Mei-Po Kwan

Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework

Conventional integral measures of accessibility, although valuable as indicators of place accessibility, have several limitations when used to evaluate individual accessibility. Two alternatives for overcoming some of the difficulties involved are explored in this study. One is to adapt these measures for evaluating individual accessibility using a disaggregate, nonzonal approach. The other is to develop different types of measures based on an alternative conceptual framework. To pursue the former alternative, this study specifies and examines eighteen gravity-type and cumulative-opportunity accessibility measures using a point-based spatial framework. For the latter option, twelve space-time accessibility measures are developed based on the construct of a prism-constrained feasible opportunity set. This paper compares the relationships and spatial patterns of these thirty measures using network-based GIS procedures. Travel diary data collected in Columbus, Ohio, and a digital data set of 10,727 selected land parcels are used for all computation. Results of this study indicate that space-time and integral indices are distinctive types of accessibility measures which reflect different dimensions of the accessibility experience of individuals. Since space-time measures are more capable of capturing interpersonal differences, especially the effect of space-time constraints, they are more "gender sensitive" and helpful for unraveling gender/ethnic differences in accessibility. An important methodological implication is that whether accessibility is observed to be important or different between individuals depends heavily on whether the measure used is capable of revealing the kind of differences the analyst intends to observe.

1. INTRODUCTION

Accessibility has not only been an important explanatory factor in a multitude of geographic phenomena (for example, Huff 1964; Lakshmanan and Hansen

The support of NSF grant no. SBR-9529780 and a grant from the Urban Affairs Committee of the Ohio State University for this research is gratefully acknowledged. The author is also grateful for NSF grant no. 9512451 which enabled the acquisition of the SGI Power Challenge server used for the computation in part of this study. Thanks also to three anonymous reviewers for their helpful comments and suggestions.

Mei-Po Kwan is assistant professor of geography at the Ohio State University.

Geographical Analysis, Vol. 30, No. 3 (July 1998) Ohio State University Press
Submitted: 10/9/97. Revised version accepted: 1/7/98.

1965; Harris 1954; Stegman 1969; Stone 1973), it has also been applied in the past for various analytical and evaluative purposes. Accessibility measures have been used to evaluate the performance of transportation systems and access to employment opportunities and other facilities for different social groups (Allen, Liu, and Singer 1993; Davidson 1977; Dodgson 1974; Ewing, Haliyr, and Page 1994; Ihlanfeldt and Raper 1990; Handy 1993; Linneker and Spence 1992a,b; McLafferty 1982). Yet when the concept of accessibility was applied in past studies, it was often defined and operationalized in different ways depending on the problem and context of its application (Handy and Niemeier 1997; Ingram 1971; Morris, Dumble, and Wigan 1979). For instance, accessibility can be an attribute of locations indicating how easily certain places can be reached (Dalvi and Martin 1976; Song 1996), while in other cases it is a property of people revealing how easily an individual can reach activity locations (Guy 1983; Hanson and Schwab 1987).[1] Besides this distinction between place and individual accessibility, accessibility measures can also be differentiated in terms of their complexity, from simple measures that express either the presence of physical connections or the degree of physical separation between two locations (for example, Muraco 1972; Taaffe, Gauthier, and O'Kelly 1996), to more comprehensive ones where accessibility is determined by both the urban environment and the person-specific space-time autonomy of individuals (for example, Burns 1979; Miller 1991; Villoria 1989).

As differential access to urban opportunities for individuals of various gender/ethnic subgroups has been an important concern in recent research (for example, Hanson and Pratt 1990, 1995; Ihlanfeldt 1993; McLafferty and Preston 1992, 1996; Wyly 1996), accessibility measures that can help unravel the person-specific experience of individuals and its particular sociospatial context are sorely needed. Although most conventional accessibility indices such as gravity-type and cumulative-opportunity measures are valuable as indicators of place accessibility, there are several difficulties when they are used to evaluate personal accessibility. First, they ascribe the same level of accessibility to different individuals in the same zone even though what these individuals experienced may suggest otherwise (Pirie 1979). Second, as these conventional indices are integral measures which evaluate accessibility based on a single reference location such as the home, they ignore the fact that many trips that contribute to individual accessibility are made in the context of the sequential unfolding of a person's daily activity program (Hanson 1980a,b; Richardson and Young 1982).[2] Third, these measures do not take into account the effect of spatio-temporal constraints that may render many opportunities in the urban environment unreachable by an individual (Burnett 1980; Landau, Prashker, and Alpern 1982).

Although similar concerns have been raised in the context of evaluating gender differences in the access to urban opportunities (Pickup 1985), few studies have examined the methodological implications of using these integral measures for the analysis of individual accessibility. In those studies where individual-level data were used to implement person-specific formulations of these

[1] This distinction between place (or physical) and individual (or personal) accessibility, although seldom elaborated in the literature, is especially important for identifying the valid research questions for a particular study. See Hanson (1995) and Pirie (1979) for helpful discussion on these two concepts of accessibility and the methodological problems involved.

[2] The distinction between relative and integral accessibility measures was first made by Ingram (1971). Relative accessibility measures describe the degree of connection between two points, while integral accessibility indices express the degree of interconnection between a particular reference location (for example, home) and all others in the study area.

measures (for example, Guy 1983; Hanson and Schwab 1987), the primary objective was not to evaluate the suitability of these indices for representing personal accessibility. As a result, very little is known to date about what kind of interpersonal differences these indices are capable of capturing, and what kind are less likely to be uncovered. Further, although there are some comparative studies on aggregate integral measures of place accessibility in recent years (for example, Linneker and Spence 1992a; Song 1996), few studies have examined how the use of a particular formulation or parameter may affect results of the analysis when integral measures are applied to the study of individual accessibility.

In view of the difficulties and limited knowledge discussed above, this study takes two distinctive directions to examine the methodological issues pertaining to the measurement of individual accessibility. On one hand, two types of conventional integral accessibility measures are adapted for the evaluation of individual accessibility using a point-based spatial framework. With this disaggregate, nonzonal approach, as used in Guy (1983) and Hanson and Schwab (1987), the unit of analysis is the individual and all locations are represented as distinctive points in space. The spatial patterns of accessibility generated by these point-based integral measures can then be compared with each other for examining the effect of different formulations and parameters. However, unlike the two earlier studies, which used Euclidean distance to evaluate accessibility, impedance between two locations is computed in this study using network travel time and GIS operations on a detailed digital street network.

Another direction taken by this study is to explore other alternative measures of individual accessibility and to compare results obtained from using these alternatives with those generated by integral measures. As several studies in the past have showed, prism-constrained space-time measures of accessibility based upon the time-geographic perspective have the advantage of avoiding some of the inherent difficulties of integral measures such as the ignorance of individual activity sequence and space-time constraints (Lenntorp 1976; Burns 1979). Further, since no study has examined whether the results obtained from using space-time measures are similar to those obtained from using conventional integral measures, a comparative analysis of these two types of measures would enhance our understanding of their suitability as measures of individual accessibility. Despite some past attempts (for example, Miller 1991; Villoria 1989), operationalization of space-time measures still faces many difficulties, including the detailed individual activity-travel data needed, their computational intensity, and the lack of feasible operational algorithms. To overcome these difficulties, this study provides a formulation of the space-time prism from which three types of operational space-time accessibility measures are derived using a GIS algorithm modified after the one developed by Kwan and Hong (1998).

After all the measures are operationalized and enumerated, the relationships between conventional integral measures and space-time measures of individual accessibility are examined. Comparison of these two types of indices will help clarify many important methodological and conceptual issues pertaining to the measurement of personal accessibility. For instance, in what ways are the accessibility patterns of these measures similar or different? Can different types of measures with distinctive characteristics be identified based on these patterns of similarities and differences? Further, if results from using space-time measures are similar to those from using integral measures, the extra effort involved in operationalizing the complex space-time measures may be avoided in future research. However, if significant differences exist between the accessibility patterns produced by these two types of measures, identifying the nature of these differences and the kind of variations they capture becomes an important methodological concern. Results from the above analysis perhaps may allow us to answer one important question, "To what extent can integral and space-time measures uncover interpersonal differences in the accessibility experienced by individuals in their everyday lives?" This question is especially pertinent to recent debates on the importance and role of accessibility in various substantive areas (for example, gender/ethnic differences in the access to jobs or other opportunities in a particular locale).

Various operational forms of space-time measures and two types of integral accessibility indices, namely, gravity-type and cumulative-opportunity measures, are specified for this comparative analysis.[3] Overall, a total of thirty measures are compared using a travel diary data set collected in Columbus, Ohio. These indices are enumerated for fifty-two household locations and the eighty-seven individuals of these households with respect to 10,727 selected land-use parcels in the study area.

2. INTEGRAL AND SPACE-TIME ACCESSIBILITY MEASURES

Accessibility measures in general use the impedance effect of distance, time, or generalized transport costs and the spatial distribution of urban opportunities to produce numerical indices of accessibility for each location in a study area. As the most commonly used accessibility measures, both gravity-type (GRAV) and cumulative-opportunity (CUM) indices of accessibility are integral measures.

Gravity-type (GRAV) accessibility indices, introduced by Hansen (1959), are derived by weighing the opportunities in an area by a measure of attraction and discounting each opportunity by a measure of impedance (for example, Geertman and Ritsema van Eck 1995; Handy 1993; Knox 1978; Wyatt 1997). Depending on the problem at hand, various measures of attraction such as total retail floor space or the number of households have been used. The impedance function, on the other hand, was sometimes based on a composite formulation of the generalized transport costs (for example, Gutierrez and Gonzalez 1995; Linneker and Spence 1992b). More often, a relatively simple inverse power function $d_{ij}^{-\alpha}$ or a negative exponential function $\exp(-\beta d_{ij})$ of distance or travel time (d_{ij}) is used as the main variable in the impedance function. Ingram (1971) showed that both of these forms tend to decay too rapidly close to the origin in comparison with empirical evidence. He suggested that a modified Gaussian function $\exp(-d_{ij}^2/v)$ is superior since it has the advantage of having a slow rate of decline close to the origin, and declines not as rapidly as the negative exponential and inverse power functions toward zero at a greater distance.

Cumulative-opportunity (CUM) measures, also called isochronic indices, evaluate accessibility in terms of the number or proportion of opportunities that can be reached within specified travel distances or times from a reference location (Black, Kuranami, and Rimmer 1982; Breheny 1978; Hanson and Schwab 1987; Oberg 1976; Sherman, Barber, and Kondo 1974). Wachs and

[3] These three types of accessibility indices are selected based on three criteria: (a) They take into account the effect of both the transportation network and spatial distribution of opportunities. (b) They do not require the derivation of additional theoretical constructs like the utility function and therefore the operationalization tasks of the study are simplified. (c) They do not merely focus on accessibility to infrastructural facilities such as hospitals or fire stations, but are generally applicable to the problem of access to various urban opportunities. Accessibility measures not examined in this study include utility-based measures (for example, Ben-Akiva and Lerman 1979; Burns and Golob 1976; Koenig 1980; Richardson and Young 1982; Williams 1976); graph-theoretic measures (for example, Baxter and Lenzi 1975; Kirby 1976; Muraco 1972); and location-allocation approach to accessibility (for example, Bach 1980, 1981; Oppong and Hodgson 1994; Rushton 1984, 1988; Walsh, Gesler, Page, and Crawford 1995).

Kumagai (1973) constructed a CUM index for measuring the access to jobs. Since more distant opportunities are given equal weights as the closer ones, the value of this index increases steadily with increase in the travel time limit. This undesirable characteristic due to the lack of "spatial discounting" was noted and modified in later formulations. For example, Black and Conroy (1977) developed a CUM index that measures the area under the curve of the cumulative distribution of opportunities reached within a specified travel time from the origin. As distance decay is modeled by a negative linear impedance function, their index takes into account the spatial distribution of opportunities in a study area. A main difficulty remains for all CUM measures in their arbitrary selection of isochrone increments and the travel time limit (Ben-Akiva and Lerman 1979; Handy and Niemeier 1997; Pirie 1979).

As integral measures, both GRAV and CUM measures are useful for comparing accessibility between different locations or zones. The use of impedance functions that incorporate a distance decay effect into these indices also makes them congenial to observed travel behavior and individual perception of the attractiveness of urban opportunities (Fotheringham 1981; Wilson 1971). However, as these measures were operationalized in most cases using aggregate data and zone-based methods, concerns about the modifiable areal unit problem and ecological fallacy have been raised. For instance, sensitivity of zonal GRAV measures to zone sizes, zonal configuration, and aggregation has been observed (Dalvi and Martin 1976; Davidson 1977). The measurement of inter- or intrazonal distance is also prone to problems (Geertman and Ritsema van Eck 1995). The assumptions that all parts of each zone have the same accessibility as the zone centroid and that all individuals in a zone have the same level of accessibility were criticized (Hanson and Schwab 1987; Linneker and Spence 1992b). Even at a local scale where the zone area is small, significant variation in individual accessibility around the mean zonal accessibility was found (Handy and Niemeier 1997). Accessibility measured at this scale also hides differences in the composition and nature of local opportunities that bear upon the accessibility experience of individuals. Overall, as zonal accessibility measures ascribe the same level of accessibility to people in the same zone, they reveal only aggregate place accessibility and are therefore not suitable for evaluating individual accessibility (Pirie 1979).

In response to these characteristics of zonal integral measures, researchers have attempted various methods for adapting them for the evaluation of individual accessibility. Disaggregation has been one of the most often pursued alternatives. It takes the form of computing accessibility separately for different trip purposes, transport modes, age, gender, income, and occupational groups, and activity types such as work or shopping (Ben-Akiva and Lerman 1979; Dalvi and Martin 1976; Handy and Niemeier 1997; Wachs and Kumagai 1973). Another alternative is to use nonzonal methods for deriving integral accessibility indices. For example, Guy (1983) derived GRAV and CUM measures using point locations of households and retail shops and measured distance on a point-to-point basis, whereas Hanson and Schwab (1987) used geocoded point-locations of homes and shops to compute CUM indices for individuals. Part of this study pursues this latter direction where integral measures were derived using a point-based spatial framework.

However, since integral measures evaluate accessibility based on a single reference location such as the home location or the workplace, two particular difficulties cannot be overcome by disaggregation or a point-based method. On one hand, their implicit assumption that all travel that contributes to individual accessibility is based on a single origin is problematic (Hanson 1980a,b). This is especially true for multipurpose, multistop nonwork trips, where some destinations may contribute very little to accessibility when the home or the workplace is used as the origin but may in reality be quite accessible in relation to other stops in a linked trip chain (O'Kelly and Miller 1984). Richardson and Young (1982) showed that accessibility measures that ignore trip linking or trip chaining may considerably underestimate the accessibility to activities of noncentral urban locations. Further, integral measures also overlook the important impact of spatio-temporal constraints since many opportunities in the urban environment may be out of reach for an individual because of them (Burnett 1980; Kwan and Hong 1998). The ignorance of individual activity sequence and space-time constraints points to the need for alternative measures of individual accessibility which avoid the inherent difficulties of integral measures. With respect to this, space-time measures of accessibility are attractive alternatives.

Unlike integral accessibility measures which are based on the concept of geographical proximity to a single reference location, space-time (ST) measures evaluate accessibility in terms of an individual's ability to reach activity locations given the person's daily activity program and spatio-temporal constraints (Landau, Prashkar, and Alpern 1982). All space-time (ST) measures were developed based upon Hägerstrand's (1970) time-geographic framework. For instance, Lenntorp (1976) used the volume of the space-time prism (or potential path space, PPS) and the area of its projection on planar space (potential path area, PPA) as measures of accessibility. Alternatively, Burns (1979) derived two accessibility measures in terms of the space-time autonomy of individuals using the prism construct. A significant aspect of Burns' (1979) work is the incorporation of the effect of transport network geometry, nonuniform travel speed and multiple travel modes into measures of individual accessibility. Villoria (1989) provides another formulation of individual accessibility using the volume of the space-time prism. Miller (1991) developed an operational method for implementing the space-time prism using GIS procedures.

Overall, ST measures express personal accessibility in terms of the space-time feasibility of opportunities to an individual using the volume of PPS, area of PPA, or number of opportunities in PPA as indicators. They are person-specific measures that provide a framework for incorporating the spatial configuration of the transportation system, spatial distribution of urban opportunities, and individual spatio-temporal constraints into a single measure of accessibility. Since they are not based on a single origin but take into account the sequence of activity, the effect of complex travel behavior such as multistop, multipurpose trips can be expressed by this type of measure. Yet, operationalization of ST measures is particularly difficult due to their computational intensity and the lack of feasible operational algorithms for handling the complexity of real-world transportation networks. Earlier studies that developed various formulations of the space-time prism, from which ST accessibility measures were derived, did not actually implement the prism construct in an operational sense (for example, Burns 1979; Hägerstrand 1970; Lenntorp 1976). Later studies that computed ST measures often used geometric methods to reduce the complexity and computational demand of the problem (for example, Nishii and Kondo 1992; Villoria 1989), where the solution may not be satisfactory. For instance, as shown in Kwan and Hong (1998), the volume of the space-time prism derived through geometric methods may not bear direct relationship to the number of opportunities accessible to an individual due to the spatial distribution of urban opportunities. To overcome some of the operational difficulties, this study provides formulations of ST measures based on the concept of the feasible opportunity set and implements them using network-based GIS procedures. Accessibility patterns generated by these ST measures are then compared with those generated by integral measures.

3. THE STUDY AREA AND DATA COLLECTION

The study area for this paper is Franklin County, Ohio, which is at the center of the seven-county Columbus Metropolitan Statistical Area (MSA). Its main urban area consists of the city of Columbus and fourteen other smaller cities. The county is 542 square miles in area and has a projected population of 1,006,990 in 1995 (City of Columbus 1993).[4] Data for this study come from three main sources. The first source is a travel diary data set collected by the author through a mail survey in the study area in November 1995. In addition to questions about the activity-travel characteristics of the respondent, two specific items used in this study are street addresses of all activity locations and the subjective spatial and temporal fixity ratings of all out-of-home activities (that is, the difficulty in changing the location or time of an activity). The method and questions used to obtain information on fixity of activities are based on Cullen, Godson, and Major (1972) [see Kwan (1998a) for details]. A total of fifty-two family households including eighty-seven adults from the sample are selected on the basis that both male and female adults of the household normally use their own cars as the mode of travel. The reason for restricting travel mode to private vehicle is that the number of individuals in the sample who do not have such access is small (which makes a separate analysis for the subgroup impossible). This filtering also sharpens the comparative focus of the study since differences in individual accessibility between the male and female adults of the same household are no longer due to differences in travel mobility. The selected households are in general spatially scattered throughout the study area in a random pattern.

The second source of data is a digital geographic database of Franklin County collected and maintained by the Franklin County Auditor's Office. It provides detailed information about all land parcels, their attributes, and other features of the county. Since geographic information in this database is in ARC/INFO Library format where data are stored in 696 different digital map sheets, a polygon coverage of all nonresidential parcels was first extracted using ARC/INFO Librarian procedures. Among the 34,442 nonresidential parcels extracted, 10,727 parcels belonging to seven land-use categories are selected as the urban opportunities for this study. These land-use types include various kinds of shopping and retail facilities, restaurants, personal-business establishments such as banks, entertainment, outdoor activities, educational institutions (except higher education), and office buildings. Since the average area of these parcels is 0.00379 square mile, they can be treated as point entities given the spatial

[4] A concern for such a bounded study area is the problem of edge effects that may seriously distort values of accessibility indices evaluated at locations close to the county boundary. In response to this concern, some characteristics of the spatial distribution of opportunities in the Columbus MSA may suggest that edge effects are not likely to be a serious problem in this study. First, the study area contains a substantial proportion of the population and economic activities of the entire MSA (both over 80 percent), whereas the small proportion left is located in the remaining six counties of the MSA (City of Columbus 1993). Further, important concentrations of commercial development outside the county are found in locations quite distant from the Columbus core area (for example, both Newark and Lancaster are more than thirty miles away). In other words, the number of urban opportunities located in areas near but outside the county boundary is not significant. There seems to be a spatial discontinuity in commercial development in the MSA roughly marked by the county boundary. In view of this, edge effects are not likely to constitute a significant source of distortions for the accessibility measures computed in this study.

scale of the study area. A point coverage of the centroids of these parcels was generated for later analysis. For the calculation of accessibility indices, a weighted area that equals the parcel area multiplied by a building-height factor is computed for each parcel to represent quantitatively the opportunities in a particular parcel.[5]

The third data source is a detailed digital street network of Franklin County, Dynamap/2000, provided by Geographic Data Technology, Inc. (GDT). The network database contains 47,194 arcs and 36,343 nodes of Columbus streets and comes with comprehensive address ranges for geocoding locations. Activity locations collected in the travel diary survey are geocoded on this street network using ArcView GIS. All point-to-point distances are measured in terms of travel time in minutes on this network. Travel time between two locations is the time taken to traverse the shortest path between them.[6]

4. SPECIFICATIONS OF THE ACCESSIBILITY MEASURES

Three types of accessibility measures are evaluated in this study: gravity-type, cumulative-opportunity, and space-time measures. A total of thirty measures are specified by combining different formulations, impedance functions, and parameters.

4.1 Gravity-Type Accessibility Measures

The first type of index consists of twelve gravity-type (GRAV) measures whose specifications are given in Table 1. Three impedance functions used are the inverse power (POW), negative exponential (EXP), and the modified Gaussian functions (GAUSS). Ideally, their parameters should be generated in the calibration stage of trip generation models based on observed travel behavior in the study area (assuming that estimates generated by zone-based method can be applied to point-based studies) (Fotheringham and O'Kelly 1989). In the absence of such estimates, four parameters are set for each impedance function after examining the changes in its rate of decline and the point where the function approaches zero. These parameters, as shown in Figure 1(a) to 1(c), produce a value of 0.1 for the impedance function at about 5, 10, 15, and 20 minutes of travel time from the origin. The power function is an exception where the parameters producing a value of 0.1 at 15 and 20 minutes for the function are so close that only one of them (0.8) is used. Instead, 2.0 was

[5] This building-height factor is set to one except that (a) a value of 0.5 is assigned to multistory retail structures where nonretail functions such as storage occupy upper stories; (b) a value of 2 is assigned to walk-up commercial buildings with three or more stories; and (c) elevator commercial buildings with three or more stories (4 for nondowntown locations and 10 for downtown locations). This rather arbitrary scheme was necessitated by the lack of other parcel-based information such as employment or retail floor space in the database which may better reflect the amount of opportunities in a particular parcel.

[6] To simplify computation, the seven road classes in the digital street network are reclassified into three categories and arc impedance is assigned as follows: (a) 55 miles per hour for controlled access freeways; (b) 25 miles per hour for state highways and municipal arterials without access control; and (c) 15 miles per hour for other city streets. The travel time so obtained is further adjusted upward 25 percent to take into account delays at traffic lights and turns. Visualization of the results from a series of travel time calculations and arc allocation runs confirmed that this scenario generates a realistic travel environment for the study area without introducing additional data structure such as turn impedance, which may substantially increase the computational overhead of the GIS procedures. Further, although time-dependent travel speed and the effect of localized congestion can be incorporated into the GIS database, involving these data in the calculation of space-time measures would not only complicate the task of algorithm development at this stage of the research, it would also increase the computational intensity of the algorithm.

TABLE 1
Specifications of the Thirty Accessibility Measures

Types of Measure and Impedance Function	Name of Measure	Parameter
1. Gravity-type, inverse power $\Sigma W_j d_{ij}^{-\alpha}$	*POW0.8*	$\alpha = 0.8$
	POW1.0	$\alpha = 1.0$
	POW1.5	$\alpha = 1.5$
	POW2.0	$\alpha = 2.0$
Gravity-type, exponential $\Sigma W_j e^{-\beta d_{ij}}$	*EXP0.12*	$\beta = 0.12$
	EXP0.15	$\beta = 0.15$
	EXP0.22	$\beta = 0.22$
	EXP0.45	$\beta = 0.45$
Gravity-type, Gaussian $\Sigma W_j e^{-d_{ij}^2/\nu}$	*GAUSS10*	$\nu = 10$
	GAUSS40	$\nu = 40$
	GAUSS100	$\nu = 100$
	GAUSS180	$\nu = 180$
2. Cumulative-opportunity, rectangular $\Sigma W_j f(d_{ij})$	*CUMR20*	$T = 20$
$f(d_{ij}) = \begin{cases} 1 & \text{for } d_{ij} \leq T \\ 0 & \text{otherwise} \end{cases}$	*CUMR30*	$T = 30$
	CUMR40	$T = 40$
Cumulative-opportunity, negative linear $\Sigma W_j f(d_{ij})$	*CUML20*	$T = 20$
$f(d_{ij}) = \begin{cases} (1 - t/T) & \text{for } d_{ij} \leq T \\ 0 & \text{otherwise} \end{cases}$	*CUML30*	$T = 30$
	CUML40	$T = 40$

3. Space-time (see main text for derivation),	(a) Length of network arcs	(b) Number of opportunities	(c) Weighted area
Male high:	*MHLEN*	*MHNO*	*MHWA*
Male low:	*MLLEN*	*MLNO*	*MLWA*
Female high:	*FHLEN*	*FHNO*	*FHWA*
Female low:	*FLLEN*	*FLNO*	*FLWA*

NOTE: W_j is the weighted area of location j, d_{ij} is the travel time in minutes between location i and j, and the summations are for all j from a single-origin i.

added as a parameter to preserve the range of variation for the power function. Specifying parameters in this way is preferable to arbitrary assignment as done in past studies (Geertman and Ritsema van Eck 1995; Wyatt 1997) since impedance functions with arbitrary values may fall too sharply and may produce extreme accessibility patterns that are unlikely to be realistic [for example, a power function with $\alpha = 2.5$ as shown in Guy (1983)].

4.2 Cumulative-Opportunity Accessibility Measures

The second type of accessibility index consists of six cumulative-opportunity (CUM) measures, each of which enumerates a weighted sum of urban opportunities within reach in 20, 30, and 40 minutes of travel time, designated as T, from the reference location (Table 1). Two different impedance functions are specified: (a) the rectangular function used by Wachs and Kumagai (1973) which gives the same weight to opportunities independent of distance from the origin, and (b) the negative linear function derived by Black and Conroy (1977) where opportunities are weighted linearly by the distance from the reference location. Accessibility measures derived with the rectangular function are designated as CUMR, whereas those derived with the negative linear function are designated as CUML. Figure 1(d) gives a comparative portrayal of some impedance functions already specified.

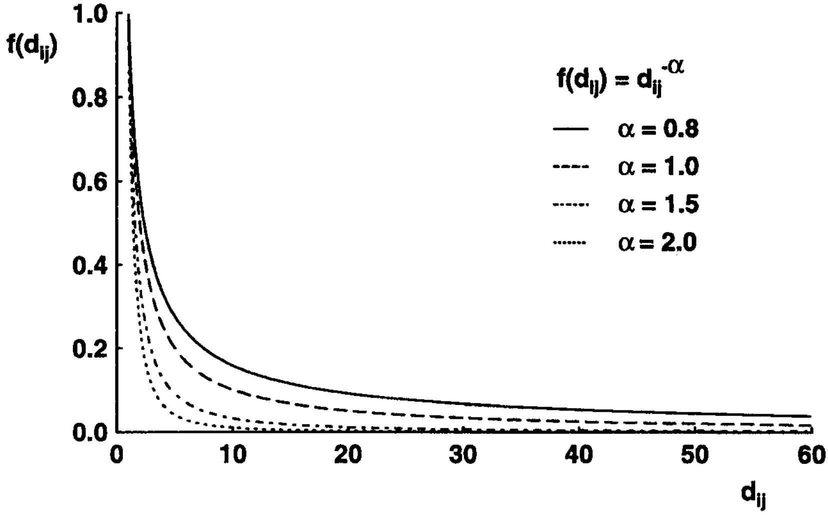

FIG. 1a. Impedance Functions for the Gravity-Type and Cumulative-Opportunity Accessibility Measures: Power Function

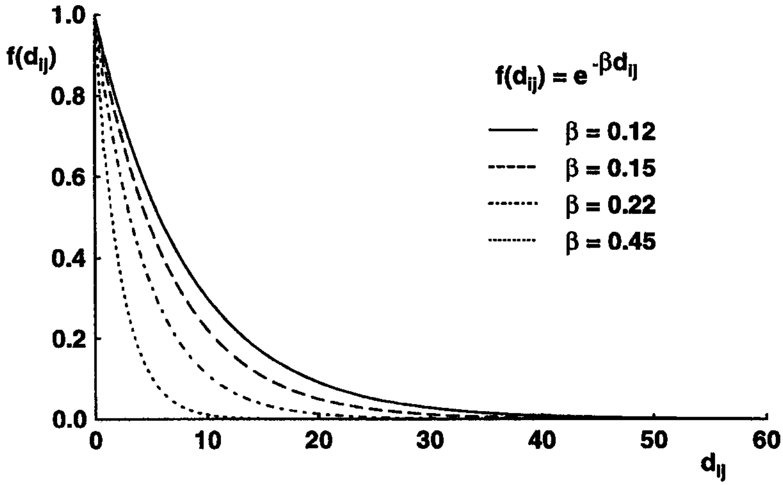

FIG. 1b. Impedance Functions for the Gravity-Type and Cumulative-Opportunity Accessibility Measures: Exponential Function

4.3 Space-Time Accessibility Measures

The third kind of accessibility index consists of twelve space-time (ST) measures, which include three types of indicators derived from individual daily potential path area (PPA).[7] Based on the formulations of the space-time prism by Burns (1979) and its extension by Kwan and Hong (1998), the derivation of

[7] See Miller (1991) for an excellent exposition of the time-geographic terminology, such as potential path area (PPA) or potential path space (PPS), used in this section.

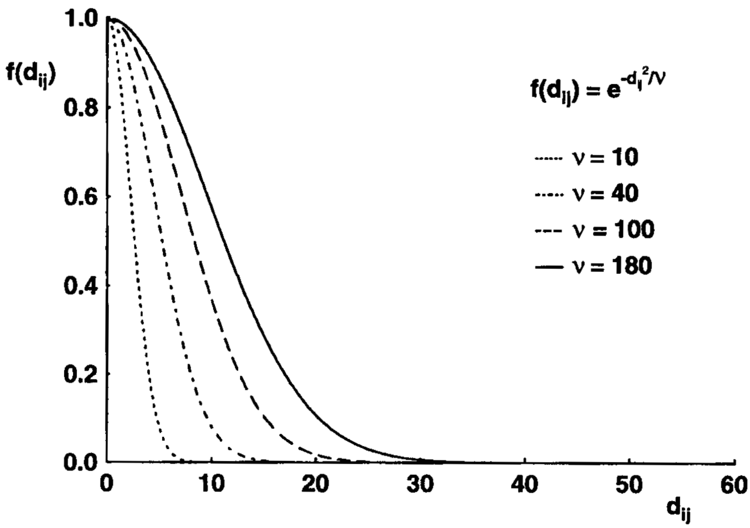

FIG. 1c. Impedance Functions for the Gravity-Type and Cumulative-Opportunity Accessibility Measures: Gaussian Function

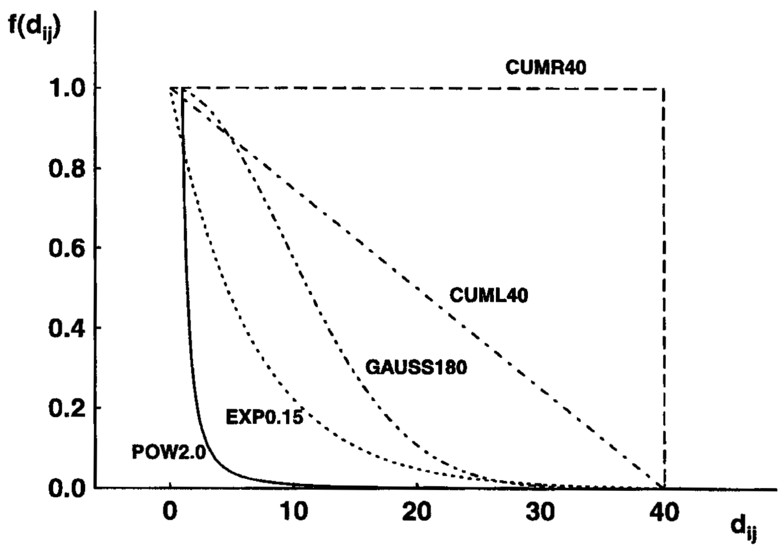

FIG. 1d. Impedance Functions for the Gravity-Type and Cumulative-Opportunity Accessibility Measures: Alternative Impedance Function

the daily PPA is given as follows.[8] Consider an individual s who has a daily activity program consisting of m out-of-home activities. Among these activities, some need to be performed at locations fixed to the individual (for example, work-

[8] The full formulation elaborated in Kwan and Hong (1998) includes the effect of opening hours of facilities and stores. Since the parcel data used in this study do not provide information about the opening hours of establishments, the formulation used here is a modified one which does not incorporate this effect.

place, child's school, or family doctor), while others can be undertaken at locations chosen at the individual's discretion (for example, gas stations or grocery stores). The former type of activities are referred to as "fixed activities." Since the daily potential path area (DPPA) for the individual is determined by the spatio-temporal constraints imposed by the fixed activities of the day, the potential path area (PPA) for each pair of consecutive fixed activities can first be found, and then aggregated for deriving the daily PPA. For any pair of consecutive fixed activities F_i at location i and F_j at location j, and a given time constraint $t_j - t_i$ for activity and travel between these two activities, location k is reachable if it is included in the space-time prism or potential path space (PPS) which is defined as

$$PPS = \left\{ (k,t) \middle| t_i + \frac{d_{ik}}{v} \leq t \leq t_j - \frac{d_{kj}}{v} \right\} \tag{1}$$

where t_i = the latest ending time of the activity at location i, which is the origin fixed location in the pair; t_j = the earliest starting time of the activity at location j, which is the next fixed destination after k; v = the average travel speed on the transport network; d_{ik} = distance from the first fixed location i to location k; and d_{kj} = distance from k to the next fixed location j. The projection of this three-dimensional PPS on the x-y geographic plane produces a corresponding two-dimensional potential path area (PPA), which contains all feasible locations k given the space-time constraints as specified in the equation. If there are n pairs of consecutive fixed activities on the day, a series of PPAs for the day can be specified in a similar manner as: PPA_1, $PPA_2 \ldots PPA_n$. The daily PPA (DPPA) is formed by aggregating all these n PPAs. The set containing all opportunities in this DPPA is the feasible opportunity set (FOS) of the day for the individual.

Based on this delimitation of the DPPA and the specification of the FOS, three indices can be derived as space-time measures of accessibility: (a) the cardinality of the set FOS which gives the number of opportunities (NO) it contains; (b) a weighted sum of the opportunities (WA) contained in the FOS of individual s which can be represented as

$$A_s = \sum W_k I(k) \tag{2}$$

where $I(k)$ is an indicator function such that

$$I(k) = \begin{cases} 1 & \text{if } k \in \text{FOS}, \\ 0 & \text{otherwise;} \end{cases}$$

and (c) the length of the network arcs (LEN) included in the DPPA. These three specifications of space-time measures, however, are not susceptible to any simple computational procedure. An operational method is needed for their enumeration through deriving DPPA and identifying the FOS.

One method is to precalculate a distance matrix for all locations using the shortest path algorithm. Feasibility of each network arc is then tested exhaustively by going through the entire matrix and identifying those arcs that are reachable within the spatio-temporal constraints for any given pair of fixed activity locations (Kwan 1997). Another option is to use Miller's (1991) GIS method which consists of two steps: (i) conduct an arc allocation up to the travel time budget from the first fixed activity location i; (ii) test each arc for feasibility by computing the shortest path from each candidate arc in the allocation to the second fixed activity location j and noting the arc's cumulative travel time from i. While both of these methods are robust and their solution exhaustive, they are not feasible for this study because of the large number of computationally intensive shortest-path calculations required and the size of the street network involved (as indicated by several trial runs of both methods on a SGI dual-processor Power Challenge server). This study instead uses a GIS algorithm extended after Kwan and Hong (1998) which, although it provides only an approximate solution of the exhaustive set generated by more robust procedures, is computationally more tractable. Its main advantage is its avoidance of any shortest-path computation which renders it highly efficient. The method uses the intersection of a series of paired arc allocations to generate individual network-based PPAs, each of which is defined by the space-time coordinates of two fixed activities. The union of these individual PPAs, which is the DPPA, is then derived.

The travel diary data provide two-day activity-travel data of thirty-nine male and forty-eight female adults of fifty-two family households. The eighteen· GRAV and CUM indices specified above are enumerated for each of the fifty-two home locations with respect to the 10,727 land-use parcels using the weighted area of each parcel as the opportunity measure and network travel time between each home location and parcel centroid as the distance measure. Since both the female and male adults of each household in the sample use private vehicles for their daily travel and enjoy similar travel mobility, their levels of accessibility as enumerated by all integral measures are the same (for there is no difference in either their home location or travel mobility). On the other hand, the three ST indices (*NO*, *WA*, and *LEN*) are computed for each of the eighty-seven individuals using the GIS method described in the last section. Two dimensions of the original data are retained in the analysis: the gender of the individual (*M* and *F*), and whether the DPPA is the larger or smaller one of the two survey days (*H* for high or large, and *L* for low or small).[9] The designation of each ST measure thus has three components: the gender of the person in question, whether the measure is derived from the larger of smaller DPPA, and what is being enumerated (Table 1). For example, *MHLEN* stands for accessibility measured in terms of the length of network arcs (*LEN*) contained by the larger DPPA (*H*) of the two days for the male adult (*M*) of the household in question, whereas *FLWA* stands for accessibility measured in terms of the weighted area (*WA*) of the opportunities contained in the smaller DPPA (*L*) of the two days for the female adult (*F*) of the household. All geoprocessing in this study is performed using ARC/INFO GIS.

5. ANALYSIS OF ACCESSIBILITY MEASURES

5.1 Relationships between the Thirty Accessibility Measures

Relationships between the thirty accessibility indices are evaluated by examining the Pearson correlation coefficients showed in Table 2. The table reveals that all GRAV and CUM measures have strong correlations with each other (except *POW2.0* and *CUMR40*). Both *POW2.0* and *CUMR40* have very low correlations with most other measures, including all ST measures. On the contrary, all ST measures in general have weak correlations with both GRAV and CUM measures, where correlation coefficients are consistently below 0.5. Further, the

[9] The small sample size precludes grouping of the individuals using multivariate criteria or composite dimensions. Differentiating between the larger and smaller daily PPA, however, retains some of the day-to-day variation in individual activity-travel patterns as observed by Huff and Hanson (1986).

TABLE 2
Pearson Correlation Coefficients for the Accessibility Measures

Accessibility Measures	*POW* 0.8	*POW* 1.0	*POW* 1.5	*POW* 2.0	*EXP* 0.12	*EXP* 0.15	*EXP* 0.22	*EXP* 0.45	*GAUSS* 10	*GAUSS* 40	*GAUSS* 100	*GAUSS* 180	*CUMR* 20	*CUMR* 30	*CUMR* 40
POW0.8	1.00	0.997	0.851	0.285	0.996	0.993	0.975	0.887	0.753	0.899	0.973	0.991	0.948	0.836	0.354
POW1.0		1.000	0.883	0.337	0.989	0.990	0.978	0.907	0.784	0.909	0.973	0.984	0.933	0.811	0.327
POW1.5			1.000	0.731	0.815	0.820	0.822	0.829	0.786	0.764	0.805	0.810	0.760	0.624	0.229
POW2.0				1.000	0.227	0.228	0.230	0.303	0.369	0.184	0.211	0.227	0.227	0.150	0.073
EXP0.12					1.000	0.998	0.978	0.871	0.716	0.901	0.982	0.998	0.952	0.823	0.326
EXP0.15						1.000	0.990	0.897	0.743	0.927	0.992	0.996	0.934	0.791	0.288
EXP0.22							1.000	0.944	0.801	0.969	0.995	0.976	0.884	0.725	0.218
EXP0.45								1.000	0.941	0.973	0.912	0.859	0.737	0.588	0.112
GAUSS10									1.000	0.841	0.747	0.696	0.590	0.486	0.098
GAUSS40										1.000	0.952	0.893	0.761	0.599	0.105
GAUSS100											1.000	0.984	0.892	0.724	0.223
GAUSS180												1.000	0.953	0.803	0.306
CUMR20													1.000	0.840	0.383
CUMR30														1.000	0.549
CUMR40															1.000
CUML20															
CUML30															
CUML40															
MHLEN															
MLLEN															
MHNO															
MLNO															
MHWA															
MLWA															
FHLEN															
FLLEN															
FHNO															
FLNO															
FHWA															
FLWA															

TABLE 2 (Continued)

Accessibility Measures	*CUML* 20	*CUML* 30	*CUML* 40	*MHLEN*	*MLLEN*	*MHNO*	*MLNO*	*MHWA*	*MLWA*	*FHLEN*	*FLLEN*	*FHNO*	*FLNO*	*FHWA*	*FLWA*
POW0.8	0.859	0.848	0.782	0.324	0.285	0.373	0.360	0.451	0.436	0.172	0.137	0.131	0.208	0.238	0.277
POW1.0	0.842	0.826	0.757	0.320	0.280	0.360	0.347	0.441	0.426	0.166	0.128	0.125	0.191	0.237	0.267
POW1.5	0.669	0.644	0.588	0.238	0.183	0.238	0.205	0.319	0.272	0.097	0.060	0.057	0.074	0.155	0.150
POW2.0	0.176	0.166	0.164	0.020	−0.017	−0.026	−0.064	0.017	−0.045	−0.050	−0.048	−0.083	−0.092	−0.060	−0.072
EXP0.12	0.859	0.840	0.769	0.318	0.291	0.371	0.365	0.452	0.446	0.172	0.133	0.128	0.210	0.246	0.285
EXP0.15	0.839	0.810	0.735	0.317	0.295	0.360	0.363	0.446	0.451	0.164	0.128	0.120	0.199	0.247	0.284
EXP0.22	0.786	0.745	0.662	0.315	0.300	0.334	0.355	0.428	0.455	0.143	0.117	0.101	0.173	0.242	0.275
EXP0.45	0.646	0.599	0.510	0.303	0.282	0.268	0.304	0.362	0.406	0.102	0.087	0.080	0.102	0.212	0.220
GAUSS10	0.527	0.493	0.415	0.247	0.208	0.225	0.212	0.294	0.287	0.128	0.089	0.117	0.078	0.193	0.175
GAUSS40	0.664	0.611	0.520	0.313	0.310	0.273	0.343	0.374	0.457	0.067	0.080	0.037	0.110	0.195	0.233
GAUSS100	0.794	0.749	0.670	0.303	0.294	0.344	0.358	0.439	0.456	0.155	0.125	0.106	0.185	0.254	0.289
GAUSS180	0.858	0.828	0.757	0.309	0.286	0.368	0.358	0.453	0.442	0.182	0.133	0.135	0.213	0.257	0.291
CUMR20	0.897	0.877	0.818	0.323	0.285	0.344	0.351	0.406	0.405	0.184	0.111	0.164	0.236	0.235	0.253
CUMR30	0.770	0.895	0.861	0.273	0.210	0.376	0.342	0.394	0.347	0.151	0.126	0.120	0.183	0.156	0.201
CUMR40	0.553	0.635	0.754	0.220	0.129	0.377	0.264	0.295	0.185	0.166	0.335	0.110	0.424	−0.020	0.231
CUML20	1.000	0.952	0.921	0.407	0.319	0.463	0.388	0.491	0.419	0.179	0.203	0.091	0.333	0.108	0.287
CUML30		1.000	0.981	0.362	0.265	0.475	0.383	0.478	0.385	0.190	0.227	0.121	0.323	0.120	0.276
CUML40			1.000	0.347	0.243	0.488	0.374	0.473	0.359	0.222	0.298	0.157	0.394	0.121	0.310
MHLEN				1.000	0.915	0.726	0.821	0.750	0.842	0.202	0.278	0.143	0.241	0.150	0.220
MLLEN					1.000	0.542	0.872	0.573	0.910	0.153	0.193	0.086	0.226	0.096	0.127
MHNO						1.000	0.667	0.960	0.633	0.493	0.505	0.322	0.260	0.385	0.327
MLNO							1.000	0.614	0.955	0.181	0.361	0.064	0.331	0.074	0.239
MHWA								1.000	0.643	0.514	0.485	0.331	0.188	0.446	0.328
MLWA									1.000	0.187	0.334	0.065	0.308	0.113	0.256
FHLEN										1.000	0.647	0.827	0.556	0.808	0.513
FLLEN											1.000	0.519	0.833	0.443	0.832
FHNO												1.000	0.521	0.935	0.484
FLNO													1.000	0.389	0.875
FHWA														1.000	0.479
FLWA															1.000

ST measures for males have slightly stronger correlations with integral measures than the ST measures for females. What is remarkable is that all correlations between measures within the male ST or female ST group are strong, with all coefficients significant at the 0.01 level, while the correlations of all ST measures between the two gender groups are considerably weaker.

Since some of the weak correlations observed may be due to a few extreme values within the distribution of a particular measure, Spearman's rank correlation coefficients are also calculated for all pairs of accessibility indices (table not shown). With rank correlations, the weak relationships of *POW2.0* with all other measures improve considerably, while the weak correlations of *CUMR40* with all other measures do not improve much. This suggests that low correlations of *POW2.0* are mainly due to extreme values, while the low correlations of *CUMR40* with other measures are largely genuine. Overall, correlations between GRAV and CUM measures remain high, while correlations of all ST measures with either GRAV or CUM measures remain low, although their association improves slightly after using rank correlation.

These patterns of correlation indicate that GRAV and CUM measures are more similar to each other than they are to ST measures, thus identifying integral measures and ST measures as distinctive types of accessibility indices. Integral measures like GRAV and CUM measures are single-origin indices evaluated with respect to the home location of an individual. Their values are determined largely by the spatial distribution and locational proximity of opportunities in the study area relative to that reference location, as well as the form and parameter of the impedance function. Values of the ST measures, however, are determined mainly by the structure of an individual's activity program and space-time constraints. Since opportunities enumerated by ST measures are based upon their space-time feasibility, the number of opportunities included in the daily potential path area of an individual may only have a weak relationship with the spatial distribution of opportunities in the urban environment. As a result, the correlations of ST measures with GRAV and CUM measures also tend to be weak.

5.2 *Spatial Patterns of Accessibility*

Spatial patterns of the thirty accessibility measures are examined through visualization of the accessibility surfaces they generated using ARC/INFO GIS. The surfaces of selected indices, whose values are standardized to a mean of one, are shown in Figures 2 to 4.[10] The boundary of the x-y plane in these diagrams corresponds closely to the boundary of the study area, whereas the center of the plane is about one mile north of downtown Columbus. These figures reveal that both GRAV and CUM measures produce distinctive spatial patterns of accessibility, while the patterns for ST measures are difficult to generalize.

In the case of GRAV measures, all of the three impedance functions (POW, EXP, and GAUSS) generate similar spatial patterns whether the value of the parameter used is high or low (Figure 2). In addition, GRAV measures whose parameters produce rapidly declining impedance functions (for example, *POW2.0* or *EXP0.45*) tend to generate more pronounced accessibility patterns, with sharp peaks and troughs. In general, areas with maximum accessibility evaluated by GRAV measures are located in the northern part of the study area around the

[10] Spline interpolation was used to generate these surfaces at a resolution of 74,460 grid cells of 250,000 square feet in size. Since only a few households are located in areas near the southern edge of the county, the interpolated surface in this portion of the study area should be interpreted with caution.

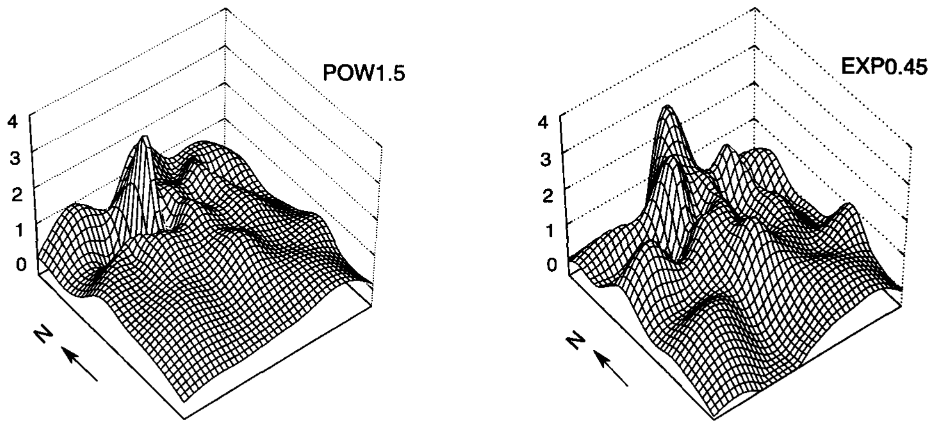

FIG. 2. Accessibility Surfaces of the Gravity-Type Measures: (a) *POW1.5*; (b) *EXP0.45*. The vertical axis is the level of accessibility standardized to a mean of one. Areas of high accessibility are represented by peaks.

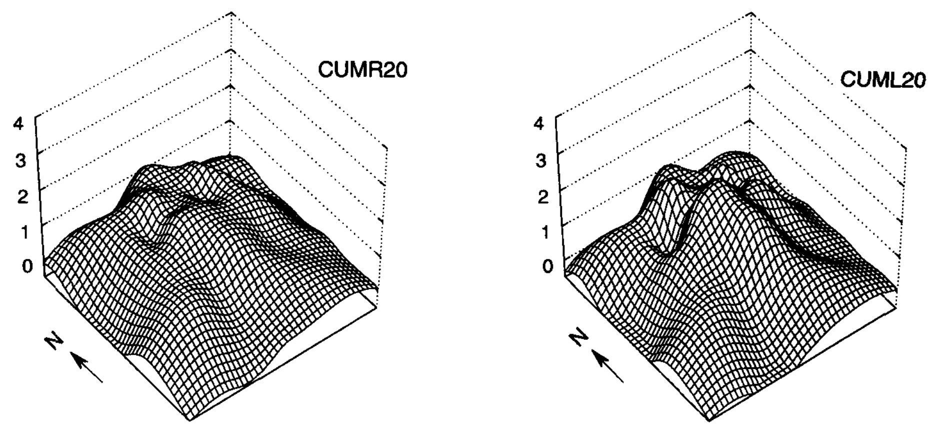

FIG. 3. Accessibility Surfaces of the Cumulative-Opportunity Measures: (a) *CUMR20*; (b) *CUML20*. The vertical axis is the level of accessibility standardized to a mean of one. Areas of high accessibility are represented by peaks.

intersections of major arterials. Distinctive peaks are found near the intersections of controlled access freeways and major arterials (for example, Interstate 270, 315 Freeway, State Route 161). Accessibility in areas at and around downtown (about center of the x-y plane) is high, but not as high as the northern peaks.

On the other hand, both CUMR and CUML indices produce rather similar spatial patterns for different time limits (that is, 20, 30, and 40 minutes from the reference location) (Figure 3). CUM measures with shorter time limits tend to generate more differentiated spatial patterns with more distinctive peaks and troughs, while CUM measures with 40 minutes of travel time limit produce very generalized surfaces where differences in accessibility between locations are small. Maximum accessibility as measured by CUM indices are found largely in areas at and around downtown Columbus (that is, center of the x-y plane), whereas the northern peaks revealed by GRAV measures become less intensive than those in the central areas. Further, CUML indices with a negative linear impedance function give more differentiated spatial patterns than CUMR measures that give the same weight to all opportunities.

Overall, some patterns are common to both GRAV and CUM measures: (a) Within each of these two groups of integral measures, similar spatial patterns are generated by different impedance functions and parameters that generate relatively differentiated surfaces. The contrasts in spatial patterns between GRAV and CUM measures are largely due to their different impedance functions. GRAV measures whose impedance functions decline and approach zero more rapidly give local opportunities more emphasis and therefore produce patterns with more localized peaks. On the other hand, by virtue of their weak distance decay effect and inclusion of a large number of opportunities in the computation (especially when the time limit is large), CUM measures tend to generate higher accessibility values for central locations. (b) Different parameters mainly affect the intensity of the peaks and troughs of accessibility surfaces, but not their spatial patterns. (c) Accessibility in general declines toward the edges of the study area (except the northern edge). (d) Accessibility in the northern half of the study area tends to be higher than areas in the south. In summary, the type of measure is more important in determining the spatial patterns than the parameter of the impedance function, whereas the parameter of the impedance function largely affects the intensity of peaks and troughs of accessibility.

Since ST measures are non-single-origin indices and bear weak relationships with the accessibility of an individual's home location, it may not be appropriate to generate surfaces of their spatial patterns. Figure 4 is constructed largely to give an impression of the spatial distribution of their values as compared to GRAV and CUM measures. Several features are noticeable: (a) Within either the male or female subgroup, spatial patterns generated by ST measures are rather similar whether accessibility is enumerated in terms of the number of opportunities (*NO*), weighted area of opportunities (*WA*), or length of network arcs (*LEN*) included in the FOS. (b) Overall, the spatial patterns generated by all ST measures are somewhat haphazard. This is expected since the accessibil-

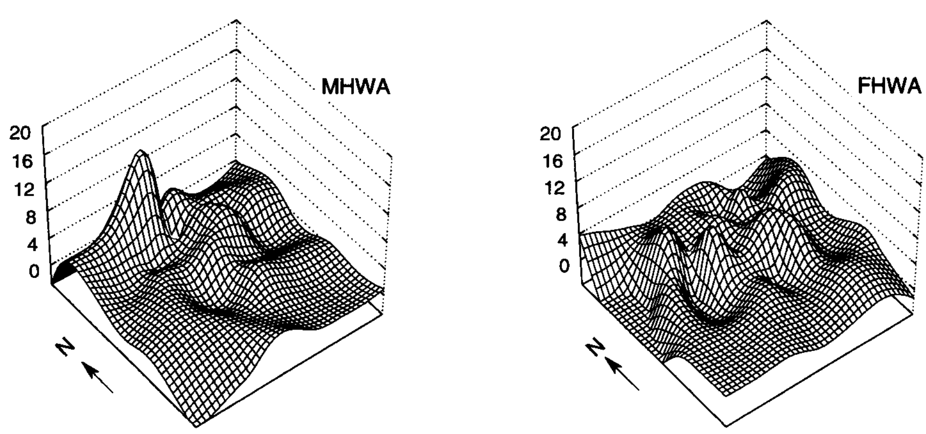

FIG. 4. Accessibility Surfaces of the Space-Time Measures: (a) *MHWA*; (b) *FHWA*. The vertical axis is the level of accessibility standardized to a mean of one. Areas of high accessibility are represented by peaks.

ities they evaluated are highly contextual and person specific, and may not have strong relationships with the spatial distribution of opportunities. (c) Compared to the surfaces generated by ST measures for females, accessibility surfaces generated by ST measures for males are more distinctive and bear stronger affinity with those generated by GRAV measures, where maximum accessibilities are found mainly in the northern part of the study area. On the other hand, the accessibility surfaces generated by ST measures for females have no distinctive spatial patterns.

5.3 Factor Analysis of Accessibility Measures

The structure of interrelationships among the thirty accessibility measures are further explored using factor analysis which helps to identify important dimensions for describing groups of similar measures and their shared variance. Four factors are extracted from the thirty measures and an orthogonal varimax rotation is performed to make these factors more interpretable. These four rotated factors together explain 84.21 percent of the total variance and the last

TABLE 3
Factor Loadings of the Accessibility Measures

Accessibility Measures	Factor Loadings				Communalities
	Factor 1	Factor 2	Factor 3	Factor 4	
POW0.8	**0.925**	0.179	0.105	0.309	0.994
POW1.0	**0.942**	0.170	0.098	0.266	0.997
POW1.5	**0.887**	0.058	0.022	0.110	0.802
POW2.0	0.395	−0.120	−0.112	−0.046	0.185
EXP0.12	**0.916**	0.187	0.108	0.303	0.978
EXP0.15	**0.932**	0.191	0.105	0.251	0.978
EXP0.22	**0.951**	0.198	0.095	0.147	0.975
EXP0.45	**0.943**	0.181	0.067	−0.045	0.928
GAUSS10	**0.848**	0.110	0.089	−0.111	0.751
GAUSS40	**0.929**	0.220	0.042	−0.009	0.913
GAUSS100	**0.936**	0.197	0.107	0.171	0.955
GAUSS180	**0.913**	0.182	0.118	0.291	0.965
CUMR20	**0.826**	0.162	0.104	0.423	0.898
CUMR30	0.655	0.141	0.059	0.591	0.802
CUMR40	0.070	0.118	0.131	**0.855**	0.767
CUML20	0.677	0.242	0.088	0.611	0.898
CUML30	0.637	0.203	0.101	**0.703**	0.951
CUML40	0.537	0.188	0.149	**0.787**	0.964
MHLEN	0.141	**0.924**	0.095	0.085	0.891
MLLEN	0.130	**0.926**	0.014	−0.008	0.875
MHNO	0.149	**0.715**	0.372	0.241	0.730
MLNO	0.143	**0.910**	0.071	0.170	0.883
MHWA	0.262	**0.707**	0.378	0.145	0.733
MLWA	0.252	**0.914**	0.074	0.079	0.910
FHLEN	0.055	0.140	**0.882**	0.010	0.802
FLLEN	−0.066	0.257	**0.783**	0.261	0.752
FHNO	0.058	0.010	**0.892**	−0.070	0.804
FLNO	−0.012	0.144	**0.724**	0.399	0.704
FHWA	0.210	0.047	**0.858**	−0.207	0.825
FLWA	0.118	0.111	**0.759**	0.226	0.653
Variance explained	12.024	5.059	4.502	3.679	25.264
% of Variance	40.08%	16.86%	15.01%	12.26%	84.21%

NOTE: Loadings over 0.7 are in bold type.

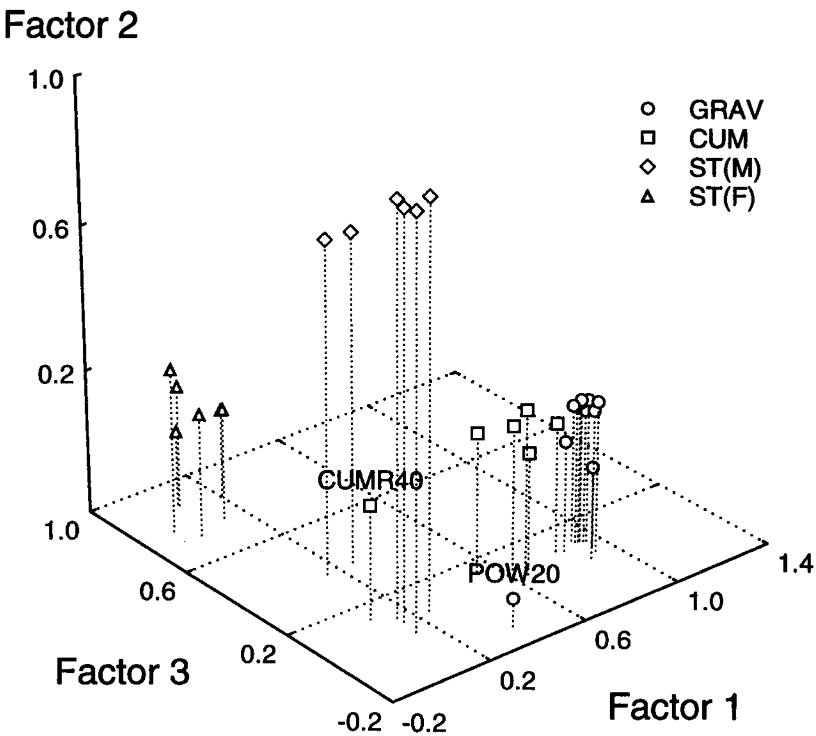

FIG. 5. Factor Loadings of the Thirty Accessibility Measures on factors 1, 2, and 3

factor extracted has an eigenvalue of 2.09 (Table 3). The large communalities for all measures indicate that a large amount of their variance has been extracted. The analysis produces a rather clean factor structure where variable loadings on the four factors facilitate their meaningful interpretation (Figure 5). Only one accessibility measure (*POW2.0*) has low loadings on all four rotated factors.

As shown in Table 3 and Figure 5, all GRAV measures have high loadings (over 0.7) on factor 1, on which all CUM measures except *CUMR40* also have moderate loadings (over 0.5). On the contrary, measures that have high loadings on factors 2 and 3 are all ST measures. Among the ST measures, all those for males have high loadings on factor 2, while all those for females have high loadings on factor 3. Lastly, all measures with high loadings on factor 4 are CUM measures with weak distance decay effects: *CUMR40*, *CUML30*, and *CUML40*. Two distinctive dimensions are therefore represented in this factor structure. The first dimension represents the effect of the impedance function on integral measures captured largely by factors 1 and 4, where integral measures with strong distance decay have high loadings on factor 1, and integral measures with weak distance decay have high loadings on factor 4. The former group consists of all GRAV measures and *CUMR20*, suggesting its close affinity to GRAV measures. The latter group consists of CUM measures other than *CUMR20*. Another dimension represented in the factor structure captures the effect of individual-specific attributes on ST measures which, in the specific context of this study, is gender. This indicates that accessibility as measured by ST indices is strongly influenced by individual-specific attributes, of which gender is one important differentiating dimension.[11] Overall, results of the factor analysis, as depicted in Figure 5 by distinctive clusters of different types of accessibility measures, further corroborate an earlier observation that GRAV and CUM measures are more similar to each other than they are to ST measures, and ST measures constitute a distinctive group of accessibility indices.

5.4 *Discussion of Results*

Results of the correlation and factor analysis reveal the weak relationships between ST measures and all integral measures. This suggests that they are distinctive types of accessibility indices that capture different dimensions of the accessibility experience of individuals. Especially important is the fact that, given the characteristics of the selected individuals (for example, similar travel mobility) in this study, integral measures ascribe the same level of accessibility to all persons having the same reference location (home), while ST measures are able to reveal differences in individual accessibility with respect to the gender dimension. Personal accessibility as measured by ST measures can therefore be different even for individuals of the same household with the same location and travel mobility. This indicates that ST measures are capable of unraveling differences in individual accessibility that integral measures may not be able to uncover. This capability is due to the different conception of accessibility embodied in ST measures which is more sensitive to person-specific differences in an individual's life situation when compared to conventional integral measures. Personal accessibility as evaluated by ST measures is not based on the "locational proximity" of urban opportunities to one's home or workplace (as in the case of integral measures), but on the "feasibility in space-time" of various opportunities to a person given the individual's activity program and spatiotemporal constraints. Such a conception and/or measure of individual accessibility, as shown in this study, is more helpful for unraveling gender/ethnic differences in the access to urban opportunities.

Based on this capability of ST measures, two observations pertinent to the analysis of gender/ethnic differences in the access to urban opportunities deserve emphasis here. First, the levels of individual accessibility as experienced by the male and female adults of the same household, as evaluated by ST measures, have only weak relationships. This corroborates the results in another study that observed significant gender differences in individual accessibility (Kwan 1998b). Second, correlations between the ST measures for males and integral measures are stronger than the correlation between the ST measures for females and integral measures. The similarity in the spatial patterns between the ST measures for males and integral measures is also greater than the resemblance in the spatial patterns between ST measures for females and integral measures. This suggests that individual accessibility as experienced by men has a stronger relationship with place accessibility than that experienced by females.

This latter observation not only supports Pickup's (1985) assertion that conventional accessibility measures are more suitable for the analysis of men's access to urban opportunities than that of women, but also indicates that ST measures are more sensitive to person-specific life situations and gender-role constraints, which many argue are more important and restrictive to women than men (for example, Fox 1983; Salomon and Tacken 1993; Tivers 1985). As

[11] The identification of gender as an important differentiating dimension here is obviously dependent on the particular grouping scheme used in this study. This, however, does not imply that other latent dimensions cannot be discovered when the sample is large enough to allow for more complex multivariate grouping.

argued by Pickup (1985), conventional "spatial" measures of accessibility to shops or jobs were meaningless for women whose activity choices were continually facing additional time constraints from their gender role. She showed that women's gender role involves many temporally fixed activities that impose "hard constraints" on their activity-travel patterns, and that these constraints are more important than travel mobility or costs in determining women's job locations. Since gender-role constraints are important in structuring the space-time trajectory of women's lives as observed in many other studies (for example, Hanson and Pratt 1990, 1995; Kwan 1998a,b; Michelson 1985; Palm 1981; Forer and Kivell 1981), ST measures which can capture the effect of constraints are particularly suitable for studying gender/ethnic differences in the access to urban opportunities. Going beyond conventional integral measures may be an important first step in improving our understanding in this area.

6. CONCLUSIONS

The significance of this study lies not only in its contribution to feasible operational formulations of space-time measures and the development of a computational algorithm using GIS procedures. The comparative analysis also leads to several conclusions that have important methodological implications for the study of the differential access to urban opportunities. First, integral measures and space-time measures are distinctive types of accessibility indices each of which tends to reflect different dimensions of the accessibility experience of individuals. Second, as the particular nature and operational form of a measure dictate what it is capable of reflecting, space-time measures are capable of capturing interpersonal differences in individual accessibility that conventional integral measures may not be able to reveal.[12] Third, personal accessibility can be different even for individuals of the same household with the same level of travel mobility. The differences between place and individual accessibility as evaluated by different types of measures are therefore more than in the level of aggregation or the spatial framework used. This in turn suggests that, even when problems of the zone-based method are avoided, the analyst should be careful when inferring personal accessibility from place accessibility since they may have only weak relationships.

Results of this study support the findings of earlier studies (for example, Guy 1983; Handy and Niemeier 1997) that the accessibility patterns observed in a particular analytical context depend on the type of accessibility measures used even when the analysis is based on individual-level data and nonzonal methods. Besides, accessibility measures may be different in their "gender sensitivity," meaning that some measures are more capable of revealing interpersonal differences relative to gender. The implication of this observation for studies on gender/ethnic differences in accessibility is that whether these differences are observed or whether the significance of accessibility can be ascertained is affected by the accessibility measure used. The analyst needs to be aware of the sensitivity of various measures to different dimensions and evaluate their suitability for the particular research question at hand before using them. Without addressing this methodological problem of measurement, the analyst may not be able to determine the significance and confidence ascribable to a set of analytical results or empirical observations.

[12] This, however, does not imply that integral measures cannot capture any interpersonal differences in individual accessibility. Variations that integral measures can capture are those that can be handled by the impedance function parameter (for example, differences in travel mobility and the effect of distance perception on a person's willingness to travel).

Further, as the explanatory power of zonal gravity measures is known to have declined in recent years, some authors have argued that accessibility itself is becoming less important. The finding that space-time and integral measures are different kinds of accessibility measures is especially significant in this context. If it can be shown that space-time measures have better explanatory and/or predictive power than gravity measures, then the effort and resources needed for formulating and operationalizing these more complex measures may be justified. Results in several studies provide some insights to this issue. In Villoria (1989), individual accessibility as measured by space-time measures was found to be a significant determinant of the activity-travel patterns using a travel diary data set of 5,126 individuals. Activity-travel patterns in this study were derived using twelve variables including time spent traveling, number of fixed activities, and time spent in various out-of-home activities. Kwan (1998c) compared the relationships between space-time and integral accessibility measures with the characteristics of individual activity-travel patterns. The study observed that space-time measures have significant relationships with various measures of individual activity-travel behavior (including time spent in nonwork activities and distance traveled), while integral measures have only weak association with these travel characteristics. Two studies on disaggregate destination choice models showed the importance of temporal constraints on individual travel choice behavior (Landau, Prashker, and Alpern 1982; Thill and Horowitz 1997). These studies together suggest that accessibility measures that incorporate the effect of space-time constraints will improve the ability to explain and/ or predict particular characteristics of individual travel behavior. This provides additional support to the relative merit of space-time measures.

The need for measures that are sensitive to and capable of capturing fine-scale, person-specific realities of everyday life is an emerging emphasis of recent research [for example, the individual-specific analysis of job access in Hanson, Kominiak, and Carlin (1997); the multilevel conceptualization of accessibility in Handy (1993)]. In the context of this study, the following may be submitted in a similar vein to conclude this paper. To capture the effect of the complexities of activity-travel behavior and the structure of space-time constraints on personal accessibility, analysis of accessibility has to go beyond the conceptual and analytical framework of conventional integral measures. A space-time framework conceiving humans as active agents and incorporating the effects of person-specific constraints seems to be a promising alternative. In the final analysis, personal accessibility is mediated by the process of choice and spatio-temporal constraints circumscribed by the situational complexities of a person's daily life in a particular sociospatial context. This contextual and situational nature of personal accessibility reasserts Pirie's (1979, p. 307) statement that, "What is required is a measure of accessibility which is sensitive to adaptive behavior—to the fact that accessibility is always created and is not just something to be had by virtue of one's locale."

LITERATURE CITED

Allen, W. B., D. Liu, and S. Singer (1993). "Accessibility Measures of U.S. Metropolitan Areas." *Transportation Research B* 27, 439–49.

Bach, L. (1980). "Locational Models for Systems of Private and Public Facilities Based on Concepts of Accessibility and Access Opportunity." *Environment and Planning A* 12, 301–20.

——— (1981). "The Problem of Aggregation and Distance for Analyses of Accessibility and Access Opportunity in Location-Allocation Models." *Environment and Planning A* 13, 955–78.

Baxter, R. S., and G. Lenzi (1975). "The Measurement of Relative Accessibility." *Regional Studies* 9, 15–26.

Ben-Akiva, M., and S. R. Lerman (1979). "Disaggregate Travel and Mobility-Choice Models and Measures of Accessibility." In *Behavioural Travel Modelling*, edited by D. A. Hensher and P. R. Storper, pp. 654–79, London: Croom-Helm.

Black, J., and M. Conroy (1977). "Accessibility Measures and the Social Evaluation of Urban Structure." *Environment and Planning A* 9, 1013–31.

Black, J., C. Kuranami, and P. J. Rimmer (1982). "Macroaccessibility and Mesoaccessibility: A Case Study of Sapporo, Japan." *Environment and Planning A* 14, 1355–76.

Breheny, M. J. (1978). "The Measurement of Spatial Opportunity in Strategic Planning." *Regional Studies* 12, 463–79.

Burnett, P. (1980). "Spatial Constraints-Oriented Modeling as an Alternative Approach to Movement, Microeconomic Theory, and Urban Policy." *Urban Geography* 1, 53–67.

Burns, L. D. (1979). *Transportation, Temporal, and Spatial Components of Accessibility*. Lexington, MA: Lexington Books.

Burns, L. D., and T. F. Golob (1976). "The Role of Accessibility in Basic Transportation Choice Behavior." *Transportation* 5, 175–98.

City of Columbus (1993). *Growth Statement 1993*. Columbus, OH: Development Department, City of Columbus, Ohio.

Cullen, I., V. Gobson, and S. Major (1972). "The Structure of Activity Patterns." In *Patterns and Processes in Urban and Regional Systems*, edited by A. G. Wilson, pp. 281–96. London: Pion.

Dalvi, M. Q., and K. M. Martin (1976). "The Measurement of Accessibility: Some Preliminary Results." *Transportation* 5, 17–42.

Davidson, K. B. (1977). "Accessibility in Transport/Land-use Modelling and Assessment." *Environment and Planning A* 9, 1401–16.

Dodgson, J. S. (1974). "Motorway Investment and Sub-regional Growth: The Case of the M672." *Regional Studies* 8, 75–91.

Ewing, R., P. Haliyr, and G. W. Page (1994). "Getting around a Traditional City, a Suburban Planned Unit Development, and Everything in Between." *Transportation Research Record* 1466, 53–62.

Forer, P. C., and H. Kivell (1981). "Space-Time Budgets, Public Transport, and Spatial Choice." *Environment and Planning A* 13, 497–509.

Fotheringham, A. S. (1981). "Spatial Structure and Distance-Decay Parameters." *Annals of the Association of American Geographers* 71(3), 425–35.

Fotheringham, A. S., and M. E. O'Kelly (1989). *Spatial Interaction Models: Formulations and Applications*. London: Kluwer.

Fox, M. (1983). "Working Women and Travel: The Access of Women to Work and Community Facilities." *Journal of the American Planning Association* 49, 156–70.

Geertman, S.C.M., and J. R. Ritsema van Eck (1995). "GIS and Models of Accessibility Potential: An Application in Planning." *International Journal of Geographical Information Systems* 9(1), 67–80.

Gutierrez, J. P., and Gonzalez, R. E. A. (1995). "Transport in Europe: A Study of Train Accessibility Using GIS." *Proceedings of ESRI User Conference 1995*. Redlands, CA.: ESRI.

Guy, C. M. (1983). "The Assessment of Access to Local Shopping Opportunities: A Comparison of Accessibility Measures." *Environment and Planning B* 10, 219–38.

Hägerstrand, T. (1970). "What about People in Regional Science." *Papers of the Regional Science Association* 24, 7–21.

Handy, S. L. (1993). "Regional versus Local Accessibility: Implications for Nonwork Travel." *Transportation Research Record* 1400, 58–66.

Handy, S. L., and D. A. Niemeier (1997). "Measuring Accessibility: An Exploration of Issues and Alternatives." *Environment and Planning A* 29, 1175–94.

Hansen, W. G. (1959). "How Accessibility Shapes Land Use." *Journal of American Institute of Planners* 25, 73–76.

Hanson, S. (1980a). "Spatial Diversification and Multi-Purpose Travel: Implications for Choice Theory." *Geographical Analysis* 12, 245–57.

——— (1980b). "The Importance of the Multi-Purpose Journey to Work in Urban Travel Behavior." *Transportation* 9, 229–48.

——— (1995). "Getting There: Urban Transportation in Context." In *The Geography of Urban Transportation*, edited by S. Hanson, pp. 3–25. New York: Guilford.

Hanson, S., and G. Pratt (1990). "Geographic Perspectives on the Occupational Segregation of Women." *National Geographic Research* 6, 376–99.

——— (1995). *Gender, Work, and Space*. New York: Routledge.

Hanson, S., and M. Schwab (1987). "Accessibility and Intraurban Travel." *Environment and Planning A* 19, 735–48.

Hanson, S., T. Kominiak, and S. Carlin (1997). "Assessing the Impact of Location on Women's Labor Market Outcomes: A Methodological Exploration." *Geographical Analysis* 29, 281–97.

Harris, C. D. (1954). "The Market as a Factor in the Location of Industry in the U.S." *Annals of the American Association of Geographers* 44, 315–48.

Huff, D. L. (1964). "Defining and Estimating a Trading Area." *Journal of Marketing* 28, 34–38.

Huff, J. O., and S. Hanson (1986). "Repetition and Variability in Urban Travel." *Geographical Analysis* 18, 97–114.

Ihlanfeldt, K. R. (1993). "Intra-urban Job Accessibility and Hispanic Youth Employment Rates." *Journal of Urban Economics* 33, 254–71.

Ihlanfeldt, K. R., and M. D. Raper (1990). "The Intrametropolitan Location of New Office Firms." *Land Economics* 66(2), 182–98.

Ingram, D. R. (1971). "The Concept of Accessibility: A Search for an Operational Form." *Regional Studies* 5, 101–107.

Kirby, H. R. (1976). "Accessibility Indices for Abstract Road Networks." *Regional Studies* 10, 479–82.

Knox, P. L. (1978). "The Intraurban Ecology of Primary Medical Care: Patterns of Accessibility and Their Policy Implications." *Environment and Planning A* 10, 415–35.

Koenig, J. G. (1980). "Indicators of Urban Accessibility: Theory and Application." *Transportation* 9, 145–72.

Kwan, M.-P. (1997). "GISICAS: An Activity-Based Travel Decision Support System Using a GIS-Interfaced Computational-Process Model." In *Activity-Based Approaches to Travel Analysis*, edited by D. F. Ettema and H. J. P. Timmermans, pp. 117–34, New York: Elsevier Science.

——— (1998a). "Gender Differences in Non-Work Activity-Travel Behavior in Space-Time: A Case Study of Columbus, Ohio." Manuscript, Ohio State University.

——— (1998b). "Gender Differences in Access to Urban Opportunities." Manuscript, Ohio State University.

——— (1998c). "Activity-Travel Behavior and Accessibility." Manuscript, Ohio State University.

Kwan, M.-P., and X.-D. Hong (1998). "Network-Based Constraints-Oriented Choice Set Formation Using GIS." *Geographical Systems*, forthcoming.

Lakshmanan, T. R., and W. G. Hansen (1965). "A Retail Market Potential Model." *Journal of the American Institute of Planners* 31, 134–43.

Landau, U., J. N. Prashker, and B. Alpern (1982). "Evaluation of Activity Constrained Choice Sets to Shopping Destination Choice Modelling." *Transportation Research A* 16(3), 199–207.

Lenntorp, B. (1976). *Paths in Time-Space Environments: A Time Geographic Study of Movement Possibilities of Individuals*. Lund Studies in Geography B: Human Geography, Lund: Gleerup.

Linneker, B. J., and N. A. Spence (1992a). "Accessibility Measures Compared in an Analysis of the Impact of the M25 London Orbital Motorway on Britain." *Environment and Planning A* 24, 1137–54.

——— (1992b). "An Accessibility Analysis of the Impact of the M25 London Orbital Motorway on Britain." *Regional Studies* 26(1), 31–47.

McLafferty, S. (1982). "Urban Structure and Geographical Access to Public Services." *Annals of the Association of American Geographers* 72(3), 347–54.

McLafferty, S., and V. Preston (1992). "Spatial Mismatch and Labor Market Segmentation for African-American and Latino Women." *Economic Geography* 68(4), 406–31.

——— (1996). "Spatial Mismatch and Employment in a Decade of Restructuring." *Professional Geographer* 48, 420–31.

Michelson, W. (1985). *From Sun to Sun: Daily Obligations and Community Structure in the Lives of Employed Women and Their Families*. Totowa, NJ: Rowman and Allanheld.

Miller, H. J. (1991). "Modelling Accessibility Using Space-Time Prism Concepts within Geographic Information Systems." *International Journal of Geographical Information Systems* 5(3), 287–301.

Morris, J. M., P. L. Dumble, and M. R. Wigan (1979). "Accessibility Indicators for Transport Planning." *Transportation Research A* 13, 91–109.

Muraco, W. A. (1972). "Intraurban Accessibility." *Economic Geography* 48, 388–405.

Nishii, K., and K. Kondo (1992). "Trip Linkages of Urban Railway Commuters under Time-Space Constraints: Some Empirical Observations." *Transportation Research B* 26, 33–44.

Oberg, S. (1976). *Methods of Describing Physical Access to Supply Points*. Lund Studies in Geography B. Gleerup: Lund.

O'Kelly, M. E., and E. J. Miller (1984). "Characteristics of Multistop Multipurpose Travel: An Empirical Study of Trip Length." *Transportation Research Record* 976, 33–39.

Oppong, J. R., and M. J. Hodgson (1994). "Spatial Accessibility to Health Care Facilities in Suhum District, Ghana." *Professional Geographer* 46(2), 199–209.

Palm, R. (1981). "Women in Non-Metropolitan Areas: A Time-Budget Survey." *Environment and Planning A* 13, 373–8.

Pickup, L. (1985). "Women's Travel Needs in a Period of Rising Female Employment." In *Transportation and Mobility in an Era of Transition*, edited by G. R. M. Jansen, P. Nijkamp and C. J. Ruijgrok, pp. 97–113. North-Holland: Elsevier Science.

Pirie, G. H. (1979). "Measuring Accessibility: A Review and Proposal." *Environment and Planning A* 11, 299–312.

Richardson, A. J., and W. Young (1982). "A Measure of Linked-Trip Accessibility." *Transportation Planning and Technology* 7, 73–82.

Rushton, G. (1984). "Use of Location-Allocation Models for Improving Geographical Accessibility of Rural Services in Developing Countries." *International Regional Science Review* 9, 217–40.

——— (1988). "Location Theory, Location-Allocation Models, and Service Development Planning in the Third World." *Economic Geography* 64, 97–120.

Salomon, I., and M. Tacken (1993). "Taming the Peak: Time and Timing as Travel Moderators." In *A Billion Trips a Day: Tradition and Transition in European Travel Patterns*, edited by I. Salomon, P. Bovy, and J. P. Orfeuil, pp. 53–74. Dordrecht: Kluwer Academic Publishers.

Sherman, L., B. Barber, and W. Kondo (1974). "Method for Evaluating Metropolitan Accessibility." *Transportation Research Record* 499, 70–82.

Song, S. (1996). "Some Tests of Alternative Accessibility Measures: A Population Density Approach." *Land Economics* 72(4), 474–82.

Stegman, M. A. (1969). "Accessibility Models and Residential Location." *Journal of the American Institute of Planners* 35, 22–29.

Stone, P. A. (1973). *Structure, Size and Costs of Urban Settlements*. London: Cambridge University Press.

Taaffe, E. J., H. L. Gauthier, and M. E. O'Kelly (1996). *Geography of Transportation*. Upper Saddle River, N.J.: Prentice-Hall.

Thill, J.-C., and J. L. Horowitz (1997). "Modelling Non-Work Destination Choices with Choice Sets Defined by Travel-Time Constraints." In *Recent Developments in Spatial Analysis: Spatial Statistics, Behavioural Modelling, and Computational Intelligence*, edited by M. M. Fischer and A. Getis, pp. 186–208. Heidelberg: Springer.

Tivers, J. (1985). *Women Attached: The Daily Lives of Women with Young Children*. London: Croom Helm.

Villoria, O. G., Jr. (1989). "An Operational Measure of Individual Accessibility for Use in the Study of Travel-Activity Patterns." Ph.D. Dissertation, Graduate School of the Ohio State University, Columbus, Ohio.

Wachs, M., and T. G. Kumagai (1973). "Physical Accessibility as a Social Indicator." *Socio-economic Planning Science* 7, 437–56.

Walsh, S. J., W. M. Gesler, P. H. Page, and T. W. Crawford (1995). "Health Care Accessibility: Comparison of Network Analysis and Indices of Hospital Service Areas." *Proceedings of GIS/LIS '95*. Bethesda, Maryland: American Society for Photogrammetry and Remote Sensing.

Williams, H. C. W. L. (1976). "Travel Demand Models, Duality Relations, and User Benefit Analysis." *Journal of Regional Science* 16(2), 147–66.

Wilson, A. G. (1971). "A Family of Spatial Interaction Models, and Associated Developments." *Environment and Planning* 3, 1–32.

Wyatt, P. J. (1997). "The Development of a GIS-Based Property Information System for Real Estate Valuation." *International Journal of Geographical Information Systems* 11(5), 435–50.

Wyly, E. K. (1996). "Race, Gender, and Spatial Segmentation in the Twin Cities." *Professional Geographer* 48, 431–44.