ARTICLES

Bringing Time Back In: A Study on the Influence of Travel Time Variations and Facility Opening Hours on Individual Accessibility*

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Although recent studies of individual accessibility have used detailed representations of urban street networks, unrealistic measures of travel time based on assumptions about constant travel speeds through the network were often used. Utilizing constant travel times does not allow for daily congestion and assumes that the effects of congestion are uniform throughout the city and affect all people equally. This research measures individual space-time accessibility in order to show that the incorporation of locally specific travel times within a street network allows a significant increase in the ability to realistically evaluate individual accessibility within cities. The results show that the accessibility of individuals within cities is not homogenous, and neither does access to employment or shopping opportunities vary according to common expectations about urban form and human behavior. Instead, the role of distance in predicting accessibility variations within cities is quite limited. This article also shows that incorporating time into accessibility measures in the form of congestion and business hours leads to additional (and highly spatially uneven) reductions in accessibility, revealing that the temporal dimension is very important to accurately assessing individual accessibility.
Key Words: accessibility, geographic information systems, time.

Introduction

Geographers have devoted considerable attention to the study of individual accessibility, the accurate measurement of which depends on accurate representations of the urban environment and possibilities for movement in this environment. The use of geographic information systems (GIS) has enormous utility for such research because of its ability to represent the components of the urban environment, such as the home locations of individuals and employment opportunities, and to model the spatial relationships among these components through the use of network-based geocomputational methods. The value of GIS is particularly apparent with the use of space-time accessibility measures because of their requirement of a high degree of spatial and temporal resolution of the urban environment and their need to accurately represent the movement possibilities of individuals through urban transport networks.

In this article, we argue that previous studies on accessibility suffer from several limitations that can be overcome through utilizing the representational and geocomputational capabilities of GIS. For instance, the assumption about constant travel speed throughout the day ignores the temporal variations in travel speed due to daily congestion. Applying a constant travel speed to all areas of a city is also questionable, because it assumes that the effects of peak hour congestion are uniform throughout the entire urban area and affect all people equally. Past studies also ignore the effect of the business hours of urban opportunities by assuming them to be available throughout the day.[1] Thus, the capabilities of GIS to represent localized traffic congestion and the opening hours of urban opportunities can offer significant insight into the ways that the accessibility

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of individuals and social groups are affected not only by geographical location, but also by temporal variations in travel speed and facility opening hours in an urban area.

This study intends to show that the incorporation of locally specific travel times within a street network does in fact allow a significant increase in the ability to realistically evaluate individual accessibility within cities. Using an activity-travel diary data set collected in Portland, Oregon, this research shows that individual accessibility within Portland is not homogenous. Neither does access to employment or shopping opportunities vary according to common monocentric and polycentric expectations about urban form and human behavior. Instead, the role of distance in ordering or predicting accessibility variations within cities appears to be quite limited relative to variations in individual travel behavior, mobility offered by the street network, and the location and size of activity opportunities. This article also shows that incorporating time into accessibility measures in the form of evening congestion and business hours leads to additional (and highly spatially uneven) reductions in accessibility, revealing that time is very important to accurately assessing individual accessibility, perhaps as important as space.

Distance and Time in Accessibility Measures

While the measurement of individual accessibility within urban areas has long been an important topic, there has been little agreement regarding definitions, appropriate measurements or interpretation. Although a variety of classifications exist (Morris, Dumble, and Wigan 1979; Pirie 1979; Handy and Niemeier 1997), recent work strongly supports distinguishing between space-time accessibility measures derived from time geographic concepts and conventional measures, because of the fundamentally different ways in which these measures represent accessibility (Kwan 1998). While space-time measures are based on people's movement through space within time and mobility constraints, conventional measures evaluate proximity to opportunities, using a distance decay function to limit the importance of more distant opportunities. A wide range of conventional accessibility formulations exist, including distance (Ingram 1971), topological (Garrison 1960), gravity (Carrothers 1956), and cumulative-opportunity measures (Wachs and Kumagai 1973), but all are based on identifying the proximity of opportunities to a given location. As distance is fundamental to each, the accurate representation of this distance is essential to their valid use.

Several representations of distance have been used with network applications of conventional accessibility measures. These include linear distance measured through the transport network (as by Vickerman 1974; Knox 1982; Talen and Anselin 1998), travel cost (Gauthier 1968; Kissling 1969), and the number of intermediate links between points (Garrison 1960). Travel time through networks has also been used as a representation of distance, but a wide variety of methods exists for establishing these travel times. For interurban rail networks, travel time can be found relatively easily using published timetables (Murayama 1994; Gutierrez, Gonzalez, and Gomez 1996), though the issue becomes more complex at the intraurban level, especially if mode changes are allowed (O'Sullivan, Morrison, and Shearer 2000). For interurban or large-scale intraurban applications, highway travel time has been evaluated using observed speeds obtained from traffic studies (Linneker and Spence 1992a, 1992b; Spence and Linneker 1994; Gutierrez and Gomez 1999) or assumptions about speeds over different kinds of highway types, often adjusted according to experience (Kissling 1969; Marchand 1973).

For intraurban studies, the results have been more diverse, and the challenge of measuring and representing travel times for large numbers of street links is considerably greater. Some have used estimates or averages of interzonal network travel times to overcome this problem. Handy (1993) used free-flow travel time estimates between zones, Scott (1998) selected median travel times between census tracts, and Helling (1998) worked with peak-period travel times between census tracts. Others have more directly measured interzonal travel times through transport networks. For example, Muraco (1972) used speed limits to estimate travel time in a pioneering intraurban topological accessibility analysis of Columbus and Indianapolis. Wachs and Kumagai (1973) chose morning peak-period auto travel times between zones reported by households (and calibrated to network conditions to allow estimation of travel times between zones not reported by households) with a cumulative-opportunity measure, while Black and Conroy (1977) made use of field surveys of peak-period auto and transit travel times between census zones with a similar accessibility measure.

Similarly, Knox (1978) used a sample to estimate average travel time by car or bus between zone centroids in a population potential accessibility analysis, and Shaw (1991) worked with field observations to estimate auto and bus travel times when evaluating accessibility to light rail stations in Miami. Although based on actual traffic conditions, Shaw's estimates apparently represent daily averages and so do not allow for more temporally precise variations in travel times. Geertman and Van Eck (1995) used travel times between zone centroids for contemporary and future traffic conditions in a GIS-based population potential accessibility analysis in the Netherlands. The basis of the travel-time calculation was not given, but the times included "delays due to congestion or transfer" (Geertman and Van Eck, 75). Wang (2000) selected network travel times (using major roadways only) between traffic analysis zone (TAZ) centroids with travel times derived from posted speed limits.

Unlike conventional accessibility measures, space-time measures are highly dependent on individual data and detailed representations of urban environments, and so have relied on the use of point-to-point network travel times. In early examples of time geographic simulation, Lenntorp (1976, 1978) used assumed speeds for transit vehicles and other modes of travel, calculated through a network as appropriate. Miller (1982) estimated network travel times for nineteenth-century Philadelphia using assumptions for four distinct travel modes (along with waiting times for public transportation), while Forer and Kivell (1981) produced transit travel times from a timetable, along with estimated waiting times. More recently, Kwan (1998, 1999a) and Kwan and Hong (1998) assigned travel times based on assumptions about driving speeds over different street types (e.g., freeways, major arterials, and local streets). Such an approach is not limited to accessibility studies, as Brainard, Lovett, and Bateman (1997, 1999) used a similar approach to create isochrone surfaces for predicting visitors to a recreational facility. There has also been development in representing travel times to opportunities more precisely at the microscale. For instance, Miller (1999) developed a method for interpolating travel times between nodes within a transport network. This method takes into account the effect of activities or opportunities that lie between network nodes when assessing individual accessibility.

Although requiring more detailed data, the use of point-to-point network distances not only allows travel times to be represented more realistically, it also allows congestion to be incorporated with a higher degree of spatial resolution than with interzonal distances. When used with individual activity-travel data, it allows the effects of congestion to be felt unevenly by different individuals rather than being applied equally to all people living within a zone. Depending on an individual's own temporal scheduling of trips and the location of those trips, people living within the same household may have very different experiences of congestion. The measurement of these travel times under both free-flow and congested conditions and their use within space-time accessibility measures will be discussed in the next section.

Data and Procedures

This study examines the effect of travel times variations and facility opening hours on individual accessibility using a range of data. These include an activity-travel diary data set of Portland, Oregon, a digital network model with estimates of free-flow and congested travel times, and a comprehensive geographic database of the study area. The analytical procedures involved creating a realistic representation of the temporal attributes of the transport network and urban opportunities in the study area, as well as developing a geocomputational algorithm for implementing space-time accessibility measures within a GIS environment. All geoprocessing was performed using ARC/INFO and ArcView GIS.

Activity and Opportunities Data

To measure individual accessibility, data for both individual activity-travel behavior and the location and business hours of activity opportunities in the Portland metropolitan area are required. Individual activity-travel data for the Portland metropolitan area was obtained from the "Household Activity and Travel Behavior Survey" carried out during 1994 and 1995 by Metro, the Portland metropolitan government (Cambridge Systematics, Inc. 1996). This is a highly detailed two-day travel diary survey that recorded all activities involving travel and all in-home activities with a duration of at least thirty minutes for all individuals in the sampled households. The data set provides information about 128,188 activities and 71,808 trips performed by 10,084 individuals from 4,451 households.

Besides the information commonly obtained in travel diary survey, this data set comes with the geocodes (x-y coordinates) of all activity locations, including the home and workplace of all individuals in the sample. This greatly facilitates its incorporation into a geographic database and use with geocomputational algorithms. However, due to the computational intensity of the GIS algorithm used to compute space-time accessibility, only 200 individuals who traveled exclusively by the automobile during weekdays from the original sample were selected for this study (Figure 1). These 200 individuals were selected using a stratified random sample based on the geographic zones used to collect the original travel diary data, with individuals represented in the sample according to the proportion of respondents in each zone. The sample includes 101 males and 99 females from 187 households. Of these, 157 are employed full-time and 28 part-time, and 15 are not employed or are retired. The sample is racially homogenous, as almost all individuals (185) are European Americans (white).

To represent potential activity opportunities in the study area, a geographic database containing 27,749 centroids of commercial and industrial land parcels in the Portland metropolitan region, with an average size of 0.00273 square miles, was assembled from local land-use data. Data for Oregon was obtained from Metro's Regional Land Information System (RLIS), a comprehensive GIS database for land use and transportation planning purposes (Metro 1998), while similar data for Clark County, Washington, was obtained from the local planning agency. For computing accessibility measures, attractiveness of individual opportunities in the study area was represented in two ways. One is the area of each land parcel (in acres), which takes into consideration that some activity opportunities are considerably larger in size and therefore more attractive than others. In addition, because buildings lo-

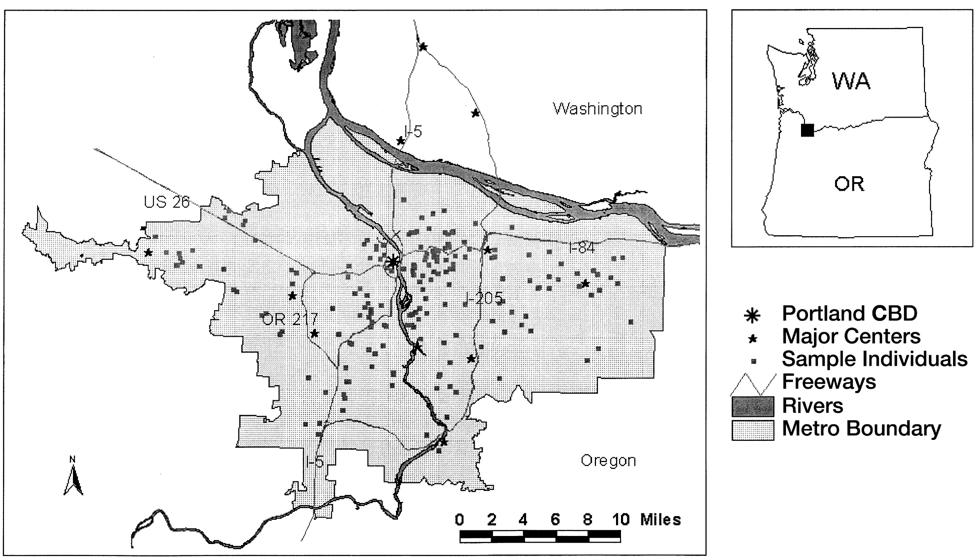

Figure 1 *Portland, Oregon, study area.*

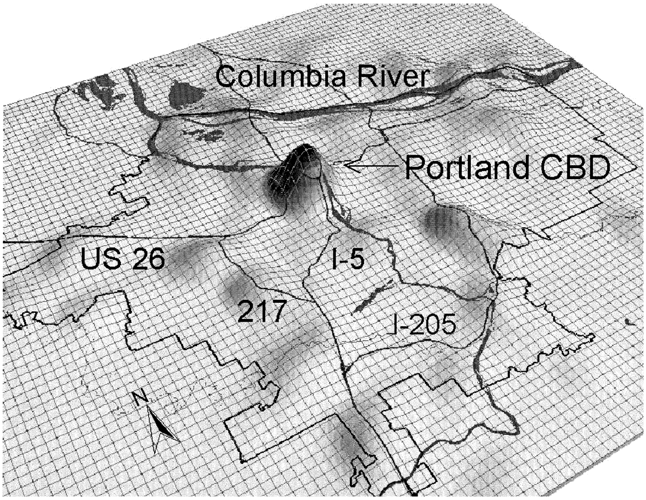

Figure 2 *Weighted opportunity density surface of Portland study area.*

cated in downtown and major suburban centers often have multiple floors and higher ratios of building size to parcel size, the square footage of these parcels was weighted to take this into account.[2] This weighted area was the second measure of attractiveness used in the accessibility computation. Figure 2 shows the opportunity density surface of the study area using the weighted area of each opportunity.[3]

Digital Street Network and Travel Times

The digital street network used in this study is an enhanced U.S. Census topologically integrated geographic encoding and referencing system (TIGER) street network that covers the four counties of the study area (i.e., Clark, Clackamas, Multnomah, and Washington). This street network has 130,141 arcs and 104,048 nodes. While the TIGER functional classification for each link could be used to estimate free-flow speeds and capacity, this would still leave peak traffic volumes unspecified. To estimate link-specific travel speeds under both normal and congested conditions at different times of the day, a planning network developed by Metro for transportation modeling was used. Although this planning network contains only the major streets and freeways and lacks the spatial and temporal resolution needed for space-time accessibility measures, it was useful for estimating free-flow and peak-period link-specific travel times.

Free-flow travel times were taken from this network for links within specific functional and locational classifications and applied to the equivalent TIGER classes and link lengths. These classifications were based on grouping roadways according to function (freeway, primary street, secondary street, or other street) and by location inside or outside the downtown area as well as the Portland regional planning boundary (which approximates the urbanized area). Congested (or peak-period) speeds were used for travel between 4:00 PM to 6:00 PM and were calculated in the same manner using the standard Bureau of Public Roads (BPR) speed-flow equation, with free-flow speeds, link capacity, and peak traffic volumes taken from the local planning network (Dowling Associates 1997).[4] These congested speeds were transferred to the TIGER network using the same functional and locational classifications as before.[5]

As various methods can be used to introduce variable travel times into space-time measures of accessibility within GIS, a computationally efficient one was implemented in this study. It identifies the midpoint of the open block of time between fixed activities (for example, 4:00 PM for an open time period running from 3:00 to 5:00 PM) and selects the congested speeds if this midpoint falls within the time-of-day ranges for congested traffic flow, and the free-flow speeds if the midpoint falls outside that range. While such "instantaneous congestion is unrealistic" (Burns 1979, 29), the method can be readily implemented within a GIS algorithm for calculating space-time measures of accessibility.

Space-Time Measures

Several space-time accessibility measures, which are based on the concept of the potential path area (PPA), were implemented in this study (Kwan 1998, 1999a; Kwan and Hong 1998; Miller 1991, 1999). This concept can be explained by considering the case of an individual with a daily activity schedule for a number of in-home or out-of-home activities. Some of these activities are considered to be fixed, in that the individual has little or no control over when and where the activity must take place (such as the workplace). The individual's mobility is therefore limited by the need to move from the location of the previous fixed activity to the location of the next fixed activity within the time available between these activities. Only the time between successive fixed activities is available for other activities. These include activities, such as grocery shopping or filling a car with gas, that can be carried out at several possible locations and when convenient, and so can be considered flexible activities.

The ability to engage in flexible activities, therefore, depends on the amount of time and mobility available between fixed activities. The area an individual can reach between any two successive fixed activities is the PPA. A PPA contains all possible routes an individual could traverse and urban opportunities an individual could potentially reach, given the space-time constraint of the two particular fixed activities in question. When the effect of all successive pairs of fixed activities are considered and their respective PPAs aggregated, these PPAs create a daily potential path area (DPPA) that can be used to assess accessibility for the individual.

Because the DPPA depends on each individual's activity schedule, travel through the street network, and the spatial pattern of potential opportunities in the urban area, it can only be found using a dedicated algorithm implemented by GIS-based geocomputational procedures. The spatial and network analytic capabilities of GIS allow not only the measurement of network-based travel times within the context of activity schedules, but also the incorporation of the number and size of potential activity opportunities into the computation. Implementing these procedures using Avenue, the object-oriented scripting language in the ArcView 3.2 GIS environment, five space-time accessibility measures were computed. The first is the length of the road segments contained within the DPPA (MILES). The second is the number of opportunities within the DPPA (OPPORTUNITIES). The total area (AREA) and total weighted area (WEIGHTED AREA) of the land parcels within the DPPA comprise the third and fourth space-time accessibility measures. Finally, to incorporate the effect of business hours on accessibility measures, opportunity parcels were assumed to be available (and could therefore be accessible to an individual) only from 9:00 AM to 6:00 PM.[6] This creates a fifth accessibility measure, called TIMED AREA. This inclusion of temporal availability adds additional detail to the analysis by emphasizing that while individuals may have considerable constraints on their mobility during the daytime, limited business hours at night will further reduce their accessibility. Both physical mobility and temporal flexibility are therefore necessary to attain high accessibility. To facilitate comparisons of these five measures, the level of accessibility is standardized to a mean of 100 throughout the following discussion.

Results and Discussion

In order to help visualize resulting accessibility patterns, a surface was interpolated for the WEIGHTED AREA measure (Figure 3).[7] However, it must be remembered that the values of the surface depend not on location, but rather on individuals who may travel widely throughout the urban area. Not surprisingly, this surface shows that individual accessibility is highly variable, with no clear geographic pattern evident within the Portland urban area. A number of sharp peaks, representing individuals with above-average accessibility, are evident in several suburban locations, but there is no peak at or near the CBD. This is in contrast to the opportunity density surface, which shows that the Portland CBD contains by far the greatest area of potential activities. Therefore, living adjacent to the CBD does not guarantee high accessibility. This is consistent with the findings of space-time accessibility measures that it is an individual's behavior, rather than

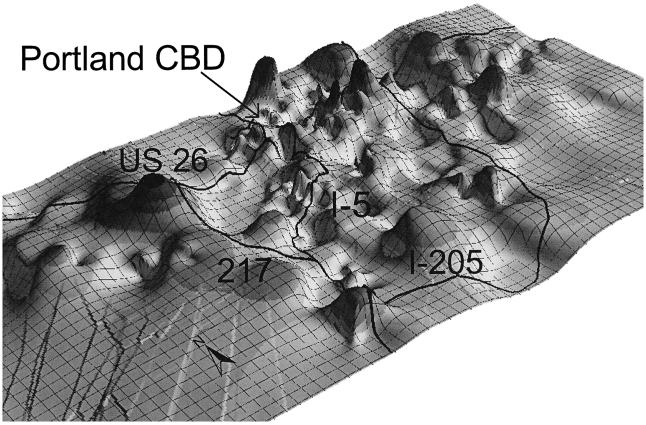

Figure 3 *Weighted opportunity individual accessibility surface for Portland study area.*

simply their location, that most strongly influences their accessibility (Kwan 1998).

Accessibility Patterns and Monocentric Expectations

Individual accessibility in Portland can also be visualized by plotting it as a function of distance from the Portland CBD. This approximates the standard monocentric urban model and assumes that accessibility should decline with distance from the CBD. Although the continued relevance of the monocentric model (as well as the related polycentric model discussed below) has been strongly challenged (Giuliano 1989, 1995), the underlying logic of this model, in which individuals act to minimize distance to work and accessibility declines with distance from the CBD, remains in common use. Statements about increasing traffic congestion (Hodge 1992), the potential impacts of Intelligent Transportation Systems (Hodge, Morrill, and Stanilov 1996) and the urban village (Pickus and Gober 1988) and neotraditional development (Bookout 1992) concepts all make use of monocentric logic, even when no assertion is made that urban land uses can still be adequately described by this model. For this reason, it is appropriate to question whether the model continues to provide a useful conceptualization for discussing individual accessibility. While this does not allow the full capabilities of space-time measures in showing individual activity patterns to be utilized, it is important to test whether common statements about individual behavior and accessibility remain valid.

The average accessibility of individuals living within five-minute driving time intervals from the CBD is shown in Figure 4 and Table 1. With the exception of TIMED AREA, the accessibility measures all show a strikingly similar pattern, with access remaining relatively constant until a peak of higher than average accessibility can be seen at a distance of about twenty to twenty-five minutes driving time. These are actually the highest accessibility values observed, with individuals possessing values up to 136 percent of the average. Beyond this distance accessibility declines, and at the periphery of the city (beyond thirty-five minutes driving time) the values are far below average (as little as 40 percent of the citywide average). People living in suburban locations therefore appear to have the highest accessibil-

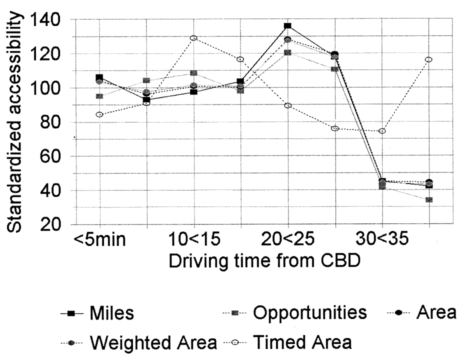

Figure 4 *Average individual accessibility by distance from the Portland central business district (CBD).*

Table 1 *Average Accessibility under Monocentric Expectations*

		MILES			OPPORTUNITIES			AREA			WEIGHTED AREA			TIMED AREA		
		Accessibility			Accessibility			Accessibility			Accessibility			Accessibility		
	N	**Free Flow**	**Con-gested**	**Reduc-tion**	**Free Flow**	**Con-gested**	**Reduc-tion**	**Free Flow**	**Con-gested**	**Reduc-tion**	**Free Flow**	**Con-gested**	**Reduc-tion**	**Free Flow**	**Con-gested**	**Reduc-tion**
Average personal accessibility	200	3580.45	2559.37	−28.52	15718.93	12241.85	−22.12	18489.19	13457.18	−27.22	19604.13	14404.65	−26.52	6590.16	5526.04	−16.15
Standardized accessibility																
Driving time from CBD																
Less than 5 minutes	13	**106.29**	101.31	111.75	*95.03*	**99.97**	**81.72**	**104.20**	103.16	102.65	**103.22**	102.90	100.88	84.17	83.96	101.30
5–10 minutes	44	**93.07**	96.03	92.03	*104.06*	**107.41**	**88.69**	**96.32**	97.05	97.95	**97.59**	98.71	96.82	90.90	88.48	113.82
10–15 minutes	49	**97.32**	103.44	84.23	*108.25*	**112.73**	**85.41**	**100.79**	106.00	86.18	**101.44**	106.70	85.63	128.89	139.60	56.86
15–20 minutes	21	**103.56**	99.29	110.33	*97.80*	**96.24**	**105.62**	**100.25**	96.99	108.68	**100.71**	97.94	107.63	116.45	106.48	144.44
20–25 minutes	33	**136.00**	135.14	101.57	*120.12*	**116.90**	**109.45**	**128.21**	130.59	95.02	**127.27**	128.58	97.17	89.20	92.17	82.69
25–30 minutes	18	**117.77**	108.12	120.52	*110.44*	**99.82**	**133.86**	**119.45**	108.22	125.11	**117.60**	106.27	126.70	75.72	71.87	126.37
30–35 minutes	17	**44.83**	36.78	145.02	*41.59*	**33.77**	**166.21**	**44.75**	36.70	148.07	**43.95**	35.96	150.38	74.08	55.97	226.89
More than 35 minutes	5	**42.03**	54.69	24.55	*33.79*	**40.24**	**32.83**	**44.34**	55.37	33.51	**42.96**	53.28	33.48	115.78	130.43	34.26

Note: Bold indicates differences are significant at $p < 0.05$; italics indicates differences are significant at $p < 0.01$.

ity, while those on the edge of the city have the least.

The pattern observed for the TIMED AREA measure is quite different, with the highest values around ten to fifteen minutes distance, and lower than average values found both beyond that distance and adjacent to the CBD. The difference between this measure and WEIGHTED AREA is due solely to behavior, as people living at different locations engage in varying amounts of travel during the daytime and so possess greater or lesser access to businesses while they are open. Because individuals living ten to fifteen minutes from the CBD engage in the least amount of nighttime activities, they have the least reduction in accessibility when business hours are incorporated, and so possess higher than average accessibility using this measure (although the absolute values of TIMED AREA is everywhere less than that of WEIGHTED AREA, with an average of a 58.4 percent reduction resulting from the use of business hours). Conversely, people living twenty to thirty-five minutes from the CBD engage in a higher proportion of nighttime activities and suffer a considerable decline in access to opportunities. Their accessibility as evaluated by the TIMED AREA measure is therefore well below average. Incorporating time directly into the measure clearly produces a considerably different geography of accessibility in Portland than observed with the other measures.

The effects of congestion on accessibility can also be shown by distance from the Portland CBD (this time with percent change standardized to a mean of 100, so that values above 100 indicate greater than average reduction, and vice versa). With the exception of TIMED AREA, the pattern is similar to that for accessibility under free-flow conditions (Figure 5). Reductions are relatively consistent until a suburban peak is reached, followed by below-average values on the periphery of the city. This shows that the effects of congestion are greatest at suburban locations (ranging from 145 percent to 166 percent of the average), and are least severe on the edge of the city (as low as 25 percent of the average effect). However, the peak reductions are actually at thirty to thirty-five minutes driving time from the CBD, which is an area of below-average accessibility under free-flow conditions. Individuals living at this

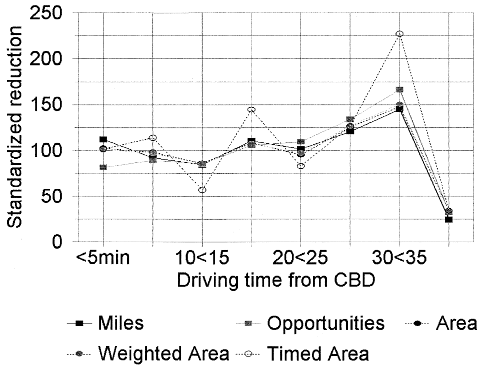

Figure 5 *Average percent reduction in individual accessibility by distance from the Portland CBD.*

location, therefore, tend to have low access to employment and services, as well as suffering more from congestion than individuals in other areas, and so are doubly disadvantaged.

The TIMED AREA measure tends to exaggerate this pattern, with values for this measure tending to be well above average where WEIGHTED AREA is above average, and vice versa. Because congestion is applied to travel during the time period that businesses were available, it could be expected that where people tend to do considerable travel during the daytime they would therefore be more likely to be subject to congestion, as well as having greater access to opportunities. However, this is not the case, as people in these areas (such as ten to fifteen minutes from the CBD) actually tend to possess both above-average accessibility with the TIMED AREA measure and a below-average reduction in accessibility due to congestion. These people are engaging in many activities during the daytime hours but are not suffering much from congestion. The opposite is also true, so that people living at thirty to thirty-five minutes distance with relatively few daytime activities may have below-average accessibility using the TIMED AREA measure but also suffer above-average accessibility reductions during the evening peak traffic period. Once again, low accessibility is reinforced by severe reductions as a result of congestion. This probably occurs because individuals in these areas are driving on very congested roadways and so experience considerable congestion during the relatively few activities that they take part in during the evening rush hour. It is not just when they carry out the activities but where they travel that influences the severity of the congestion they face.

Accessibility Patterns and Polycentric Expectations

The importance of distance to individual accessibility can also be assessed within a polycentric framework, using the twelve regional centers defined by Metro in its "Portland 2040 Growth Plan" (Metro 1997). These centers include the Portland CBD, the downtowns of several suburbs, major shopping centers, and suburban employment concentrations. For this reason, they can be considered important and highly visible areas around which accessibility can be usefully evaluated. As with the monocentric model, distance again should determine accessibility, but this time from multiple points. Because these centers are so widely distributed there are fewer distance intervals, but strong patterns can nonetheless be observed (Figure 6, Table 2). For all but the TIMED AREA measure, accessibility is highest close to centers and lowest at farthest distances, though there is not a direct relationship between distance and access. This pattern is seen more strongly with TIMED AREA, especially the very high accessibility values (154 percent of the average) adjacent to the centers (though the absolute values of this measure were on average 65.7 percent lower than WEIGHTED AREA). These high values are again due to behavior, with individu-

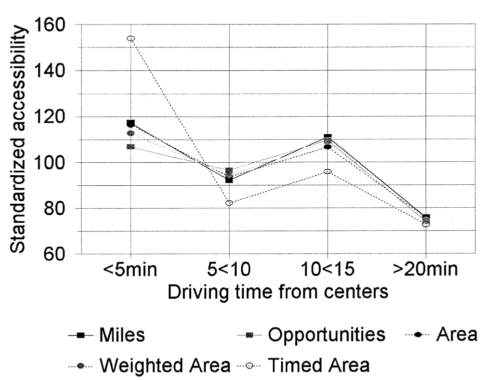

Figure 6 *Average individual accessibility by distance from twelve regional centers in the Portland metro area.*

Table 2 *Average Accessibility under Polycentric Expectations*

	N	MILES			OPPORTUNITIES			AREA			WEIGHTED AREA			TIMED AREA		
		Accessibility			Accessibility			Accessibility			Accessibility			Accessibility		
		Free Flow	Con-gested	Reduc-tion	Free Flow	Con-gested	Reduc-tion	Free Flow	Con-gested	Reduc-tion	Free Flow	Con-gested	Reduc-tion	Free Flow	Con-gested	Reduc-tion
Average personal accessibility	200	3580.45	2559.37	−28.52	15718.93	12241.85	−22.12	18489.19	13457.18	−27.22	19604.13	14404.65	−26.52	6590.16	5526.04	−16.15
Standardized accessibility																
Driving time from centers																
Less than 5 minutes	45	116.63	120.16	92.40	106.83	111.02	**86.21**	115.49	120.58	**88.21**	113.97	118.84	**88.18**	153.89	154.19	98.97
5–10 minutes	121	93.32	92.50	102.21	97.55	97.51	**100.15**	94.49	93.52	**102.74**	94.86	93.86	**102.91**	82.27	82.54	98.33
10–15 minutes	28	107.41	111.96	89.37	105.14	104.37	**102.58**	103.84	106.37	**93.46**	104.78	107.54	**92.69**	95.82	100.88	72.55
More than 20 minutes	6	75.39	44.24	203.55	74.09	47.16	**228.01**	77.04	46.71	**205.26**	76.68	47.30	**206.16**	72.78	41.63	322.19

Note: Bold indicates differences are significant at $p < 0.05$.

als adjacent to the regional centers engaging in a higher proportion of their activities during the daytime than people living farther away.

When congestion is applied, reductions in accessibility are very even except at the farthest distances, where very high reductions are observed (Figure 7). This pattern is true of all measures, though the TIMED AREA measure shows the greatest reductions at the farthest distances (322 percent of the average reduction). This is interesting, as it is at these locations that individuals engage in a lower proportion of daytime activities and so would not be expected to be subject to reductions as a result of daytime congestion. However, as with the monocentric model, it may also be that these individuals live or move about in areas of the city with highly congested streets, and so suffer considerably from congestion during the daytime activities in which they do engage. And again, those individuals possessing the least accessibility also suffer the most from congestion. Taking part in few daytime activities may in fact be a response to the congestion they face during the daytime.

Conclusions

The incorporation of time into the evaluation of individual accessibility within cities has produced interesting and sometimes unexpected results. Link-specific travel times produce very uneven accessibility patterns, with access to services and employment varying considerably

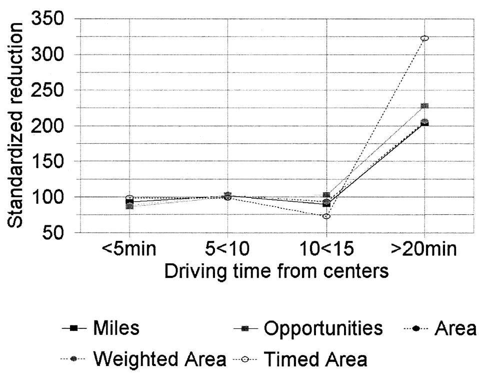

Figure 7 *Average percent reduction in individual accessibility by distance from twelve regional centers in the Portland metro area.*

within Portland. The time of day during which activities were carried out has also been shown to have an effect on accessibility, as evening congestion sharply reduced individuals' access throughout the city. The effects of this congestion on mobility is highly spatially uneven, even though in this study congested traffic speeds were only applied to a two-hour time period in the evening. More temporally precise applications of congestion (perhaps capturing hourly variations) would therefore probably reduce accessibility for all individuals to a much greater extent than has been observed in this study, and for some people and areas more than others. The use of business hours to limit access to opportunities at certain times of the day with the TIMED AREA variable has shown that time of day can be incorporated into accessibility measures and that non-temporally-restricted accessibility measures produce inflated values by treating these opportunities as being available at all times of the day. Incorporating time does not just reduce accessibility; it also produces a very different—and perhaps unexpected—geography of accessibility. This geography depends much on individual behavior and so cannot be discerned from the location of opportunities or congestion alone.

Another important finding of this research is the fact that the use of greater spatial and temporal detail in accessibility measures produces patterns that do not fully support monocentric and polycentric notions of urban form and human behavior. With the monocentric model, people living in suburban locations tend to have the highest accessibility (despite the observed CBD peak of opportunities), while those living at the periphery of the city have the lowest. Areas closer to the CBD, which Abbott (1983) has characterized in a monocentric discussion of Portland as including several distinct types of pre-automobile neighborhoods, show more even accessibility patterns (except for TIMED AREA, which incorporates the importance of the time of day that activities are carried out). Reductions due to congestion are biased against more recently developed suburban areas, perhaps reflecting the inability of street improvements to keep up with traffic and the presence of heavy cross-commuting patterns within suburban areas. Stronger evidence may exist in favor of the polycentric model, which is rather surprising given the limitations of this model in capturing human behavior in other urban contexts (Pickus and Gober 1988; Hoch and Waddell 1993; Waddell, Berry, and Hoch 1993; Fujii and Hartshorn 1995). However, the TIMED AREA measure again varies from this pattern by greatly increasing the accessibility of those adjacent to centers, while the effects of congestion also fail to support this model, as they are very uneven with distance. Thus, even while it does appear to provide some explanation for accessibility patterns in Portland, the fact remains that there are significant differences from the behavior expected of individuals by these models, due in large part to the role of time within the accessibility measures. Instead, the results here confirm findings by other space-time accessibility research that these measures do not reflect proximity to features within the urban environment but instead are based on individuals' own experiences of the city (Kwan 1998; Takeda 1998; Ohmori et al. 1999). This is significant, because while the importance and role of distance in influencing human behavior and land use in these models has been strongly questioned by recent evidence (Giuliano 1989, 1995), their influence is nonetheless still common in a variety of urban applications (Hanson and Pratt 1988; Giuliano 1989; Hodge 1992; Berry and Kim 1993; Hodge, Morrill, and Stanilov 1996) and has recently become apparent in several visions of urban planning, such as the urban village (Pickus and Gober 1988) and neotraditional development (Bookout 1992) concepts.

These issues are also important because work on gender, commuting, and accessibility, as well as the very existence of congestion, has shown that much of daily travel is carried out at particular times of the day, especially in the evening. The accurate modeling of congestion resulting from this travel-activity scheduling can be expected to be crucial to realistically evaluating accessibility. This is especially the case because the amount of travel and its temporal scheduling have been shown to vary by gender and employment status (Blumen 1994; Kwan 1999b). This means that congestion will almost certainly affect men and women, as well as part- and full-time workers, differently. And while this study has focused on those traveling exclusively by personal auto, the importance of time to individuals' access to employment or services will probably be even greater for those dependent on public transit, for whom mobility depends not only on their own space-time constraints but also on the scheduling of transit systems (which will vary by time of day and day of week).

A final and important issue that requires resolution is the teasing apart of the relationship between individuals or household travel-activity characteristics and the urban environment. An individual may possess high accessibility because they spend substantial time in areas that allow for considerable mobility or proximity to many opportunities, but the extent to which this accessibility is due to the individual's own travel activity behavior (which allows them considerable open blocks of time for traveling) or the urban environment (which allows for high mobility and the presence of opportunities) is not easy to determine. Research that seeks to separate the influences of location and travel behavior of individuals, as well as relating travel behavior to socioeconomic characteristics, is therefore very important. Considerable research has been carried out on this issue, especially regarding the relationship between household travel behavior and land-use mix or density (Ewing, Haliyur, and Page 1994; Frank and Pivo 1994; Kitamura, Mokhtarian, and Laidet 1997), travel behavior in newer neotraditional neighborhood urban designs (Handy 1992; Friedman, Gordon, and Peers 1994), and the relationship between accessibility and travel behavior at the local neighborhood and regional metropolitan scales (Handy 1992, 1993; Handy and Niemeier 1997). Unfortunately, many studies rely on aggregate data and so do not necessarily allow for the identification of individual behavior or isolation of socioeconomic differences on travel behavior, and there is some debate over the appropriate methods and questions (Steiner 1994). Methods such as multilevel modeling (Jones and Duncan 1996) offer untapped potential to explore these issues by distinguishing the effects of location within the urban environment from individual and household characteristics. This approach can also be expected to be useful for modeling accessibility at different scales. ■

Notes

[1] However, there are studies that examine the impact of facility opening hours on aggregate demand in space and time. For instance, Baker (1994) showed that changes in the opening hours of suburban shopping centers might lead to a shift in people's shopping location. Using GIS methods, Takeda (2001) analyzed the effect of business opening hours on the space-time demand.

[2] Weighting was needed because the floor area of buildings on each land parcel was not consistently available. Because the Portland central business district (CBD) comprises an important employment concentration, the parcel area of opportunities located within the Portland CBD (defined as everything within a radius of 0.75 miles from a central intersection) was weighted by a factor of 10. Through personal experience the authors also identified two additional concentrations outside the CBD, the Washington Square area in eastern Washington County and the Lloyd Center area in central Portland. These areas contain several high-rise office buildings and can be distinguished from surrounding areas by the criteria outlined by Giuliano and Small (1991) for identifying employment centers, with TAZs in these areas containing both a total employment of at least 10,000 workers and a minimum density of 10 workers per acre. The parcel area of opportunities located within a radius of 0.5 mile from each center was weighted by a factor of 1.5 to reflect their greater importance relative to surrounding opportunities.

[3] This density surface was generated using kernel estimation with a search radius of 2.0 miles and a resolution of 17,436,749 cells of 2500 square feet. For details of this procedure, see Kwan (2000).

[4] Selecting only evening hours allows the effects of congestion to be more easily isolated, as observed reductions in accessibility can be attributed solely to the evening peak travel period. This allows the direct comparison of congestion effects among individuals and areas without having to control for time of day. Because most discretionary travel occurs during the afternoon and evening hours (Kwan 1999b), this period can also be expected to have a much greater impact on accessibility than does morning congestion, making evening hours more useful for assessing the effects of congestion.

[5] Local streets that do not show up within the planning network were assigned a speed of ten miles per hour for both free-flow and peak-flow conditions, while travel times for all streets were further increased by 25 percent to reflect various delays and parking/walking times. Both free-flow and peak-flow travel times obtained from these speed assumptions were evaluated based upon the authors' driving experience in Portland and the assessment of two residents using a 8×8 matrix of travel time between eight locations in the study area. These locations are Hillsboro, Tualatin, Beaverton, Gresham, Vancouver (WA), the CBD of Portland, Mount Tabor, and the Portland International Airport. This assessment indicates that such speed assumptions produced realistic representation of the actual travel times for the study area.

[6] Because the land-use data used to construct the opportunity data set does not contain business hours, these hours had to be assumed. Unfortunately, the land-use classification scheme allows opportunities to be disaggregated only as commercial or industrial functions (of which there were few), so these two land-use types were the basis for assigning business hours. Several estimates of business hours were tested (9:00 AM to 6:00 PM, 9:00 AM to 9:00 PM, and 9:00 AM to midnight), with 9:00 AM to 6:00 PM providing the greatest contrast between WEIGHTED AREA and TIMED AREA due to relatively few home activities being carried out after 9:00 PM.

[7] Inverse Distance Weighted (IDW) interpolation was used to generate this surface, using a resolution of 52,104 cells of 250,000 square feet. The data have been standardized to a mean of 100, so that peaks and valleys show deviations from average individual accessibility. Vertical exaggeration is 40 times.

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