary created in Step 1 are removed (Fig. 6).

In Step 3 of the algorithm, some of these opportunities are further removed in consideration of facility opening hours. The limited facility opening hours are assigned based on the type of land-use of a parcel. Industrial opportunities are assumed to be available from 9 a.m. to 5 p.m. and commercial opportunities from 9 a.m. to 9 p.m., as in the case of Weber and Kwan (2002). In this example, the end time of the fixed activity at the origin is 5:21 p.m. and the start time of the fixed activity at the destination is 6:40 p.m. Since industrial facilities are assumed to close at 5 p.m., all the opportunities for industrial land use are considered unavailable to the person and are therefore removed.

Figure 7 shows the opportunities based on their temporal availability (*T*). Only 7,745 (*NumT*) are available out of the 9,847 identified in Step 2 due to limited facility opening hours (see Table 3). Figure 8 shows the spatial pattern of the level of possible activity duration (*DUR*) at the feasible opportunities derived in Step 3, given their business hours and the time budget constraint of the individual in question. In general, the closer an opportunity is to either of the fixed activity locations, the longer is the possible activity duration at that opportunity.

Another feasible opportunity set (FOS) is created for the last pair of fixed activities from the kid's school to home (activity 7~9). The FOS contains 592 opportunities (*NumT*) out of a total of 606 (*Num*) due to limited facility opening hours. In addition to the reduction in the number of feasible opportunities, the temporal availability of opportunities also reduced the possible activity duration (*Dur*) within the space-time prism due to a slight temporal mismatch between the facility opening hours and the arrival and departure time for the activities at the origin and destination. Therefore,

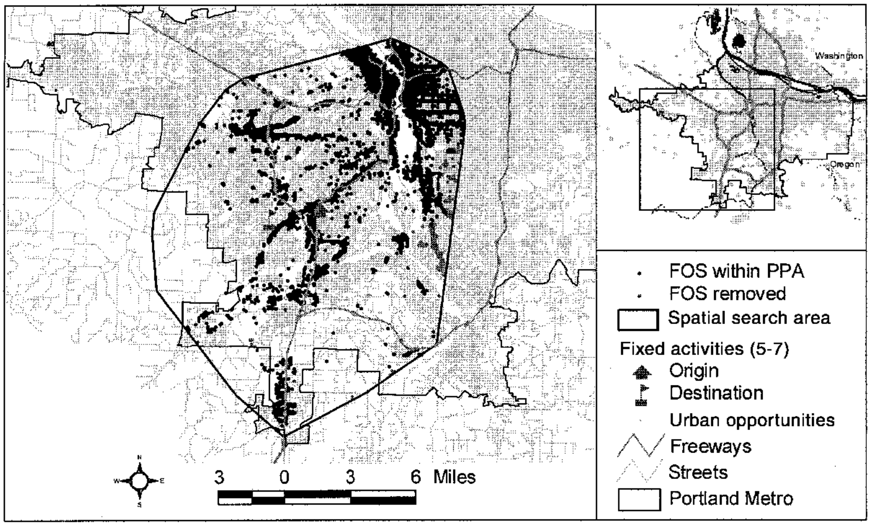

Fig. 6. The opportunity set delimited in Step 2

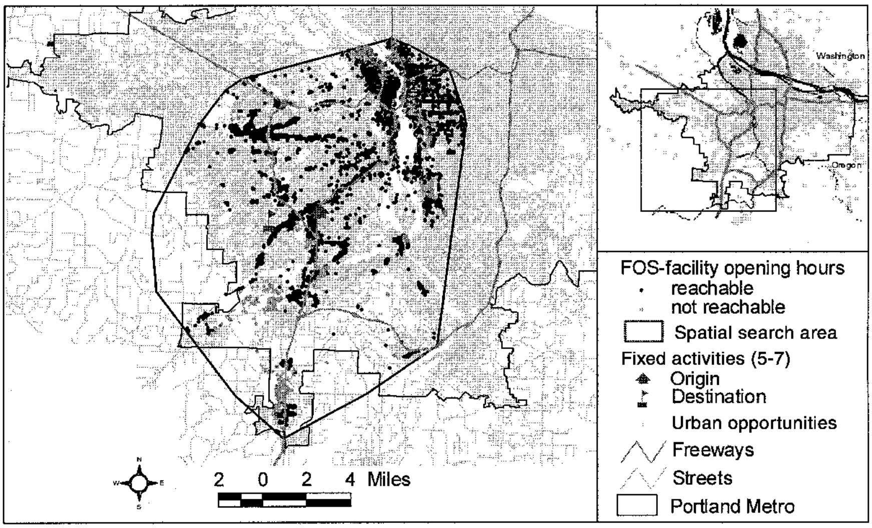

Fig. 7. The opportunity set delimited in Step 3

possible activity duration (*Dur*) is much smaller than the maximum activity duration (*Act* or *ActT*).

Various space-time accessibility measures are finally derived through summing up the values from these two FOSs for the day. The accessibility measures for each space-time prism are shown in Table 3. Various space-time accessibility indicators are a function of the attractiveness of opportunities (*Num, Area, WArea*), and the activity duration available within the space-time prism (*Act, ActT* or *Dur*) either with or without the consideration of facility opening hours (*T*) of each opportunity. The suffix "*T*" represents those measures that incorporate the effect of the temporal availability of opportunity (i.e. reachable and non-reachable). "*Area*" refers to the sum of the unweighted area of opportunities and "*WArea*" refers to the sum of weighted area of opportunities. "*Act*" represents the maximum activity duration at each feasible opportunity as determined by the space-time prism. Excluding those opportunities not available because of opening hours gives "*ActT*." While "*ActT*" represents the *maximu*m activity duration of opportunities that are reachable within their opening hours, "*Dur*" refers to the *possible* activity duration at each opportunity given its opening hours and the timing of activity. The measure proposed in this research as the most desirable is "*WAreaDur*" which is a sum of opportunities weighted by their areas and possible activity duration. As shown in Table 3, all space-time accessibility measures become smaller after considering the effect of facility opening hours (*T*). This suggests that space-time accessibility measures that do not consider this effect will tend to over-estimate individual accessibility.

After identifying the FOS and space-time prism for different pairs of fixed activities, daily space-time accessibility measures are generated by summing up the individual accessibility scores for a particular measure. As shown in Table 3, the person had time for discretionary activities only in the evening

Table 3. Various space-time accessibility measures for the person on the sample day

Activity ID	Activity location	Space-time accessibility measures									
		Num	NumT	Area	AreaT	WArea	WAreaT	Act	ActT	Dur	WareaDur
1	drop-off										
2	workplace	0	0	0	0	0	0	0	0	0	0
4	workplace										
5	pick-up	9,847.00	7,745.00	9,452.78	6,616.90	10,698.14	7,856.96	249,729.72	204,485.34	204,485.34	147,288.04
7	kid's school	606.00	592.00	949.13	876.74	1,199.89	1,127.50	8,975.91	8,794.12	8,140.52	5,584.39
9	home										
DPPA (# of PPA = 2)		10,453.00	8,337.00	10401.92	7,493.64	11,898.04	8,984.46	258,705.63	213,279.46	212,625.86	152,872.43

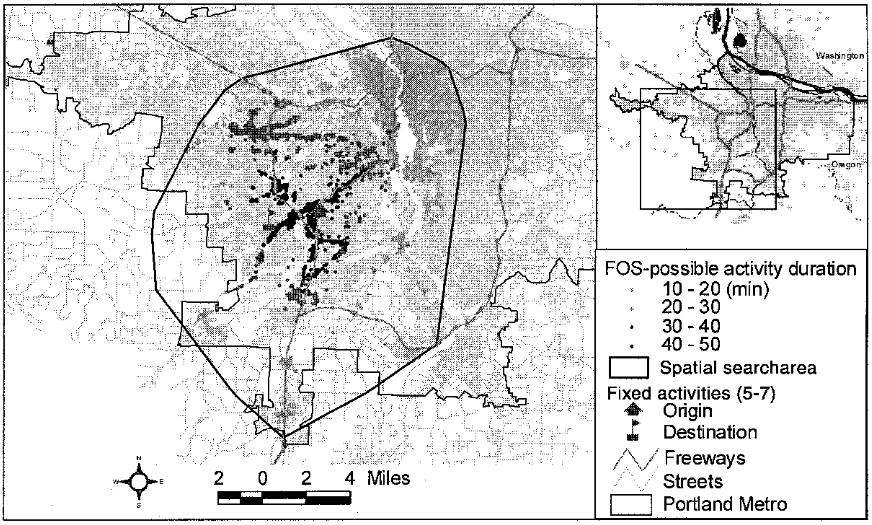

Fig. 8. The spatial pattern of possible activity duration

and after work. Due to the person's tight activity schedule, she was not able to undertake other discretionary activities on the sample day. As she was not able to reach many urban opportunities during their opening hours, the number of feasible opportunities and the possible activity duration at feasible locations were considerably reduced.

7 Conclusion

The purpose of this study is to enhance space-time accessibility measures through developing a new operational method and GIS-based algorithm that better represents the space-time characteristics of urban opportunities (e.g. their geographical distribution and opening hours), human activity-travel behavior (e.g. delay times, minimum activity participation time, maximum travel time threshold) and the effect of transport network topology (e.g. one-way streets, turn restrictions and over-pass). Using this framework, this study evaluates space-time accessibility based not only on the number or size of accessible opportunities but also on the duration for which an individual can enjoy these facilities given an individual's space-time constraints and the spatial and temporal availability of opportunities. Incorporating these elements into space-time measures helps to overcome several shortcomings of previous approaches to evaluating space-time accessibility.

Several areas still call for much future research. First, most of previous studies on space-time accessibility have only examined small samples of individuals due to the computational intensity of the algorithm. Implementing the geocomputational algorithm in a GIS environment is still a daunting and time-consuming task. Future research should seek to develop more efficient algorithms that deploy the power of massively parallel computing, which will ultimately allows the incorporation of even greater details of the urban environment and the examination of interpersonal differences in accessibility using large data sets. Further, space-time accessibility research has largely focused on automobile users to date because of data limitations. However, as the accessibility of individuals of marginalized or disadvantaged social groups is of particular concern, it is imperative to develop operational methods that will also allow the study of non-automobile users and/or joint travel mode.

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