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. However, only few attempts have been made to operationalize them to date due to a lack of readily available geocomputational algorithms. This paper describes a GIS-based algorithm that seeks to improve the representation of 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). The results show that the number of feasible opportunities, the possible activity duration at feasible locations as well as individual accessibility as evaluated by all formulations of space-time measures are considerably smaller when the effect of facility opening hours is taken into account. This suggests that space-time accessibility measures that do not consider this effect will tend to over-estimate individual accessibility.

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 due to a lack of readily available geocomputational algorithms. Research that seeks to improve space-time accessibility measures is still sorely needed. Furthermore, construction of the space-time prism or potential path area (PPA) and identification of the feasible opportunity set (FOS) by previous space-time accessibility measures still calls for improvement. This paper describes a GIS-based algorithm that seeks to improve the representation of 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). The new geocomputational algorithm developed 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 help to overcome several shortcomings of previous approaches to evaluating space-time accessibility. The algorithm was developed using Avenue scripts in ArcView GIS environment.

The next section discusses 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 in Section 3. The geocomputational algorithm proposed is described in Section 4. After the data description used for accessibility measures, the presentation of an example is followed in the Section 5 and the results of the space-time accessibility measure are described in Section 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 space-time prism 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 projection of the three-dimensional space-time prism onto two-dimensional geographical space is called the potential path area (PPA). The space-time prism delimits the area within reach given an individual's space-time constraint. More specifically it 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. Figure 1 illustrates six possible types of space-time accessibility measures in dealing with the spatial and/or temporal properties of urban opportunities.

The first type of accessibility measures (Figure 1a and 1b) is geometric or mathematical calculation of accessibility based upon the Euclidean distance between two fixed activities (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. 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). By simply measuring the spatial extent of the reachable area, this type of formulation, as shown in Figure 1a, does not pay attention to any of the space-time properties of the prism (e.g. the geographical distribution and temporal availability of opportunities). Another type of geometric method which measures the volume of the prism, as shown in Figure 1b, does not properly represent the space-time properties of opportunities and the urban space realistically as well. 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 such limitations of geometric methods. Various operational methods have been proposed for deriving a network-based space-time prism that takes the spatial distribution of urban opportunities into account (Kwan 1998, 1999; Kwan and Hong 1998; Miller 1999; Miller and Wu 2000; Weber 2003; Weber and Kwan 2002). 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 Figures 1c to 1f) (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.

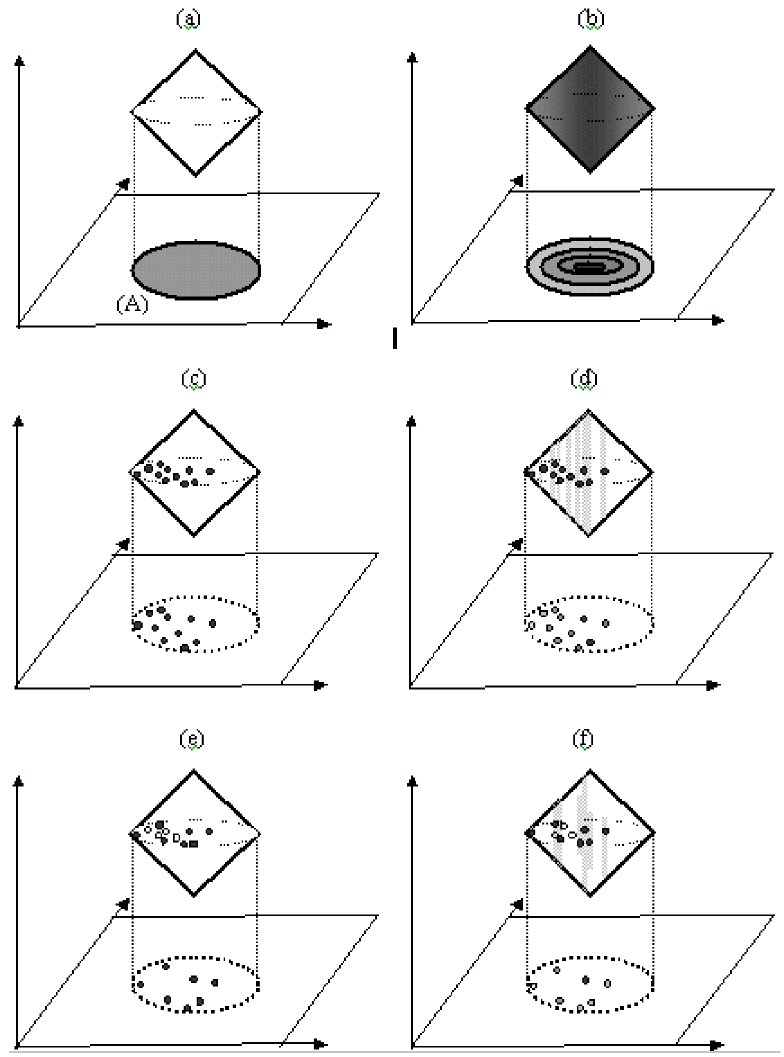

Figure 1: Different approaches to evaluating space-time accessibility of individuals.

Another type of GIS-based methods takes the effect of the spatial distribution of opportunities within a PPA into account (Figure 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 in to account by the method implemented in Weber and Kwan (2002, 2003) (Figure 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 Figure 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 to make travel worthwhile and also to make the measure more realistic. Consider, for instance, an individual who has a 5-hour time budget for flexible activities between two fixed activities. The resulting maximum travel time (2.5 hours) 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 (Figure 2a). It is unreasonable to assume that people will travel for 2.5 hours in order to participate in a discretionary activity for just one minute. Rather, people would likely spend time on participating activities within certain acceptable travel distances as shown in Figure 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).

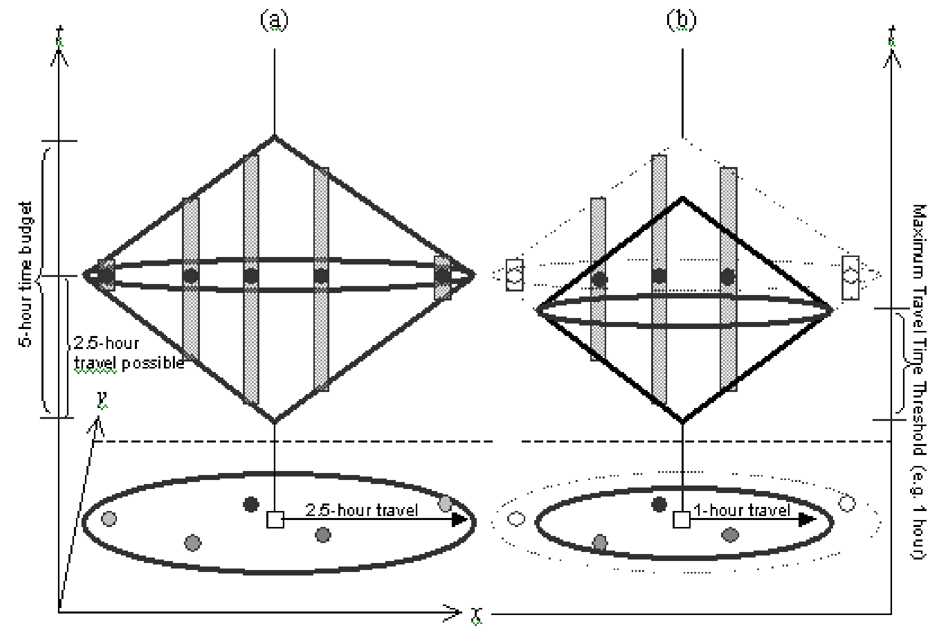

Figure 2: The effect of the maximum travel time threshold on the space-time prism and potential path area (PPA).

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 are made between 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 Figure 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 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 or are weighted according to the possible activity duration (*DUR*).

Six cases are included in Figure 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 with the more time available for 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.

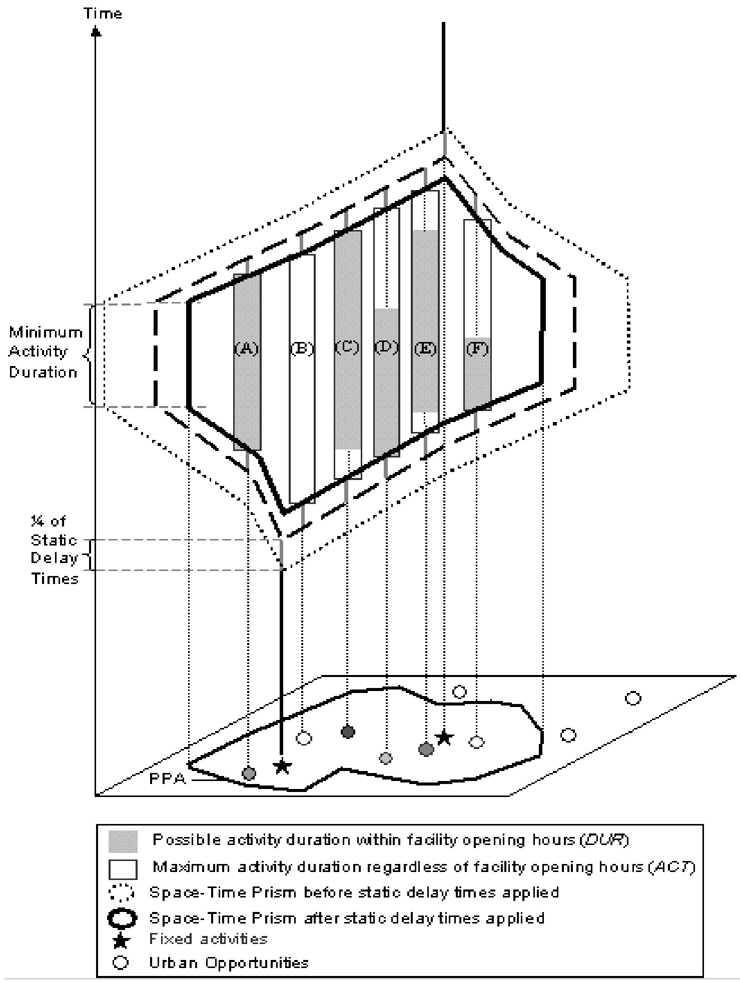

Figure 3: The proposed conceptual framework.

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. 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 two sets of "*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 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 Figure 4.

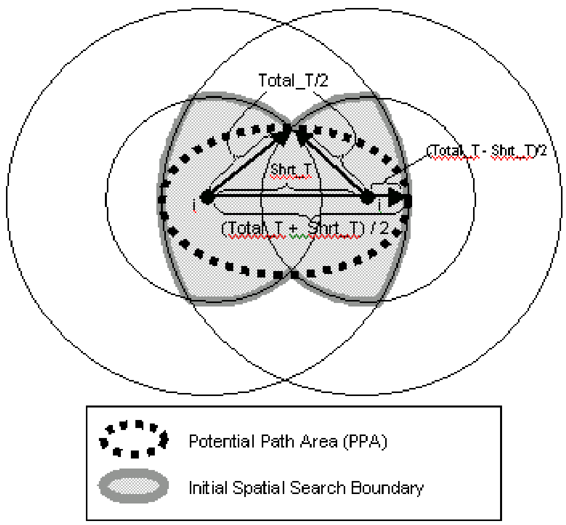

Figure 4: Procedures implemented by the geocomputational algorithm.

The resulting feasible opportunity candidate set (FOSc) within the spatial search boundary is identified in Step1. 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*).

StartTime	= departure time at first fixed location, *i*
EndTime	= arrival time at next fixed location, *j*
ExtMinAct	= the extended minimum activity time
Total_F	= EndTime – StartTime
Total_T	= Total_F – 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* ≥ *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*.

Serv_Tbig = Shrt_T + (Total_T - Shrt_T) / 2
Serv_Tsm = TotalT / 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 ∩Serv2) ∩ (Serv3 ∪ 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

The GIS procedures and geocomputational algorithm outlined above was implemented using 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). In addition to these data, facility opening hours and other elements were also incorporated into the database in order to allow for a more realistic and rigorous estimation of travel times and individual space-time accessibility. Those include 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 which were constructed and provided by Weber (2001) (see also Weber and Kwan 2002, 2003). In addition, the effect of the morning peak-period (7 AM ~ 9 AM) on travel speeds, static delay times before or after arriving at or leaving activity locations (see the next section for their assignment), one-way streets, minimum activity duration, and maximum travel time threshold on the space-time prism are taken into account.

The next section demonstrates the example of an individual selected to explain how the geocomputational procedure works. Then the results of space-time individual accessibility measures in Portland are shown in Section 7 with total 1713 individuals selected who are employed and exclusively use car for commuting and driving from/to activity locations.

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).

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

Fixed Activity			Trip (Minutes)			Time Budget (minutes)		Travel Cost (minutes)		Search Area Radius (minutes)	
	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

Table 2: Various temporal parameters used in the computation.

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 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 minutes and the static delay times before and after each activity location are assumed to be 5 minutes 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 minutes for discretionary activities beyond the minimum activity duration and delay times. A space-time prism can be constructed with the 49-minute time budget (*Total_T*) and 9.41-minute travel time between the two fixed activities (*Shrt_T*).

The boundary of the initial spatial search in Step 1 of the algorithm (see Figure 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 minutes) 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 minutes). 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 Figure 5. It contains 10,223 opportunities.

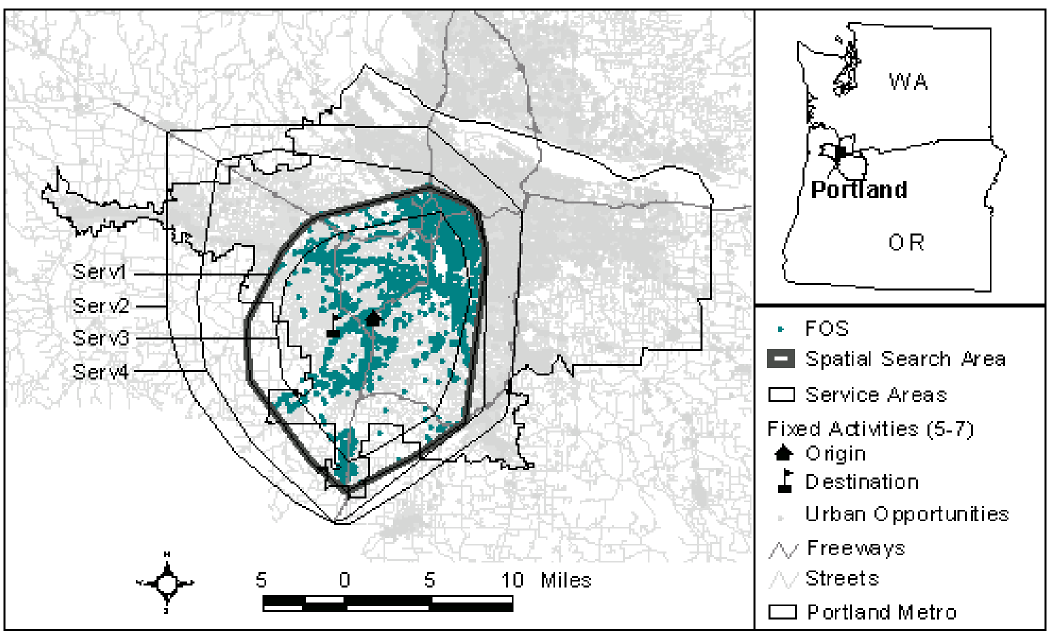

Figure 5: The opportunity set delimited in Step 1.

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 Figure 4 by the dotted ellipse. 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 (Figure 6).

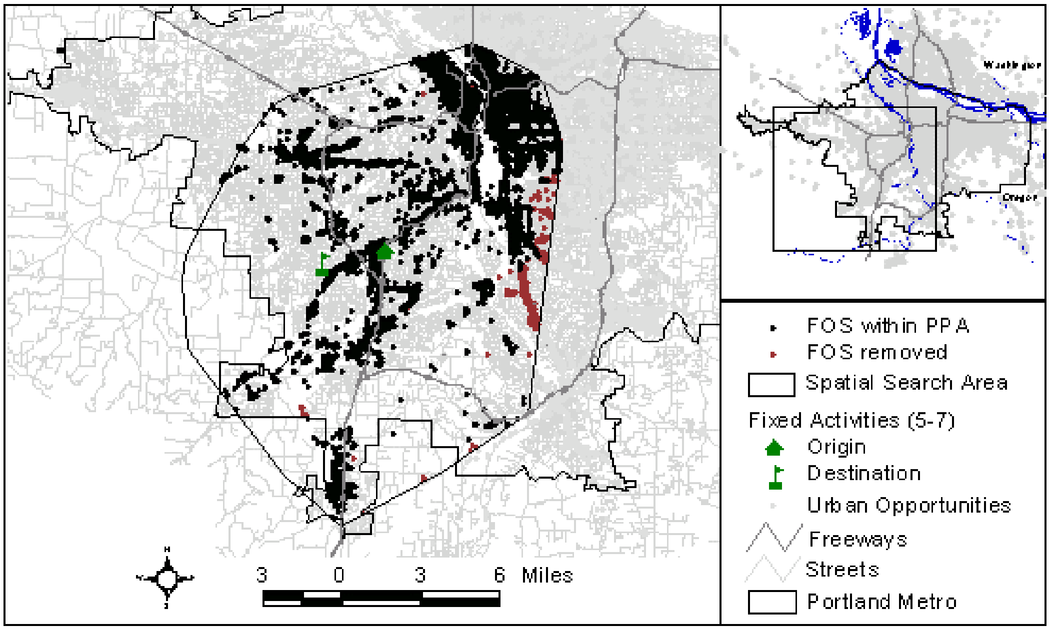

Figure 6: The opportunity set delimited in Step 2.

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 PM and the start time of the fixed activity at the destination is 6:40 PM. Since industrial facilities are assumed to close at 5 PM, 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.

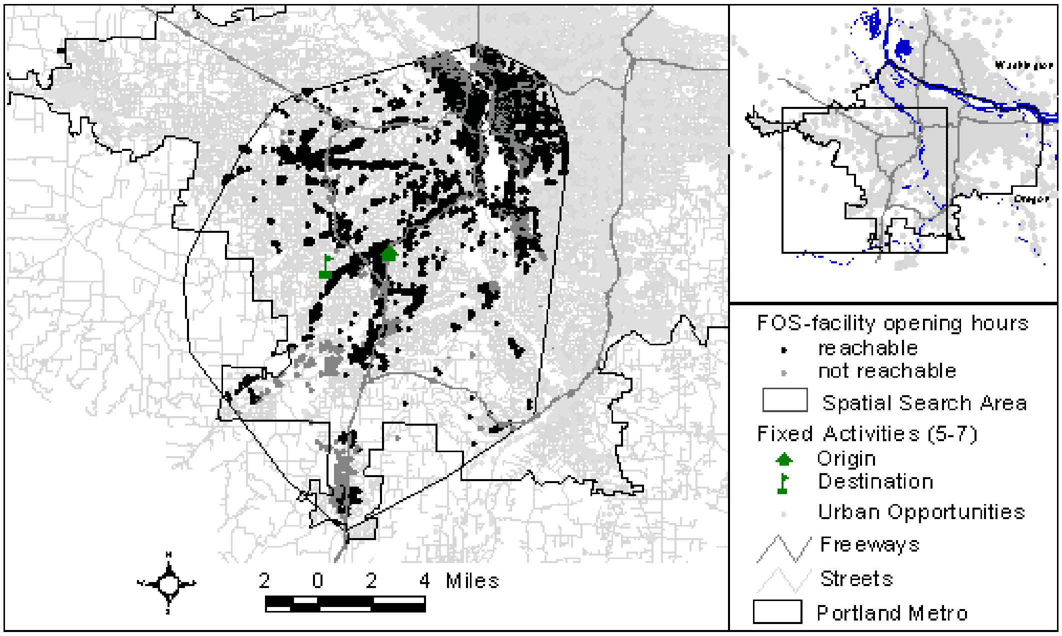

Figure 7: The opportunity set delimited in Step 3.

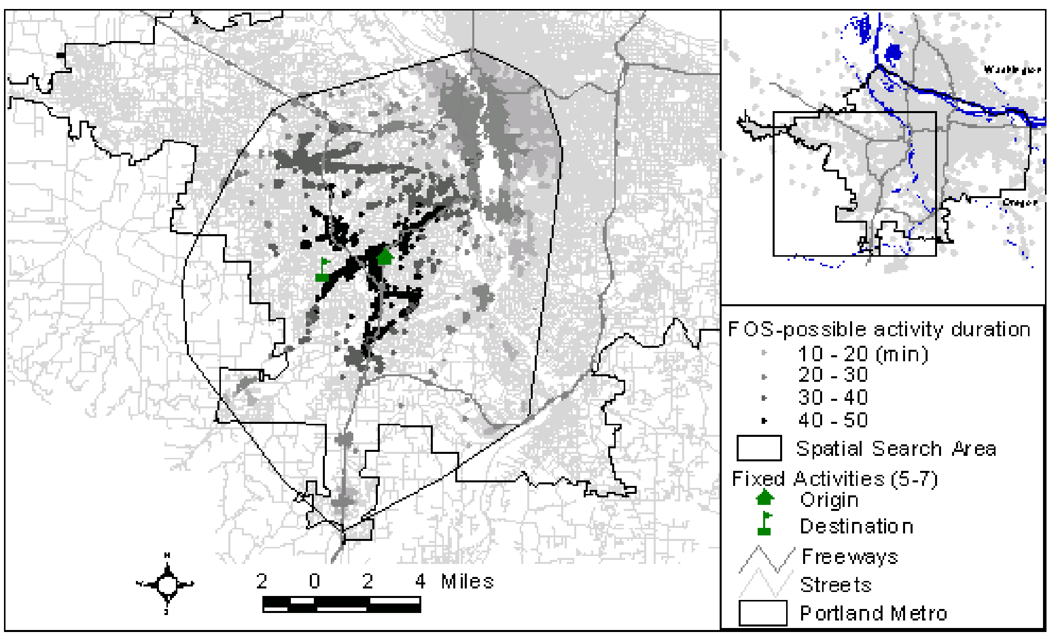

Figure 8: The spatial pattern of possible activity duration.

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

Activit y 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	7,745	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	592	949.133	876.741	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*	*8,337*	*10401.92*	*7,493.64*	*11,898.04*	*8,984.46*	*258,705.63*	*213,279.46*	*212,625.86*	***152,872.43***

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

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 (pick up a family member) only in the evening 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 was considerably reduced.

7 Results of Space-Time Accessibility in Portland

This section demonstrates the results of space-time accessibility measures by subpopulation group (basically, with respect to race, employment status and gender) and the importance of incorporating possible activity duration and temporal availability of opportunities into the measure. Total 1713 individuals' level of access to urban opportunities in Portland was examined using the geocomputational method proposed in this paper.

Table 4 shows the results of individual accessibility in Portland, Oregon, based on several space-time accessibility measures calculated with the geocomputational procedures discussed in the previous section. Table 4a includes the accessibility measures of the number (*Num*) or the area (*Area* or *Warea*) of feasible opportunities. Table 4b demonstrates the accessibility measures of either the activity duration (*Act*, *Dur*) or the combination of both size and activity duration at feasible opportunities. Raw values of average individual accessibility for each measure are shown in the first row. Since the accessibility values for each type of measures are so large and recorded in different units (e.g. the number of parcels for *Num*, the square footage of parcels for *Area*, the minutes for *Act* and *Dur*, etc.), values are standardized to a mean of 100 for easier comparison between measures and among population group. Less than 100 values of measure means lower accessibility than the average and vice versa.

With such standardized accessibility values for each measure, interpersonal differences are examined with respect to race, employment status and gender. Regarding race, the result shows that whites have lower accessibility than non-whites in terms of both spatial and temporal dimension of feasible opportunities. In the case of employment status, full-time workers tend to have lower accessibility values due to their longer work-hours throughout a day compared to part-time workers. Women regardless of race and employment status have lower accessibility than men. And also, when gender is combined to race and employment status, the accessibility pattern becomes more complicated and shows women do not follow the general pattern of accessibility variations among female population as expected along with their race and employment status while men do. While non-white part time female workers are expected to have higher accessibility than the white counterpart and even white full-time female workers, in fact, they are found to have even much lower accessibility than white fulltime female workers. Furthermore, the gender gap in accessibility intensifies when race is combined with gender together. The result reveals that gender gap in accessibility becomes bigger for non-whites compared to whites, and for part-time workers compared to full-time workers. Non-white part-time female workers are not only the most disadvantaged in access to urban opportunities but also show the biggest gender gap among sub-population group. Therefore, it is evident that owing to the greater influence of gender, the effect of race and employment status on individual accessibility becomes unstable and more complicated than expected. It shows that gender would be one of most significant axis of ascribing to social inequality in access to urban opportunities.

In addition, the results demonstrate that interpersonal differences in accessibility become significant and well captured when activity duration is incorporated into the measure as shown in Table 4b. Especially, when the possible activity duration within business hours as well as the size of opportunities is considered into the measure, interpersonal differences for race, employment, and gender turned out to be significant. Remarkably, *AreaDur* and *WareaDur* are not only conceptually more robust but also more sensitive measures to interpersonal differences in accessibility. Such findings suggest that more rigorous and more sensitive measures are achievable when possible activity duration with respect to the limited facility hours are explicitly take into account on one hand and when both spatial ("how many (or large)") and temporal ("how long") properties of accessibility are simultaneously taken into account into the measure on the other hand. When both size and activity duration based on the business hour are incorporated into the measure (*AreaDur* or *WareaDur*), the interpersonal differences remain statistically significant for all types of subgroup-population.

				N	(%)	Num	NumT	Area	AreaT	Warea	WareaT
Average Individual Accessibility				1,713	100	18641.31	15914.81	22185.57	17998.84	23411.39	19157.65
Standardized Accessibility						100	100	100	100	100	100
Race	White			1,633	95.33	99.79	99.73	99.73	99.63	99.75	99.65
	Non-White			80	4.67	104.29	105.46	105.51	107.53	105.20	107.07
Employment Status		Full Time		1,503	87.74	99.87	99.64	99.61	99.07	99.64	99.16
		Part Time		210	12.26	100.95	102.57	102.81	106.66	102.56	106.04
Gender			Male	939	54.82	99.92	99.77	100.18	100.33	100.17	100.25
			Female	774	45.18	100.10	100.28	99.78	99.60	99.79	99.69
	White	Full Time		1,432	83.60	99.75	99.44	99.42	98.78	99.47	98.89
	White	Part Time		201	11.73	100.04	101.84	101.94	105.68	101.69	105.10
	Non-White	Full Time		71	4.14	102.14	103.76	103.40	104.87	103.07	104.53
	Non-White	Part Time		9	0.53	121.26	118.88	122.14	128.50	121.98	127.06
	White		Male	886	51.72	*98.77*	98.58	*98.89*	*98.90*	*98.90*	*98.86*
	White		Female	747	43.61	*101.00*	101.10	*100.73*	*100.50*	*100.75*	*100.59*
	Non-White		Male	53	3.09	*119.18*	119.59	*121.89*	*124.29*	*121.41*	*123.49*
	Non-White		Female	27	1.58	*75.07*	77.73	*73.35*	*74.62*	*73.38*	*74.82*
		Full Time	Male	870	50.79	99.53	99.32	99.79	99.57	99.78	99.55
		Full Time	Female	633	36.95	100.32	100.09	99.36	98.38	99.45	98.61
		Part Time	Male	69	4.03	104.79	105.45	105.16	109.88	105.03	109.06
		Part Time	Female	141	8.23	99.07	101.17	101.66	105.08	101.35	104.57
	White	Full Time	Male	824	48.10	98.60	98.29	98.72	98.38	98.73	98.39
	White	Full Time	Female	608	35.49	101.32	100.98	100.37	99.33	100.47	99.57
	White	Part Time	Male	62	3.62	101.00	102.41	101.12	105.76	101.09	105.16
	White	Part Time	Female	139	8.11	99.61	101.59	102.31	105.64	101.95	105.08
	Non-White	Full Time	Male	46	2.69	116.26	117.63	118.99	120.94	118.60	120.44
	Non-White	Full Time	Female	25	1.46	76.15	78.24	74.71	75.30	74.50	75.27
	Non-White	Part Time	Male	7	0.41	138.34	132.45	140.92	146.32	139.89	143.57
	Non-White	Part Time	Female	2	0.12	61.50	71.38	56.38	66.12	59.28	69.27

Note: *Italics* indicates that differences are statistically significant at $p < 0.05$
Bold indicates that differences are statistically significant at $p < 0.01$

Table 4a. Results of Space-Time Individual Accessibility Measures

				N	(%)	Act	ActT	AreaAct	AreaActT	WareaAct	WareaActT	Dur	AreaDur	WareaDur
Average Individual Accessibility				1,713	100	2349735.30	2099175.22	2612432.05	2249105.88	2751774.72	2385752.83	1815987.75	2049910.16	2184746.34
Standardized Accessibility						100	100	100	100	100	100	100	100	100
Race	White			1,633	95.33	*98.62*	*98.57*	*98.57*	*98.52*	*98.59*	*98.54*	*98.72*	*98.61*	*98.64*
	Non-White			80	4.67	*128.07*	*129.13*	*129.13*	*130.23*	*128.68*	*129.74*	*126.18*	*128.35*	*127.70*
Employment Status		Full Time		1,503	87.74	98.99	98.62	99.06	98.50	99.05	98.52	98.16	*97.79*	*97.86*
		Part Time		210	12.26	107.24	109.85	106.76	110.76	106.81	110.58	113.17	*115.79*	*115.33*
Gender			Male	939	54.82	**107.86**	**108.30**	**108.49**	**109.24**	**108.43**	**109.11**	**106.60**	**107.26**	**107.18**
			Female	774	45.18	**90.46**	**89.93**	**89.70**	**88.80**	**89.78**	**88.95**	**92.00**	**91.19**	**91.29**
	White	Full Time		1,432	83.60	97.63	97.26	97.67	97.12	97.68	97.16	*96.97*	*96.53*	*96.62*
	White	Part Time		201	11.73	105.68	107.92	105.02	108.50	105.09	108.36	*111.15*	*113.46*	*113.04*
	Non-White	Full Time		71	4.14	126.31	126.14	127.05	126.28	126.58	125.89	*122.08*	*123.34*	*122.79*
	Non-White	Part Time		9	0.53	141.98	152.74	145.52	161.38	145.30	160.15	*158.47*	*167.86*	*166.44*
	White		Male	886	51.72	**105.46**	**105.89**	**105.93**	**106.66**	**105.90**	**106.57**	**104.31**	**104.74**	**104.71**
	White		Female	747	43.61	**90.52**	**89.90**	**89.85**	**88.87**	**89.93**	**89.03**	**92.08**	**91.34**	**91.45**
	Non-White		Male	53	3.09	**148.07**	**148.60**	**151.31**	**152.36**	**150.63**	**151.60**	**144.75**	**149.40**	**148.44**
	Non-White		Female	27	1.58	**88.81**	**90.92**	**85.58**	**86.80**	**85.61**	**86.85**	**89.73**	**87.02**	**86.97**
		Full Time	Male	870	50.79	**105.66**	**105.55**	**106.34**	**106.31**	**106.28**	**106.23**	**103.58**	**103.87**	**103.86**
		Full Time	Female	633	36.95	**89.82**	**89.11**	**89.05**	**87.75**	**89.11**	**87.92**	**90.71**	**89.44**	**89.61**
		Part Time	Male	69	4.03	**135.61**	**142.97**	**135.65**	**146.10**	**135.49**	**145.35**	**144.65**	**150.05**	**149.02**
		Part Time	Female	141	8.23	**93.35**	**93.64**	**92.62**	**93.47**	**92.78**	**93.57**	**97.77**	**99.03**	**98.84**
	White	Full Time	Male	824	48.10	**103.38**	**103.33**	**103.94**	**104.00**	**103.91**	**103.94**	**101.56**	**101.69**	**101.71**
	White	Full Time	Female	608	35.49	**89.84**	**89.03**	**89.17**	**87.79**	**89.25**	**87.98**	**90.75**	**89.54**	**89.73**
	White	Part Time	Male	62	3.62	**133.02**	**139.91**	**132.44**	**141.95**	**132.40**	**141.41**	**140.85**	**145.39**	**144.55**
	White	Part Time	Female	139	8.11	**93.49**	**93.66**	**92.80**	**93.57**	**92.91**	**93.62**	**97.89**	**99.22**	**98.98**
	Non-White	Full Time	Male	46	2.69	**146.47**	**145.33**	**149.36**	**147.72**	**148.76**	**147.25**	**139.64**	**143.03**	**142.34**
	Non-White	Full Time	Female	25	1.46	**89.21**	**90.83**	**86.00**	**86.84**	**85.75**	**86.60**	**89.78**	**87.12**	**86.80**
	Non-White	Part Time	Male	7	0.41	**158.60**	**170.08**	**164.13**	**182.84**	**162.87**	**180.18**	**178.31**	**191.30**	**188.55**
	Non-White	Part Time	Female	2	0.12	**83.82**	**92.08**	**80.35**	**86.30**	**83.81**	**90.04**	**89.02**	**85.80**	**89.09**

Note: *Italics* indicates that differences are statistically significant at $p < 0.05$
Bold indicates that differences are statistically significant at $p < 0.01$

Table 4b. Results of Space-Time Individual Accessibility Measures

In order to examine the significance of the inclusion of possible activity duration and temporal availability of feasible opportunities into the accessibility measure, the paired-samples T test procedure was employed. This test computes the differences between the mean accessibility values for each pair of measures and tests whether the incorporation of such temporal dimension into the measure had an effect on the estimation of the level of accessibility. The test result shown in Table 5 reveals that the inclusion of either activity duration and/or temporal availability of opportunities into the measure reduce the level of accessibility measure estimated and those differences are statistically significant. It therefore implies that existing accessibility measures without such consideration of temporal availability of opportunities and possible activity duration tend to significantly over-estimate the level of accessibility of individuals.

	a set of paired accessibility measures	Paired Differences Mean	Std. Dev.	Std. Error	t
Pair 1	Num - NumT	**2726.50**	4034.50	97.48	27.97
Pair 2	Area - AreaT	**4186.73**	5512.18	133.18	31.44
Pair 3	Warea - WareaT	**4253.73**	5681.16	137.26	30.99
Pair 4	Act - ActT	**223295.02**	396264.53	9574.29	23.32
Pair 5	Area - AreaT	**363326.17**	623297.51	15059.71	24.13
Pair 6	Warea - WareaT	**366021.88**	632354.83	15278.55	23.96
Pair 7	Act - Dur	**347334.44**	849536.69	20525.96	16.92
Pair 8	ActT - Dur	**124039.42**	709468.88	17141.73	7.24
Pair 9	AreaAct - AreaDur	**562521.90**	1204478.84	29101.84	19.33
Pair 10	AreaActT - AreaDur	**199195.73**	975756.24	23575.59	8.45
Pair 11	WreaAct - WareaDur	**567028.38**	1243497.66	30044.59	18.87
Pair 12	WareaActT - WareaDur	**201006.49**	1010870.21	24424.00	8.23

Note: **Bold** indicates that differences are statistically significant at $p < 0.01$

Table 5. The effect of temporal dimension incorporation into accessibility measure

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, human activity-travel behavior and the effect of transport network topology. 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 help to overcome several shortcomings of previous approaches to evaluating space-time accessibility.

The results reveal that the proper consideration of temporal properties of space-time prism makes the accessibility measure more robust and more sensitive in highlighting the differentially situated individuals in space and time as well as in society. Furthermore, the results show that the number of feasible opportunities, the possible activity duration at feasible locations as well as individual accessibility as evaluated by all formulations of space-time measures are considerably smaller when the effect of facility opening hours is taken into account. It implies that individual accessibility measures without proper consideration of such temporal dimension tend to significantly overestimate an individual's level of access to urban opportunities and makes the result less robust.

The study not only shows that space and time are closely linked in determining individual accessibility but also 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. It 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 accessibility measures.

This study, however, has limitations. Like most of previous studies on space-time accessibility, it focused just on automobile users because of data limitations. 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. Furthermore, as the wide use of the internet today has significantly affected the society in general and travel/activity patterns of individuals in the physical world in particular, we need to develop a new measure of individual accessibility which considers both cyberspatial and physical opportunities and differential level of access to them among subpopulation groups.

Acknowledgments

A version of this paper was presented at the 98th Annual Meeting of the Association of American Geographers, 2002 and was published in Journal of Geographical Systems in 2003. I thank Joe Weber for providing the digital transport network with travel speeds and a version of the geocomputational algorithm he used in his study (Weber 2001), upon which the developmental effort has been based.

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