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Individual Accessibility Revisited: Implications for Geographical Analysis in the Twenty-first Century

Analytical methods for evaluating accessibility have been based on a spatial logic through which the impedance of distance shapes mobility and urban form through processes of locational and travel decision making. These methods are not suitable for understanding individual experiences because of recent changes in the processes underlying contemporary urbanism and the increasing importance of information and communications technologies (ICTs) in people's daily lives. In this paper we argue that analysis of individual accessibility can no longer ignore the complexities and opportunities brought forth by these changes. Further, we argue that the effect of distance on the spatial structure of contemporary cities and human spatial behavior has become much more complicated than what has been conceived in conventional urban models and concepts of accessibility. We suggest that the methods and measures formulated around the mid-twentieth century are becoming increasingly inadequate for grappling with the complex relationships among urban form, mobility, and individual accessibility. We consider some new possibilities for modeling individual accessibility and their implications for geographical analysis in the twenty-first century.

1. INTRODUCTION

Accessibility has traditionally been conceptualized as the proximity of one location (whether zone or point) to other specified locations. Analytical methods for evaluating accessibility have been based on a spatial logic through which the impedance of distance shapes mobility and urban form through processes of locational and travel decision making. As a result, traditional models of urban form and accessibility are based upon a similar conceptual foundation and spatial logic, and the relationships

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between models of urban form and conceptualizations of accessibility are inextricably intertwined.

Conventional concepts and measures of accessibility are useful for studying a variety of phenomena, especially the aggregate analysis of social groups within an area-based spatial framework. Gravity-based and cumulative-opportunity measures, for example, are helpful for identifying changes in the accessibility of different locations (place accessibility) and the effect of competition on access to urban opportunities (e.g., Shen 1998; van Wee, Hagoort, and Annema 2001; Wachs and Kumagai 1973). Nodal measures are also useful for addressing issues of accessibility within transportation or information networks (e.g., Lee and Lee 1998). These conventional accessibility measures have the general form $A_i = \Sigma W_j f(d_{ij})$, where A_i is the accessibility at location i, W_j is the weight representing the attractiveness of location j, d_{ij} is a measure of physical separation between i and j (in terms of travel time or distance), and $f(d_{ij})$ is the impedance function. The most commonly used impedance functions in gravity measures are the inverse power function and the negative exponential function, while an indicator function is used in cumulative-opportunity measures to exclude opportunities beyond a given distance limit. In nodal measures, the impedance function takes the form of an indicator function that reflects the presence or absence of a network link between two nodes.

These conventional measures are, however, less suitable for understanding individual experiences because of recent changes in four broad areas: (a) the processes that shape urban form and contemporary urbanism; (b) the complexities of and individual difference in human spatial behavior; (c) the availability of new technologies, especially GIS, and data for modeling individual accessibility; and (d) the increasing importance of information and communications technologies (ICTs) in people's everyday lives.

In light of these important changes, there is an urgent need to re-examine the concepts and methods in accessibility research, especially in the context of the lived experience of individuals. We suggest that analysis of individual accessibility can no longer ignore the complexities and opportunities brought forth by these changes. Further, we argue that the effect of distance on the spatial structure of contemporary cities and human spatial behavior has become much more complicated than what has been conceived in conventional urban models and concepts of accessibility. We suggest that the methods and measures formulated around the mid-twentieth century are becoming increasingly inadequate for grappling with the complex relationships among urban form, mobility, and individual accessibility. We consider some new possibilities for modeling individual accessibility and their implications for geographical analysis in the twenty-first century. We use the analysis of accessibility as an example to argue for the need to question the usefulness of many accepted notions and methods, and to indicate ways in which limitations of past studies may be overcome.

The next four sections of the paper discuss the changes outlined above and their implications for accessibility research and geographical analysis. They focus on the limitations of traditional urban models and concepts of accessibility. We then discuss an alternative approach to evaluating individual accessibility, using our recent studies on space-time accessibility measures as examples. These studies use individual-level, georeferenced activity-travel diary data and involve the development of dedicated GIS-based geocomputational algorithms and the establishment of a comprehensive geographic database of the study areas (including a digital street network and all land parcels). We examine the strengths of this approach and the ways in which it overcomes some of the limitations of traditional methods. The concluding section discusses the implications of this kind of research for geographical analysis in the twenty-first century.

2. URBAN FORM AND CONTEMPORARY URBANISM

For much of the twentieth century, most conceptualizations and formal models of urban structure have been based on a spatial logic that shapes individual mobility and urban form through the impedance of distance. In these models, distance between locations (e.g., home and workplace), expressed in terms of travel or transport cost and modeled with an impedance function, has been the central mechanism of spatial choice of individuals and firms. For example, proximity to shops, facilities, and services is a critical factor that determines individuals' residential and travel choice. This is the central mechanism underlying the idea of monocentric cities (Burgess 1925; Hoyt 1939; Harris and Ullman 1945; Alonso 1964; Muth 1969) and the related polycentric model (Garreau 1991; Vance 1964). In such models, commuting refers to movement from peripheral home locations to the CBD or suburban employment centers (Holzer 1991), and accessibility is understood largely as an attribute of places (defined mainly as distance from the CBD or other centers), not people.

Traditional models of urban form and accessibility are therefore based upon a similar conceptual foundation and spatial logic. Such representation of urban form continues to influence the description of urban patterns and travel behavior (Davis 1998; Marshall 2000). Although straightforward, such a conception does not represent the complexities either of real urban environments or of human spatial behavior at the beginning of the twenty-first century (Dear and Flusty 1998; Giuliano and Small 1991; Waddell and Shukla 1993). This is largely the result of the belated observation of new urban forms that cannot be easily explained by such an organizing principle. It is also observed that these new urban forms cannot be described adequately in the analytical terms of traditional urban models or accessibility concepts (e.g., in terms of distinct land use types in measurable economic or social activities; see the helpful discussion in Sui 1998). A variety of research has provided new insights into these topics, and has significant implications for the study and understanding of individual accessibility.

The most significant view is perhaps that distance as conventionally understood is of declining importance as an organizing principle of urban form and accessibility. For example, distance to the CBD or suburban centers appears to provide little explanation for variations in housing value or the level of office employment within cities (Archer and Smith 1993; Heikkila et al. 1989; Hoch and Waddell 1993; Waddell, Berry, and Hoch 1993). Researchers have also shown that both distance to employment centers and the geographical distribution of urban opportunities do not have a consistent relationship with individual accessibility (Weber 2003; Weber and Kwan 2002).

This decline in the importance of distance has been attributed to a variety of forces, such as the construction of freeway networks that have increased mobility and reduced the locational advantage of central locations (Giuliano 1989). The influence of distance has therefore been reduced by the creation of a more uniform and efficient transport system. Recent trends of globalization and the operations of multinational corporations also constitute a powerful force that shapes urban processes and form but transcends the geographical boundaries of contemporary cities. Some therefore argue that the urban changes observed in recent decades represent an entirely new pattern of urbanism that requires new perspectives. This view holds that contemporary cities should be conceptualized as having instead been shaped by the various locational logics of industries, firms, and individuals (e.g., Dear and Flusty 1998; Fishman 1990). Land use patterns and individual accessibility appear to be determined by much more complicated processes in contemporary cities, and the relationships between the spatial logic of traditional urban models and notions of accessibility are becoming increasingly unclear.

3. COMPLEXITIES OF HUMAN SPATIAL BEHAVIOR

In addition to a number of studies that have found mixed relationships between distance and land uses, property values, rents, or employment levels (e.g., Waddell, Berry, and Hoch 1993), it is increasingly difficult to understand human spatial behavior within contemporary cities in terms of distance as conceived in traditional urban models. Actual commuting distances, for example, strongly suggest that very few people are acting to minimize their journey to work by relocating either their home or workplace in the intraurban context (Hamilton 1982, Small and Song 1992). The relatively minor influence of distance as conceived in traditional urban models on residential location decision making can be largely explained by the fact that homes and workplaces are not simply points in space, but instead are tightly connected within a web of economic and social relations (England 1991; Gilbert 1998; Wachs et al. 1993; Waddell 1993). As a result, residential (and workplace) mobility is far from easy or automatic.

The emphasis of traditional urban models and concepts of accessibility on either home or workplace location is therefore incomplete. Relocating a home or job will likely incur significant social and economic costs, such as the difficulty in selling a home and/or obtaining new housing, losing contact with friends and neighbors, or switching schools, potentially resulting in a high degree of inertia or "spatial fixity" (England 1993). Home locations for many individuals may therefore tend to be fixed regardless of the presence of suitable nearby employment (especially for women) or changes in workplace location (Hanson and Pratt 1995). As a result, "at any given time, a large number of (rational) household and employment locations may in fact be 'suboptimal' with respect to transport cost" (Giuliano 1989, 152). This spatial fixity and a lack of mobility can be important to accessibility, not just because of local variations in mobility or opportunities, but because of the way they influence individuals' knowledge of cities, employment prospects, and attitudes.

The role of distance as conceived in conventional accessibility measures is of declining importance in shaping human spatial behavior in another sense. These measures have conceptualized accessibility largely in terms of the proximity of one's home and/or workplace (whether represented as a zone or a point) to other specified locations. Measuring access to employment or services from these locations, however, assumes that they are the center of an individual's daily activities and the origin of each individual's daily travel. This is not always appropriate as it denies the existence of considerable amounts of multi-stop trips over the course of the day, and a person may spend considerable time away from home or the workplace during the day (Kwan 1998, 1999a). The length of the commute is not simply the distance between home and the workplace because of these multi-purpose trip chains (Kitamura, Nishii, and Goulias 1990; Michelson 1985). By not taking into account the ways in which individuals combine various activities and destinations into a single trip (trip chaining), these conventional accessibility measures may be underestimating an individual's accessibility.

4. THE SPATIAL AND TEMPORAL FRAMEWORKS OF CONVENTIONAL ACCESSIBILITY MEASURES

Traditional urban models and measures of accessibility were formulated at times when modern GIS technology and digital geographic data of the urban environment and human spatial behavior were not available. Such limitations in tools and data had an inevitable influence on the type of models and methods formulated, and on the kind of real-world complexities represented by these models and methods—as how we conceptualize the world and represent places, distances, and time depends heavily on the available conceptual and operational tools. As a result, both the spatial and

temporal frameworks of conventional proximity-based accessibility measures reflect many simplifications to which contemporary analysts no longer need to be restricted (because of the new capabilities of modern GIS technology and digital geographic data; see discussion in Kwan 2000a and Kwan et al. 2003).

4.1. The Spatial Framework of Conventional Measures

Conventional accessibility measures, for example, are often based on a zonal spatial framework as most data used in past studies were area-based (e.g., census tracts or traffic analysis zones). The notion of accessibility operationalized by these measures is therefore more a property of geographical entities such as zones than the experience of households or individuals. Households and individuals possess accessibility only by virtue of living at a particular location, which creates several problems for the use of these measures when evaluating individual accessibility (Pirie 1979). First, the zonal scheme used in a particular study may not correspond to individual perception of urban opportunities in contemporary cities, and accessibility measures based on such a spatial framework cannot capture the complexities arising from the effect of personal idiosyncrasies and individual perception of the geographical and temporal availability of urban opportunities (e.g., Fishman 1990; Kwan and Hong 1998).

Second, conventional zone-based accessibility measures cannot easily take into account certain types of individual differences even when disaggregate versions of these measures are used (although the effect of age, income, or access to different transport modes may be incorporated into disaggregate versions of these measures using individual-level data [e.g., Guy 1983]). This problem was shown in recent studies on the differential impact of space-time constraints on men's and women's spatial mobility and accessibility (e.g., Kwan 1999a, 2000b). These studies revealed that the failure to take into account the effect of individual space-time constraints on women's accessibility has rendered significant gender differences invisible.

Third, any use of zonal data is also subject to the modifiable areal unit problem (MAUP), in which zones of varying sizes and configurations will yield different results or relationships between accessibility and other characteristics. A related issue of the MAUP is to identify the proper scale of analysis, for which several methods exist (Green and Flowerdew 1996; Jones and Duncan 1996). However, even when accessibility has been measured at multiple scales, for example by measuring local access to neighborhood retail and grocery stores separately from regional access to major employment and retail centers (Handy 1992; Handy and Niemeier 1997), there is also no easy way to combine local and regional access into a single measure, or to determine how one may substitute for the other. Lastly, the issue of how to handle self-potential (the accessibility of a zone to itself) is also crucial when implementing gravity-based accessibility measures within a zone-based framework (Pooler 1987).

Fourth, another problem is the issue of representing and specifying the highly complex influence of distance on individual accessibility. A number of choices are possible, such as whether to use linear distance, travel times, or travel costs as a measure of distance, and whether to measure this distance as a straight line or through a transport network. While the representation of distance using Euclidean distance is straightforward, it is also not very accurate for most intraurban applications in which movement is confined to street networks. Further, few studies have considered the multi-modal characteristics of actual travel and trip making (e.g., one needs to walk to the car or to a transit station); while variations of travel speed among various parts of a city, road segments and times of the day are only beginning to be addressed in recent research (e.g., Weber and Kwan 2002).

4.2. The Temporal Framework of Conventional Measures

Time is an integral element of individual accessibility. This refers not only to the amount of time available to individuals for carrying out travel and activities but also to

the scheduling of activities throughout the day (Forer and Huisman 2000). Given that men and women tend to have different time constraints on their activities, as well as a different temporal scheduling of activities throughout the course of the day, the absence of time from conventional measures ignores an important source of accessibility variation (Kwan 1998, 1999a, 1999b).

These measures also ignore the importance of time to mobility due to various types of delays while traveling, traffic congestion, or changes in transit schedules at different hours of the day, which has been significant in recent research (Weber and Kwan 2002, 2003). The varying availability of opportunities throughout the day associated with different patterns of business hours is also not represented. This potentially overestimates mobility and accessibility while ignoring that many opportunities will not be available in the evening. Further, not all opportunities within reach are relevant unless the time one can spend at the activity site exceeds the threshold required for meaningful participation in that activity (Kim and Kwan 2003). Conventional accessibility measures therefore take a static, timeless view of mobility and accessibility, which denies the ways in which behavior, activity patterns, and even population composition varies by time of the day (Goodchild and Janelle 1984; Harvey and Macnab 2000).

5. ICT AND INDIVIDUAL ACCESSIBILITY

The spatial and temporal frameworks of conventional accessibility measures encounter serious limitations when the impact of information and communications technologies (ICTs) on spatial behavior is recognized (Janelle and Hodge 2000). An important transformation that may result from the increasing use of ICT is the relaxation of many space-time constraints that limit human spatial mobility and activity space. For example, as many activities no longer need to be performed at certain places or times (e.g., through e-shopping), more time may become available for undertaking other activities, and more flexible spatial and temporal arrangements of human activities become possible.

Given the importance of space-time constraints in determining individual accessibility, this increase in the flexibility in activity scheduling—for example, conducting e-banking on weekends or in the evening rather than during a very limited span of time during weekdays—is likely to have a significant influence on individual accessibility. But this does not mean that space-time constraints no longer exist. Access to ICTs may be restricted to certain times of the day or week such as while at work or when public libraries are open. Further, the existence of time zones and human sleep patterns means that instantaneous communications can reach only a portion of the world's population at any given time (Harvey and Macnab 2000).

Associated with the relaxation of space-time constraints in individuals' everyday lives are changes in individual activity patterns and hence accessibility. The time people spend using ICTs takes time away from other activities, and there may be distinctive geographical consequences associated with such time displacement, which may be described as the space-time displacement effect of ICTs (Kwan 2002; Lee and Whitley 2002; Robinson et al. 2000). For example, if people spend more time using the Internet, they may spend less time on social activities; and as Internet users purchase goods online, they may spend less time shopping in and making trips to stores in the physical world (as found by Nie and Erbring 2000; UCLA-CCP 2003). Recent studies have also observed a considerable reduction in work-related travel and a contraction of activity space by telecommuters (Henderson and Mokhtarian 1996; Pendyala, Goulias, and Kitamura 1991; Saxena and Mokhtarian 1997).

It seems quite clear, however, that the potential impacts of ICTs on human behavior and individual accessibility are highly complex, with substitution for physical

travel being only one of many possibilities (Gillespie and Richardson 2000; Graham 1998; Kitchin 1998; Mokhtarian and Meenakshisundaram 1999; Warf 2001). It has been asserted that the most important impact of ICT is that "it permits much more flexibility in whether, when, where, and how to travel, and thus loosening the constraint of having to be at a certain place at a certain time" (Mokhtarian 1990, 240). But it is far from clear how traditional urban models and accessibility measures can take the effect of constraint relaxation, space-time displacement, and telesubstitution into account.

Finally, the spatial and temporal frameworks of conventional accessibility measures cannot take into account the additional opportunities accessible to individuals through the use of ICTs. This issue arises because ICTs will give people greater ability to make use of space-adjusting technologies to overcome distance and therefore will increase their extensibility (Black 2001; Janelle 1973, 1995; Kwan 2000c). This means that ICTs will allow them to access information resources and participate in activities at the global scale although their physical activities are largely confined at the local scale. There are many issues, however, concerning how concepts of accessibility in the physical world can be extended to incorporate individual access to the opportunities in cyberspace (or cyberspatial accessibility). For example, what are the meanings of concepts like distance, impedance, attractiveness, or feasible opportunity set for cyberspace, and what space-time framework can be used to represent them (Kwan 2001)? As conventional measures are based on measures of distance in the physical world, they are not able to accommodate the increased accessibility that result from the use of ICTs. These issues are only beginning to be addressed by recent studies (e.g., Dodge 2000; Shen 1999). Further, the traditional temporal scale (hour/minute) is not adequate for studying individual accessibility in cyberspace, as cyberspatial activities may be accomplished within a few seconds.

6. ALTERNATIVE FRAMEWORKS FOR ANALYZING INDIVIDUAL ACCESSIBILITY

We have argued in previous sections that traditional urban models and accessibility measures are inadequate for understanding individual experiences in contemporary cities for various reasons. As the effect of distance is much more complex than before, and as current GIS technologies and digital geographic data allow us to incorporate and model real-world complexities in ways inconceivable before, we are no longer restricted to use traditional models or methods whose conceptual foundation was laid around the mid-twentieth century. In this section, we consider some new possibilities for modeling individual accessibility and their implications for geographical analysis in the twenty-first century. The discussion draws upon our recent research on space-time accessibility measures. While we believe that these measures are viable alternatives that may be used to overcome some limitations of conventional measures, we do not argue that they are the only good alternatives. Other new approaches for dealing with the complexities brought forth by the four recent changes discussed in the paper are also highly desirable.

6.1. Space-Time Accessibility Measures

Space-time accessibility measures are based on the time-geographic framework of Hägerstrand (1970), which conceives individuals' activities and travel as continuous trajectories or paths in three-dimensional space-time. These paths do not exist randomly in space-time but are subject to a range of personal and social constraints, including the limits on mobility resulting from the available transport technology and the biological need for resting time. For example, individuals must be in certain places for certain lengths of time for work or must arrive at or depart businesses by certain times. These times and places constitute "fixed" activities that cannot be ig-

nored or rescheduled and so provide the framework of an individual's daily activities (Burns 1979). Activities that allow for more flexible scheduling, duration, or location must be fit into the time available between successive fixed activities

The mobility allowed by the fixity constraints that an individual faces can be described in the form of a space-time prism—though because of the difficulty of working with a three-dimensional prism, these have commonly been simplified into a two-dimensional projection in geographic space, known as a potential path area, or PPA (Dijst and Vidakovic 2000; Dijst, de Jong, and van Eck 2002; Lenntorp 1976, 1978). A potential path area is the geographic area that can be reached within the space-time constraints established by an individual's fixed activities. It is the area that an individual can physically reach after one fixed activity ends while still arriving in time for the next fixed activity. Each individual will create their own PPAs through their daily activities.

The approach offered by space-time measures—coupled with the geocomputational ability of GIS, the technology for massively parallel computing and individual-level activity-travel data—has potential for overcoming many limitations of conventional analytical frameworks. This is not just because the use of GIS may greatly enhance our ability to represent real-world complexities or allow for ever larger data sets. Rather, with GIS and increasingly available disaggregate data, highly refined space-time measures of individual accessibility can be operationalized, and the conceptualization and modeling framework are no longer conditioned by a priori schema of areal units or spatial frames. Concepts of space-time accessibility based on individual-level data have been widely implemented within vector and raster GIS (Forer and Huisman 2000; Kim and Kwan 2003; Kwan 1998, 1999a; Miller 1999; O'-Sullivan, Morrison, and Shearer 2000; Weber 2001, 2003; Weber and Kwan 2002, 2003), creating a resurgence of interest in these concepts. Several examples are provided below to illustrate the advantages of using space-time measures for evaluating individual accessibility in contemporary cities.

6.2. Sensitivity to Individual Differences

Perhaps the clearest example of the issues faced by conventional concepts and measures of accessibility can be seen by directly comparing the results produced by conventional and space-time measures within a contemporary U.S. city and examining their ability to identify important factors that influence individual accessibility. One such study examined access to commercial, educational, and recreational land uses for a sample of 39 men and 48 women in Columbus, Ohio (Kwan 1998). In the study, 20 conventional measures of the gravity and cumulative opportunity variants were evaluated using the home locations of the 87 individuals as origins and 10,727 property parcels representing destinations. Distances were computed using point-to-point travel times through a digital street network with 47,194 arcs and 36,343 nodes.

Three space-time measures were also computed for each individual using a geocomputational algorithm implemented in ARC/INFO GIS. Instead of providing different representations of the importance of distance for accessibility, these three measures evaluate the size of the space that can be reached, the number of opportunities that can be reached, and the size or attractiveness of those opportunities. The results of the study reveal the contrast between conventional and space-time measures. While the values produced by most gravity and cumulative opportunity measures were highly correlated and produced similar spatial patterns, space-time measures were very different.

Gravity measures tended to replicate the geographical patterns of urban opportunities in the study area by favoring areas near major freeway interchanges and commercial developments, while cumulative opportunity measures emphasized centrality within the city by showing the downtown area to be the most accessible place. In con-

trast, space-time measures produced different spatial patterns, and the patterns for men resembled the spatial distribution of opportunities in the study area while the women's patterns were considerably different. These gender differences, however, were invisible when using conventional accessibility measures, showing the ability of space-time measures to capture certain types of differences among individuals (e.g., the effect of space-time constraints on individual accessibility).

6.3. Temporal Representation of the Urban Environment

Recent research on space-time measures has also shown that facility opening hours and variable travel speeds at different times of the day and parts of the city are important to individual accessibility. Weber and Kwan (2002) examine the effect of travel time variations and facility opening hours on individual accessibility using a range of data. These include data of 101 men and 99 women from an activity-travel diary data set of Portland, Oregon; a digital street network with estimates of free flow and congested travel times (with 130,141 arcs and 104,048 nodes); and a comprehensive geographic database of the study area. This digital geographic database, containing 27,749 commercial and industrial land parcels, was used to represent potential activity opportunities in 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. The algorithm was developed and implemented using Avenue, the object-oriented scripting language in the ArcView 3.x GIS environment. Five space-time accessibility measures were computed. The first is the length of the road segments contained within the daily potential path area (DPPA). The second is the number of opportunities within the DPPA. The total area and total weighted area (to reflect the importance of major employment centers) of the land parcels within the DPPA were the third and fourth space-time accessibility measures computed. 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 A.M. to 6:00 P.M. This creates a fifth accessibility measure.

The results show that link-specific travel times produce very uneven accessibility patterns, with access to services and employment varying considerably within the study area. The time of day that activities were carried out also has had an effect on accessibility, as evening congestion sharply reduced individual's access throughout the city. The effect of this congestion on mobility is highly spatially uneven. Further, the use of business hours to limit access to opportunities at certain times of the day shows that non-temporally restricted accessibility measures produce inflated values by treating these opportunities as being available at all times of the day. It is not just that incorporating time reduces accessibility, but that it also produces a very different, and perhaps unexpected, geography of accessibility (Weber and Kwan 2002). This geography depends much on individual behavior and so cannot be discerned from the location of opportunities or congestion alone. The study observed that the role of distance in predicting accessibility variations within cities is quite limited.

6.4. Scale and Frame Independence

While aggregate measures must contend with the MAUP due to their reliance on zones represented at particular scales, recent work with space-time measures suggests that accessibility is actually frameless; variations have little or no relationship with common spatial zones or distinct geographic scales. Evidence for the scale independence of space-time measures was discussed in Weber (2001) and Weber and Kwan (2003), in which multilevel modeling with individual-level data was used to ex-

amine the effect of geographical scale and zonal scheme on accessibility variations over the study area (Portland, Oregon). Three zonal schemes were used. In the first scheme, individuals were grouped according to residence within the cities of the study area. The second grouped individuals according to location within the school districts of the study area. In the last zonal scheme, individuals were grouped within the commutershed of the closest regional center or the CBD. The study shows that there are no substantial accessibility variations among discrete zones or at different scales within the study areas. It shows that the spatial configuration of zones would likely play a small part, if any, in MAUP issues. Selecting different neighborhood boundaries would therefore be unlikely to affect the parameter estimates or model fit.

In summary, space-time measures of individual accessibility have a number of advantages when compared to conventional measures. Accessibility is an attribute of individuals, who create it through their daily activities and movements. Time, space, and individual activity patterns are integral elements of these measures. They can also incorporate certain interpersonal differences that cannot be captured by conventional measures, even among those living in the same household. Space-time measures are built upon a conceptual foundation that corresponds more closely with theoretical expectations about urban form and human spatial behavior in contemporary cities. Rather than being proximity-based, they can be thought of as context-based measures that incorporate both the individual's own activities and constraints as well as characteristics of the individual's urban environment. Further, space-time measures may be adapted to take into account of individual access to opportunities in cyberspace (Kwan 2001). They also appear to be independent of the spatial scale or 'frames' used, and this framelessness suggests that the MAUP need not be a problem for accessibility analysis (Weber and Kwan 2003).

7. CONCLUSIONS

In this paper we suggest that the methods and measures formulated around the mid-twentieth century are becoming increasingly inadequate for grappling with the complex relationships among urban form, mobility, and individual accessibility. Distance, as the foundational construct of spatial analysis, is playing a declining but much more complex role in shaping contemporary cities and human behavior. We therefore argue for the need to go beyond conventional spatial and temporal frameworks and to rethink how we approach conceptualizing and evaluating individual accessibility. We call for approaches that are sensitive to the complexities of urban form and differences among individuals across multiple axes. Space-time accessibility measures are discussed as alternative methods that, to a considerable extent, overcome many limitations of the conceptual foundation and spatial and temporal frameworks of traditional models.

This examination of past studies on individual accessibility represents a challenge to many accepted notions and methods in geographical analysis. It is apparent that there is an urgent need not only to recognize the new opportunities offered by modern GIS technologies and digital geographic data, but also to recognize that we are no longer restricted to traditional models or methods whose conceptual foundation was established around the mid-twentieth century. GIS not only allows us to incorporate and model real-world complexities in ways inconceivable before, it also allows us to go beyond the simplifications necessitated by the use of conventional urban models and proximity-based accessibility measures. Consider the capabilities of GIS to model accessibility using the temporal attributes of more than 130,000 links of the transport network of a city (Weber and Kwan 2002), to take into account the internal structure of a building when considering human mobility (Church and Marston 2003), to visualize over 400,000 land parcels (Kwan 2000d) or GPS data with 800,000

space-time points (Kwan and Lee 2003) in a three-dimensional vector GIS environment. Recent research is just beginning to explore new representational possibilities like these. But how to materialize this potential and establish a new conceptual foundation for geographical analysis remains one of the most serious challenges for geographical analysis in the twenty-first century.

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