Volume 4 Numbers 2/3
September/December 2001
ISSN 1094-8848

SPECIAL ISSUE ON METHODOLOGICAL ISSUES IN ACCESSIBILITY

BUREAU OF TRANSPORTATION STATISTICS UNITED STATES DEPARTMENT OF TRANSPORTATION

JOURNAL OF TRANSPORTATION AND STATISTICS

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Bureau of Transportation Statistics
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Washington, DC 20590
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JOURNAL OF TRANSPORTATION AND STATISTICS

Volume 4 Numbers 2/3
September/December 2001

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Introduction to the Special Issue on Methodological Issues in Accessibility Measures with Possible Policy Implications

Fundamental to urban and regional transportation analysis is the concept of accessibility. Because of the increasing complexity of transportation systems and their impact on our quality of life, accessibility-based ideas must become an integral part of transportation planning and evaluation. Although accessibility has been studied for a long time and there are various perspectives in its definition and measurement, it is fundamentally concerned with the opportunity that an individual at a given location possesses to participate in a particular activity or set of activities.

The objective of this special issue of the *Journal of Transportation and Statistics* is to facilitate a discussion on the issues involved in making accessibility-based considerations a routine part of transportation planning and evaluation. The measurement of accessibility has a rich, substantive history in the urban and regional sciences. But, except for assessing the impacts of the transportation system on special groups and for special purposes, planners and policymakers have not routinely and continuously evaluated urban systems on the basis of accessibility. However, as transportation planners are increasingly called on to address a variety of social, economic, and environmental considerations beyond historical mobility-based considerations, accessibility measures must be developed and disseminated to practitioners to enhance planning practices and improve policy evaluations. Further, the development of data and software to estimate these measures will tremendously expedite this shift in planning practices.

The papers in this special issue reflect the diverse considerations that must be taken into account in developing means to measure accessibility. Some of the papers address conceptual issues in defining and measuring accessibility, some target the development of applications tools, while others focus on empirical examples of accessibility measures.

As accessibility-based planning approaches take hold, the need for continued research and development in this area will increase. It is our hope that the publication of this special issue will raise awareness of the need to mainstream accessibility-based measures in planning and policy analysis and evaluation.

PIYUSHIMITA (VONU) THAKURIAH
Guest Editor
University of Illinois at Chicago

Computational Tools for Measuring Space-Time Accessibility Within Dynamic Flow Transportation Networks

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ABSTRACT

The space-time prism (STP) and STP-based accessibility measures are powerful techniques for assessing the ability of individuals to travel and participate in activities at different locations and times in a given environment. However, traditional STPs and STP-based accessibility measures ignore spatial and temporal variations in travel times in an urban environment. Factors such as traffic congestion impose increasingly complex and severe constraints on individual travel and participation in activities. This paper reports on the development of dynamic STP-based accessibility measures and computational procedures for assessing individual accessibility in networks with time-varying flow. We extend static network-based STPs to the case where network flow and travel velocities vary across time due to congestion. These tools can evaluate the accessibility of travelers under different traffic congestion scenarios, alternative network flow control strategies, and activity scheduling policies (e.g., flextime and telecommuting).

INTRODUCTION

Much travel behavior research focuses on understanding an individual's decision processes and analyzing the elementary factors determining travel

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activity. Consequently, most transportation planning tools emphasize travel demand patterns and predicting travelers' responses to transportation policy and management options. These methods concern *how* or *when* travel activities will take place throughout the transportation system. Accessibility measures are alternative approaches that emphasize the potential for travel behavior conditioned by the performance of the transportation system. Accessibility measures assess an individual's freedom to participate in activities in a given travel environment rather than explaining or predicting actual travel choices. Because they highlight constraints on travel rather than revealed travel choices that intertwine preferences and constraints, accessibility measures can be a more sensitive assessment technique than analyses of actual travel behavior (Hägerstrand 1970).

Conventional accessibility measures focus on tradeoffs between the attractiveness of opportunities and the travel cost required to obtain these opportunities (see, e.g., Geertman and Van Eck 1995). These indicators usually measure attractiveness through surrogates such as the size or variety of the opportunity (e.g., store size for retail opportunities) and travel cost through physical distance, travel time, or monetary cost. Accessibility is usually measured with respect to key activity locations for individuals (e.g., home, workplace) and evaluates the transportation services provided to these key locations to assess their relative advantages (Burns 1979).

Conventional accessibility measures often neglect the fact that the temporal dimension also affects individual accessibility. Limited time "budgets" or available time for travel and activity participation can constrain the participation time for each activity and therefore reduce individual accessibility. Periodic activity schedules, conditioned by required spatio-temporal events such as a fixed work schedule or child maintenance activities, vary widely but systematically by life stage, sex, socioeconomic status, and culture. An analysis by Kwan (1998) suggests that space-time measures are more sensitive in capturing interpersonal differences in individual accessibility than conventional measures. Measures that do not capture temporal constraints created by individual activity schedules are a one-size-fits-all depiction of accessibility that is insensitive to individual differences (Kwan 1998; Miller 1999; Miller and Wu 2000).

Hägerstrand's (1970) *space-time prism* (STP) is a powerful conceptual tool that captures both spatial separation and temporal constraints that limit individuals' freedom to travel and participate in required and desired activities. Accessibility measures based on the STP consider the spatial extent of travel and available activity participation time dictated by individual activity schedules. Most of these measures capture these schedules by measuring spatial separation with respect to anchor locations (e.g., home, work) and restricting travel extent based on the individual's time budget or free time for travel and activity participation (Miller 1999; Kwan 1998).

A weakness of STP-based accessibility measures, and accessibility measures in general, is their treatment of travel times as static. Consequently, these measures cannot capture the potential impacts of transportation network congestion on accessibility. Traffic congestion is a major problem and policy issue in many cities (Cervero 1986; Plane 1995). The traditional suburb to central city journey-to-work pattern has been replaced by more complex commuting patterns involving substantial suburb-to-suburb flows. Service sector working hours tend to be staggered and occupy more of the daily clock than traditional employment. This results in congestion being spread beyond the traditional morning and evening peak periods (Hanson 1995). The increasing saturation of urban transportation networks means that localized incidents (e.g., construction or accidents) can propagate widely through the network. This suggests the need for new tools to capture dynamic congestion patterns in urban transportation networks and the potential for these tools to affect accessibility.

This paper reports on the development of dynamic space-time accessibility measures and computational procedures for assessing individual accessibility in networks with time-varying congestion. We extend static network-based space-time accessibility measures to the case where network flow and travel velocities vary across time due to congestion. We also develop a computational toolkit that uses simulated dynamic traffic conditions to calculate travel times based on the shortest path routes through a network with dynamic flows. Our computational toolkit is coupled with a geographic information system (GIS), facilitating spatial data management and visualization of the resulting accessibility regimes.

Following this introduction, there are six sections to this paper:

- Space-Time Accessibility reviews the conceptual and theoretical basis for the space-time accessibility measures.
- Dynamic Space-Time Accessibility Constructs discusses the algorithm for calculating space-time accessibility within dynamic transportation networks.
- Dynamic Congestion Modeling provides the methodology used for developing the dynamic congestion module.
- System Design describes the system configuration for the toolkit.
- Example Calculations shows some preliminary results.
- The Conclusion provides some summary comments and directions for continued system development.

SPACE-TIME ACCESSIBILITY

Temporal Constraints and Activity Participation

Since all human activities occur in space and time, these dimensions are inseparable from the intricacies of human behavior (Hägerstrand 1970). Empirical research has shown that temporal constraints can impact significantly the ability of individuals to participate in activities. Time-policy research suggests that space-time accessibility affects individual travel behavior both in space and time (Tacken 1997). Adding temporal constraints that affect the size of individuals' choice sets can improve prediction accuracy of behavioral choice models (Landau et al. 1981; 1982). The space-time constraint framework provides the fundamental physical constraints to define individuals' potential action space (Dijst and Vidakovic 1997). Many activity-based travel models (e.g., Recker et al. 1986) require time constraints to restrict the number of possible activity schedules when predicting individual activity programs.

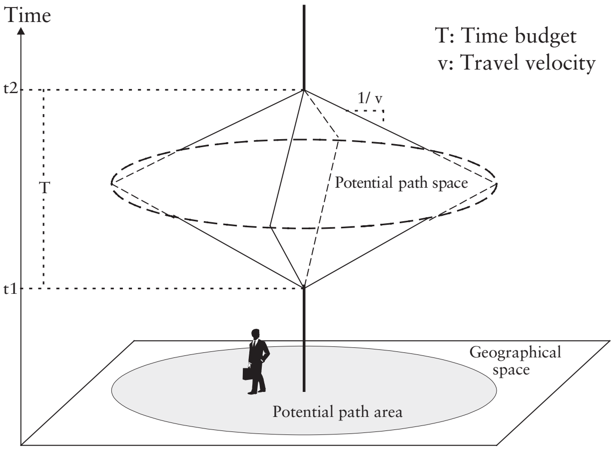
Classical Space-Time Prisms

Hägerstrand's (1970) *time geography* is an elegant and powerful framework for measuring constraints to individual accessibility. Time geography incorporates the spatial, temporal, and transportation elements that affect accessibility within a geographic environment. In its classical form, the activity pattern of an individual is a space-time path in three-dimensional space where a two-dimensional horizontal plane represents geographic locations and a vertical axis represents time. The path traces the spatio-temporal position of the individual's travel and activity behavior. The limits on this path create an accessibility regime that is a connected and continuous set of positions in space-time known as the space-time prism (Lenntorp 1976).

An individual's activity schedule is usually constrained by fixed (mandatory) activities. The *mandatory activities* typically include work, home, or other household maintenance activities (e.g., driving children to school). The STP is an extension of the space-time path during temporal intervals when the individual is free to participate, in *discretionary activities*. These are activities over which the individual has relative control with respect to location and timing; examples include shopping and recreation. The STP is the set of locations in space-time that are accessible to an individual given the locations and duration of fixed activities, a time budget for flexible activity participation, and the travel velocities allowed by the transportation system. Instead of tracing the observed movement throughout space of an individual over an interval of time, the STP indicates what portions of space are possible for an individual at each moment in time (Miller 1991). The STP also delimits the feasible set of locations for travel and activity participation in a bounded territory of space and a limited interval of time (Burns 1979; Miller 1991; Kwan 1998).

Figure 1 illustrates an STP. The three-dimensional volume bounded by the STP is called the *Potential Path Space* (PPS). An individual's time budget (available time for travel and activity participation), spatial constraints (fixed activity

FIGURE 1 Individual's Space-Time Prism (adapted from Miller 1991)



locations that determine travel origin/destination within the discretionary time period), and the available travel velocity in the environment determines the PPS. The prism boundaries demarcating the STP result from the available travel velocity within the geographic environment. In the classical STP, travel velocity is assumed to be constant across space for analytical simplicity.

The *Potential Path Area* (PPA) is the projection of the PPS to planar (two-dimensional) space. The PPA represents the purely spatial extent or area that an individual can travel within a specified time budget. It can be calculated directly without reference to the PPS, with any stationary activity participation time excluded from the overall time budget to reflect the reduced amount of time available for travel (Miller 1991).

Several researchers have developed accessibility measures based on the STP. STP-based measures view accessibility as an individual's ability to reach activity locations given the person's daily activity program and spatio-temporal constraints (Kwan 1998). STP-based measures usually include the following elements. First is a reference fixed-activity event in space and time from where and when the accessibility of an individual to other locations is measured. Second is a set of destinations (activity locations) and their attributes representing the discretionary opportunities available to an individual. Third is a transportation system that enables an individual to overcome the spatial temporal separation of activity sites. Therefore, any STP-based measure of accessibility may be defined as basically a quantification of the opportunities for activity participation open to an individual from a given location at a given time of day.

Lenntorp (1976) uses the PPS and the PPA to simulate all possible activity schedules within an urban environment. Lenntorp's simulation model (Program Evaluating the Set of Alternative Sample Paths) does not calculate the STP directly. Input variables are the general characteristics of the transportation system, the spatial distribution and operational hours of activity, and a hypothetical activity schedule as variables. The hypothetical activity schedule provides constraints imposed by the fixed activities. The fundamental assumption is that greater freedom for flexible activity participation implies greater accessibility. Therefore, the number of possible flexible activity schedules allowed by the PPS and PPA are a surrogate for accessibility.

Other researchers use mathematical and geometric methods to directly measure STP properties. For example, Burns (1979) uses geometric methods to calculate the volume of the STP under different transportation environments (e.g., continuous space versus different types of uniform network meshes, travel timing policies). The STP volume is a surrogate for individual accessibility. Similar methods can be found in Kitamura et al. (1981) and Kondo and Kitamura (1987).

Forer (1998) develops a 3-D raster model using taxels as the basic building block for constructing an STP. Its GIS-based method overlays relevant layers of geographic information (e.g., the transportation network, activity locations) during each discrete time interval comprising a temporal study horizon. This allows the analyst to visualize accessibility as a space-time "aquarium." It also creates an accessibility mask for spatio-temporal querying using customized 3-D data structures. While effective, a shortcoming is the same as for any raster model; that is, large data storage requirements as the spatial and temporal domains of the problem grow.

Network-Based Space-Time Prisms

The space-time framework provides a powerful and elegant perspective for analyzing individuals' accessibility within the environment. Instead of directly modeling travel interaction throughout the system, the STP provides a measure to describe individual possible travel behavior under physical constraints. However, it is difficult to operate and apply in its classic form as a real-world accessibility tool. The ideal geometries of the STP, PPS, and PPA result from the unrealistic assumption of a constant and uniform travel velocity.

In order to improve the realism and applicability of the space-time prism approach, Miller (1991) developed an operational method for implementing a network-based space-time prism using GIS procedures. This approach uses link-based travel speed, instead of uniform travel conditions, throughout the transportation system. The *Network Time Prism* (NTP) is comprised of arcs and nodes in the transportation network rather than an unrealistic simple geometric set that assumes constant travel velocities across space. A *Potential Path Tree* (PPT) is a subtree of the network consisting of nodes and arcs reachable given fixed activity locations and a time budget. Its root is usually the travel origin, although it can also be anchored at the travel destination. Kwan and Hong (1998) extend this approach by incorporating cognitive (information, preference) constraints into the PPT. The study defines the *feasible opportunity set* (FOS) as the subset of opportunity locations available to an individual, based on both temporal and cognitive constraints.

Miller (1999) develops *space-time accessibility measures* (STAMs) of users' benefits based on the PPT. These measures are consistent with behavioral choice theory and with the rigorous Weibull (1976) framework for spatial interaction-based accessibility measures. Miller (1999) also develops computational methods for calculating these measures within the network itself for query and visualization purposes. Miller and Wu (2000) describes the architecture of a GIS toolkit for these measures and provide examples for a detailed, urban-scale transportation network.

Using the urban transportation network to calculate space-time measures can provide a more realistic method for evaluating accessibility relative to classical time geographic measures. However, the previous approaches reviewed above do not consider the temporal dynamics of real-world transportation networks. As mentioned in the introduction, the increasing saturation of most real-world transportation networks means that assuming static network conditions is as unrealistic as assuming constant travel velocity across space. Our objective in this paper is to implement the dynamic space-time accessibility measures within a realistic time-varying transportation network.

DYNAMIC SPACE-TIME ACCESSIBILITY CONSTRUCTS

The space-time accessibility measures in the research focus on how the constraints within urban environments affect an individual's choice of activity. The space-time prism provides a direct framework for this type of accessibility measure. We use simulated time-varying flows within a transportation network to compute dynamic versions of the basic NTP constructs.

In a *Dynamic Network Time Prism* (DNTP), travel times between locations vary with both space and time. Travel between any two locations in a network with time-varying flows must be constrained by the start/stop time intervals for the travel episode and traced along a finite set of connected arcs in space-time. Given a travel origin and start time, a DNTP is a subset of a space-time network that indicates the maximum travel extent under time constraints dictated by the individual's activity schedule, including the timing of the travel and activity episode.

A *Dynamic Potential Path Tree* (DPPT) is a time-dependent maximum coverage tree from an origin to any network nodes given dynamic network flow conditions and a specified departure time. The DPPT can be combined with geographic visualization techniques, such as animation tools, to provide powerful visualizations of changing accessibility conditions over time within a congested transportation network. It could also be used to support spatio-temporal network queries based on space-time accessibility and as input to models such as activity scheduling simulations.

The DPPT can be used to construct the *dynamic opportunity set* (DOS) of activity locations for an individual. The DOS extends the FOS concept from Kwan and Hong (1998) to the case of dynamic temporal constraints imposed by time-varying traffic flow and therefore travel velocities. This opportunity set is based on the timing of travel from the origin to the activity location, net any activity participation time:

$$M = \left\{ k \in \Omega \mid T_k = T - t_i^d \left(x_i , x_k \right) \geq t_k^m \right\} \tag{1}$$

where

M = the set of accessible discretionary activity locations, given the travel origin, time budget, and dynamic network flow.

Ω = the set of total discretionary activity locations.

T_k = participation time at activity discretionary activity location k.

T = the overall time budget for travel and activity participation.

t_k^m = minimum required time for activity participation time at location k.

$t_i^d \left(x_i , x_k \right)$ = the minimum travel time from x_i to x_k given a departure at time d.

Equation (1) shows that the subset of feasible activity locations must have greater activity participation time (T_k) than the minimum required time for discretionary activity k. The minimum required time for each discretionary activity could be standardized for each activity or derived for individuals from activity diary data. The activity participation time is the time budget minus the minimum travel time $t_i^d \left(x_i , x_k \right)$. The minimum travel time is constrained by the start time from travel origin and dynamic network flows. Time budgets vary by individual; these can be extracted from activity diary data or by self-reporting (see Miller 1999). The procedure calculates the dynamic shortest path from the specified travel origin to all possible discretionary activity points. The shortest path is very easily extracted once the DPPT is created.

Equation (1) creates a set of feasible discretionary activity locations rather than a subset of the network arcs. This type of DNTP calculation only delimits feasible activity locations; it does not consider activity attractiveness as part of the accessibility measure (as in Miller 1999). However, it can be used to delimit the activity choice set for further dynamic accessibility for input into dynamic versions of the STAMs.

DYNAMIC CONGESTION MODELING

Since we need to construct DNTP measures based on time-varying flow conditions, we require some method for computing these flows. The particular dynamic flow model that provides these estimates is modular in the sense that any model is acceptable if it can generate realistic dynamic flow and travel time estimates. However, the method must be computationally efficient due to the number of calculations required for the DNTP measures.

Initial work on developing dynamic flow models began in the late 1970s with Merchant and Nemhauser (1978a; 1978b). Several approaches to the dynamic network flow problem have emerged, including: 1) simulation-based approaches; 2) optimal control theory; 3) variational inequality; 4) dynamic systems approaches; and 5) mathematical optimization. Although several dynamic network flow models are available (see Friesz et al. 1996; Ran and Boyce 1996; Chen 1999), most of these methods (particularly continuous-time formulations) are not computationally efficient to the degree required for the DNTP calculations of interest in this paper.

Equilibrium analysis is a relatively efficient approach to modeling transportation network flows. The equilibrium approach captures the relationship between users' travel decisions and network performance assuming shortest path travel. However, as Ben-Akiva (1985) argues, traditional static network equilibrium models fail to capture fundamental properties of traffic congestion. Janson greatly improved the applicability of dynamic network flow modeling to real-world network problems by developing a tractable discrete-time *dynamic user optimal* (DUO) approach (Janson 1991a; 1991b). Furthermore, the Janson DUO model can be solved for realistic, urban-scale networks with reasonable computational times (Robles and Janson 1995; Boyce et al. 1997) making it suitable for constructing DNTP. Because of its tractability, we use the Janson DUO model in our DNTP procedures, although we can swap this for other dynamic flow models in future system development if breakthroughs allow more sophisticated models to be solved efficiently.

The DUO is a direct extension of Wardrop's user optimal equilibrium conditions. The DUO condition requires that, at network equilibrium, no traveler who departed or arrived during the same time interval can reduce his or her travel costs by unilaterally changing routes. An alternative but equivalent statement is that all routes used between an origin-destination (O-D) pair have the same minimal cost, and no unused route has a lower cost for travelers that departed or arrived during the same time interval. The DUO is based on either departure or arrival times, not both. Since travel times are variable, we cannot constrain both departure and arrival times within the equilibrium conditions. Therefore, the DUO conditions assume either a known (fixed) departure or arrival time interval for flows and require equivalent minimal travel costs for all flows that depart or arrive during each interval. The DUO principle means that positive flow on a route for users who departed (arrived) during a given time interval implies that it must have a travel cost equal to the minimum cost for the users between the particular origin-destination pair. Second, any route with a cost greater than the minimum for users who departed during a given time interval implies that the flow level for those users is zero.

The DUO model assumes a known temporal O-D matrix, with each time slice corresponding to a discrete time interval over the study time horizon. Based on this exogenous data, the DUO minimization problem, when solved, determines the dynamic flow patterns that satisfies the DUO principle while meeting the O-D flow constraints imposed by the matrices. The DUO problem is

$$MIN \sum_{k \in L} \sum_{t \in T} \int_0^{x_k^t} f_k^t(w)\,dw \qquad (2)$$

Subject to

$$x_k^t = \sum_{p \in P} \sum_{d \in T} \nu_p^d \alpha_{pk}^{dt} \qquad \text{for all } k \in L, t \in T \quad (3)$$

$$q_{rs}^d = \sum_{p \in P_{rs}} \nu_p^d \qquad \text{for all } r \in Z, s \in Z, d \in T \quad (4)$$

$$\nu_p^d \geq 0 \qquad \text{for all } p \in P, d \in T \quad (5)$$

$$\alpha_{pk}^{dt} \in \{0,1\} \qquad \text{for all } p \in P, k \in K_p, d \in T, t \in T \quad (6)$$

$$\sum_{t \in T} \alpha_{pk}^{dt} = 1 \qquad \text{for all } p \in P, k \in K_p, d \in T, t \in T \quad (7)$$

$$b_{pn}^d = \sum_{t \in T} \sum_{k \in K_{pn}} f_k^t\left(x_k^t\right) \alpha_{pk}^{dt}$$
$$\text{for all } p \in P, n \in N, d \in T, t \in T \qquad (8)$$

$$\left[b_{pn}^d - t\Delta t\right] \alpha_{pk}^{dt} \leq 0$$
$$\text{for all } p \in P, n \in N, k \in L_n, d \in T, t \in T \qquad (9)$$

$$\left[b_{pn}^d - (t-1)\Delta t\right] \alpha_{pk}^{dt} \geq 0$$
$$\text{for all } p \in P, n \in N, k \in L_n, d \in T, t \in T \qquad (10)$$

where

N = set of all nodes

Z = set of all origin-destination zones (trip begin/end nodes)

L = set of all links (directed arcs)

L_n = set of all links incident from node n

P = set of all routes between all zone pairs

P_{rs} = set of all routes from zone r to zone s

K_p = set of all links on route p

K_{pn} = set of all links on route p prior to node n

Δt = duration of each time interval (same for all t)

T = set of all time intervals in the full analysis period

x_k^t = amount of traffic flow between all zone pairs assigned to link k in time interval t

ν_p^d = amount of traffic flow departing in time interval d assigned to route p

$f_k^t\left(x_k^t\right)$ = travel impedance (travel time) on link k in time interval t

q_{rs}^d = amount of traffic flow from zone r to zone s departing in time interval d via any route

α_{pk}^{dt} = 0-1 variable indicating whether trips departing in time interval d and assigned to route p use link k in time interval t (0 = no, 1 = yes)

α_{pk}^{dt} = travel time of route p from its origin to node n for trips departing in time interval d

The dynamic constraints (equations 7–10) ensure temporal flow consistency. The temporal route-link incidence variable α_{pk}^{dt} maintains correspondence between links and routes across time intervals for trips departing within a particular time interval. This is a temporal extension of the static route-link incidence variable in the static version of this problem (equations 2–5 without the time dimension). However, a major difference is that the temporal route-link incidence is an endogenous decision variable solved within the dynamic equilibrium problem. In the DUO, the link composition of routes for trips that departed within a given time period cannot be predetermined since the time interval of link use is affected by travel time, which in turn is affected by traffic flow loadings (Janson 1991a).

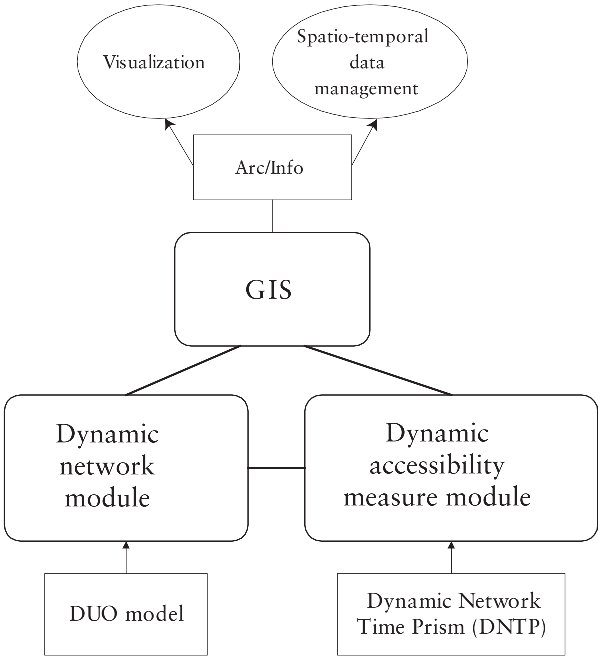
The endogenous nature of route-link incidence in the DUO requires the problem to have nonlinear dynamic flow constraints to ensure flow consistency. First, we require trips to only use each link on a given route only once within each time interval (equations 6–7). Second, we require each route to be consistent with respect to the required travel times to reach each link on the route. To ensure this, we measure the total travel time on a route from the origin to a given node for trips departing within a given time interval (equation 8). Then, we force trips to use the links on a route in a temporally consistent manner. Trips can only use a link during the interval that it reaches the from-node of the link according to the cumulative travel time to that from-node. If cumulative travel time to the from-node is greater than or less than the cumulative clock time then the temporal route-link incidence variable is forced to zero and the route cannot use that link (equations 8–10).

We can solve the DUO problem efficiently using a heuristic procedure that assigns link flows based on current flow levels, future travel demands, and flows assigned in previous intervals. An alternative, exact algorithm decomposes the main DUO problem into two subproblems, namely, a static UO assignment subproblem and a linear program that updates the temporal incidence variables and enforces conditions for temporally continuous flows. For detailed discussion of these solution procedures, see Wu et al. (2001).

SYSTEM DESIGN

Our current software system integrates three major modules for performing dynamic accessibility measures. Commercial GIS software (Arc/Info® version 7) provides the data management and visualization functions. We implement a dynamic traffic module based on Janson's (1991a) formulation for providing dynamic flow simulation. An accessibility measure module uses the dynamic network flow conditions as space-time constraints to calculate the DNTP. Both modules are stand-alone systems written in C++. Although both modules run as separate programs, the programs directly read and write Arc/Info® INFO files, allowing the GIS software to manage the input data and visualize model results. Figure 2 shows the basic system architecture.

FIGURE 2 System Architecture



Both transportation network and activity locations data are processed into Arc/Info® coverages. The dynamic traffic module reads the network structure from coverages and writes new INFO files with dynamic flow information, one file for each time interval modeled. These can be visualized and queried within the cartographic context of the network coverage using Arc/Info®. The accessibility measure module retrieves dynamic flow information from these new INFO files and calculates the DNTP. The results transfer back into Arc/Info® and create new coverages. Two discrete space versions of DNTP can be visualized and queried within Arc/Info®. *Point* entities represent an opportunity set of locations that are choices for individual activity participation. *Arc* entities represent the subset of space (defined by transport routes) that is feasible to travel. These can be used directly to access accessibility regimes given a congested network.

The current prototype performs data transfers between the three modules. The user interface is still in progress. We expect to more fully integrate the three modules using Arc/Info® version 8, which provides more powerful interface functionality than earlier versions.

EXAMPLES OF CALCULATIONS

We now provide examples of calculations of the DPPT for a realistic problem. The network in this example represents northeast Salt Lake City, Utah. It contains 7,812 directed links, 2,328 nodes, and 331 O-D zones. The discrete time interval for the DUO model is three minutes. A 2-hour study time horizon results in 40 consecutive time slices of dynamic congestion patterns. A daily O-D matrix was derived from a travel survey conducted by the University of Utah during spring 1994. We constructed a local daily peak profile curve to mimic the aggregate peak hour commute patterns in the study area. Therefore, traffic patterns during the first and last few intervals are less congested than the middle intervals within the modeled time horizon. We use the standard Bureau of Public Roads performance functions to calculate traffic flow in each time interval.

Figure 3 shows an example of a dynamic congestion pattern for the university area of the Salt

FIGURE 3 Dynamic Congestion Pattern in Salt Lake City, Interval 1 (Top) and Interval 20 (Bottom)

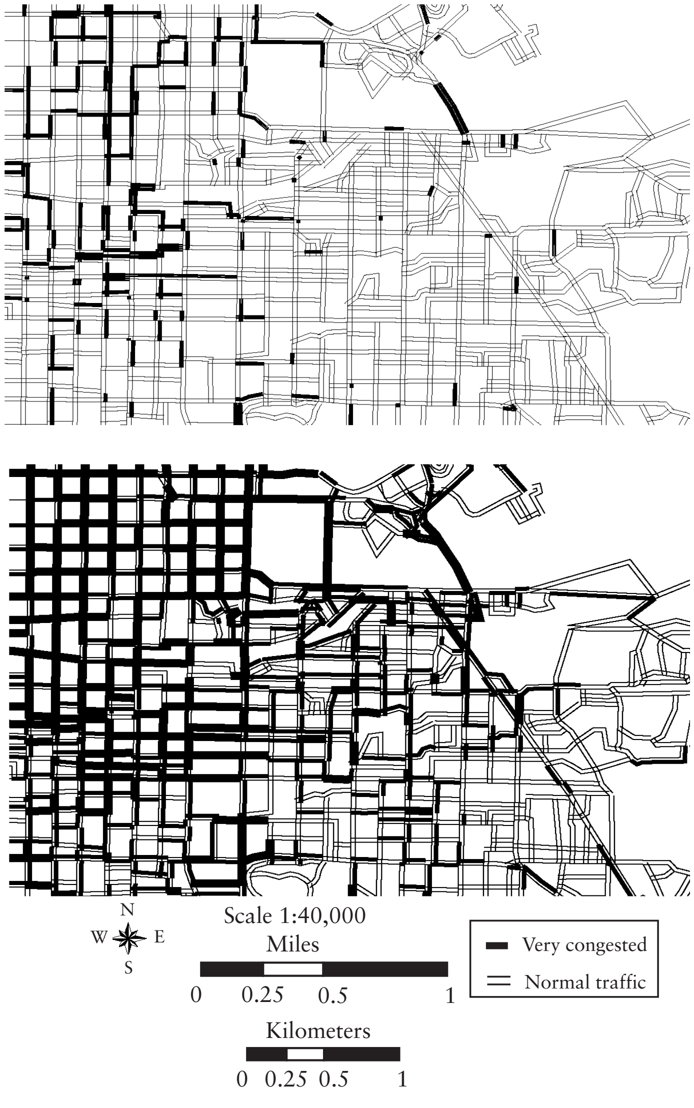
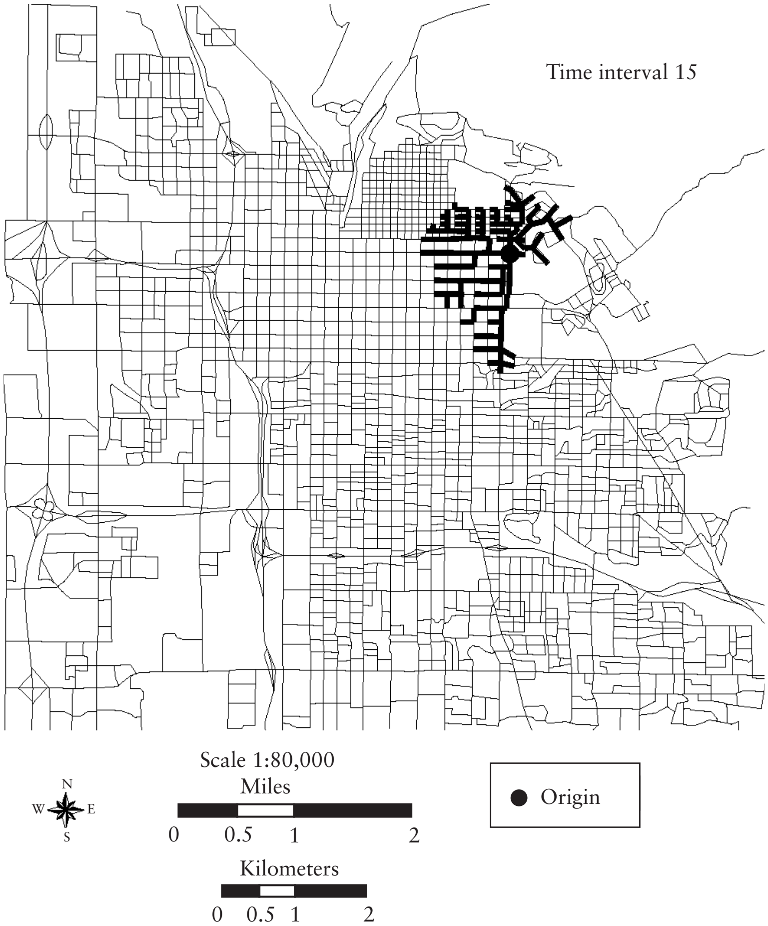


FIGURE 4 Dynamic Potential Path Tree in Salt Lake City, Given 5 Minutes Travel Time

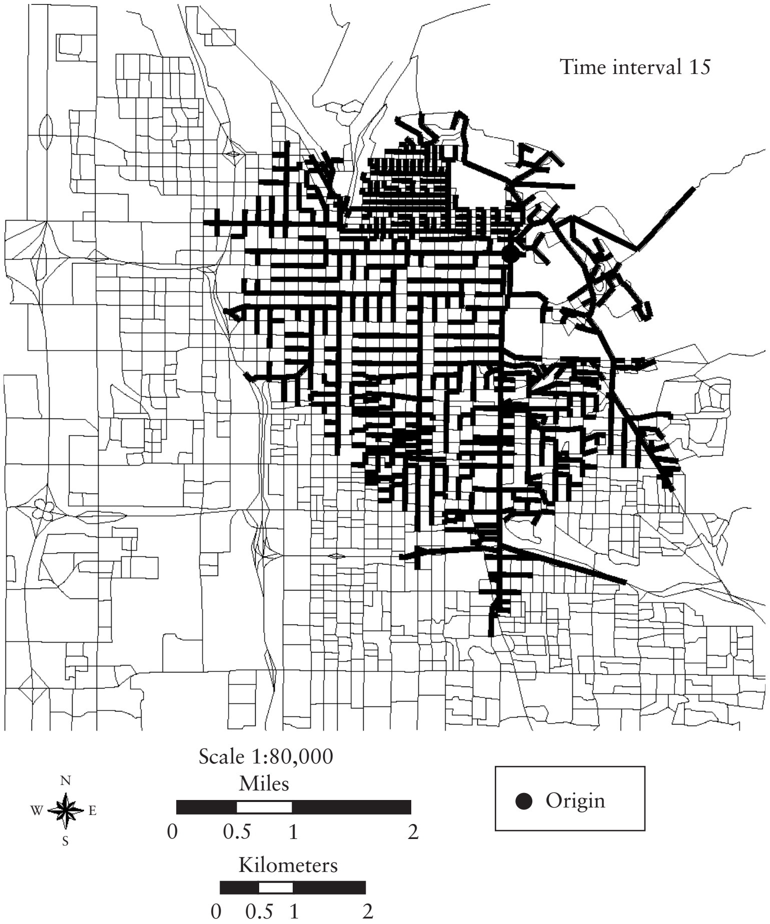


Lake City network (northeast corner of study area) in different time intervals estimated from the DUO model. For display purposes, we offset the two arcs corresponding to two-way travel within each street segment. We classify the congestion level in each arc into two categories, namely, "very congested" for flow of 80% of capacity or greater and "normal traffic" for flow levels less than 80% of capacity. The upper half of figure 3 shows the traffic conditions during time interval 1 or the first three minutes of the time horizon. The lower half of figure 3 shows the peak traffic conditions in interval 20, which is 57 to 60 minutes into the study horizon. A comparison of the two graphics shows the temporal flow complexity captured by the DUO model.

Figures 4–8 provide examples of DPPT calculations for the Salt Lake City transportation network from the GIS-DNTP software system. Figures 4 and 5 represent the DPPT for a single origin (the University of Utah) and single departure interval (time interval 15, or 42 to 45 minutes into the modeled time horizon). Figure 4 shows the accessible portion of the transportation network given a five-minute time budget for travel. Figure 5 shows the accessible portion of the network given a 15-minute time budget for travel. As is the case with the NTP, the accessible portion of the network is greater if the available time budget is larger. After calculating the DPPT, the system assigns the required travel time to each node. We can then use this information to query activity locations georeferenced at network nodes to calculate the DOS (equation 1).

Figures 6–8 show DPPTs given the same origin and time budget (10 minutes) but based on different departure time intervals. Figure 6 provides the DPPT based on departing at time interval 1 (three minutes into the modeled time horizon), figure 7 shows the DPPT based on departing in time interval 15 (42 to 45 minutes into the horizon), and figure 8 shows the DPPT based on departing during time interval 20 (60 to 63 minutes into the hori-

FIGURE 5 Dynamic Potential Path Tree in Salt Lake City, Given 15 Minutes Travel Time



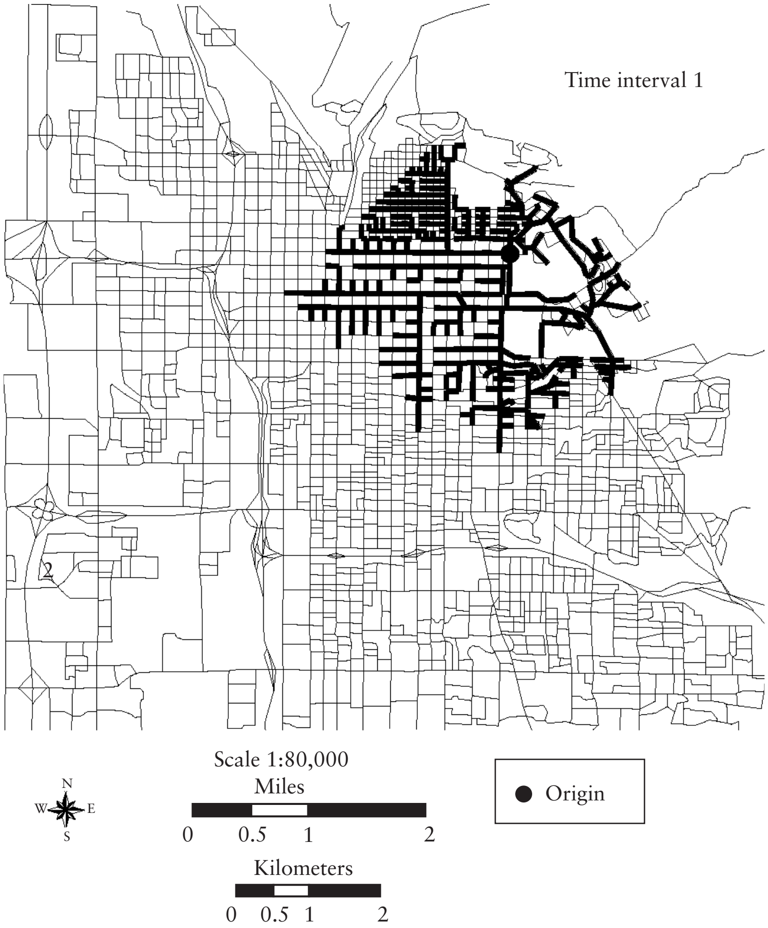
zon). Since the traffic conditions are dynamic, the reachable portion of the network varies depending on the departure interval. In figure 6, the DPPT has a relatively large spatial extent due to the low traffic flows and higher travel velocities during the initial portion of the modeled time horizon. As traffic flow builds during the middle time periods, the spatial extent of the DPPT becomes more curtailed (figure 7), particularly towards the central portion of the city (downtown is the area in the middle north of the map, just west of the DPPT extent). By the later time intervals, traffic has started to ease and the DPPT spreads outward (figure 8). Note that the DPPT extends substantially toward the south in time interval 20 since traffic flows ease first in these more peripheral locations of the city.

CONCLUSION

This paper introduces realistic conditions of time-varying flow and congestion within the transportation network for dynamic space-time accessibility measures. This allows the accessibility measures to consider the locations and time-varying travel velocities dictated by the network. These computational procedures are tractable with respect to storage space and time requirements, meaning they can be applied to urban-scale accessibility analyses with detailed networks. The GIS environment supports visualization, querying, and additional analysis of accessibility within the transportation network structure.

The dynamic space-time accessibility measures in this research only consider the space-time constraints within the urban environment. The DPPT we construct is from a specified origin given available travel time and departure time interval. Moreover, DPPT in this research is a *path tree* that depicts travel from a given origin node that terminates at network nodes. In other words, the results are the subset of original network arcs. In our continuing research, we are developing a *Dynamic*

FIGURE 6 Dynamic Potential Path Tree in Salt Lake City, Given 10 Minutes Travel Time



Potential Network Area (DPNA) that extends the potential tree into a potential area. This means that the travel path can terminate at any location in the network, even at a location within an arc. This will be a dynamic version of the *extended shortest path tree* developed by Okabe and Kitamura (1996).

In this current stage, we did not include activity schedules in the calculation of DNPT. A more sensitive dynamic accessibility tool would calculate the potential path area based on archoring mandatory activity locations (e.g., home and work locations). Moreover, the attractiveness of discretionary activity locations and participation time for activities have also been ignored in this current research. The objective of further research is to capture the interactions between transportation system performance, the locations of mandatory and discretionary activities, and the individual's activity schedule using the STAMs developed by Miller (1999).

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FIGURE 7 Dynamic Potential Path Tree in Salt Lake City, Given 10 Minutes Travel Time

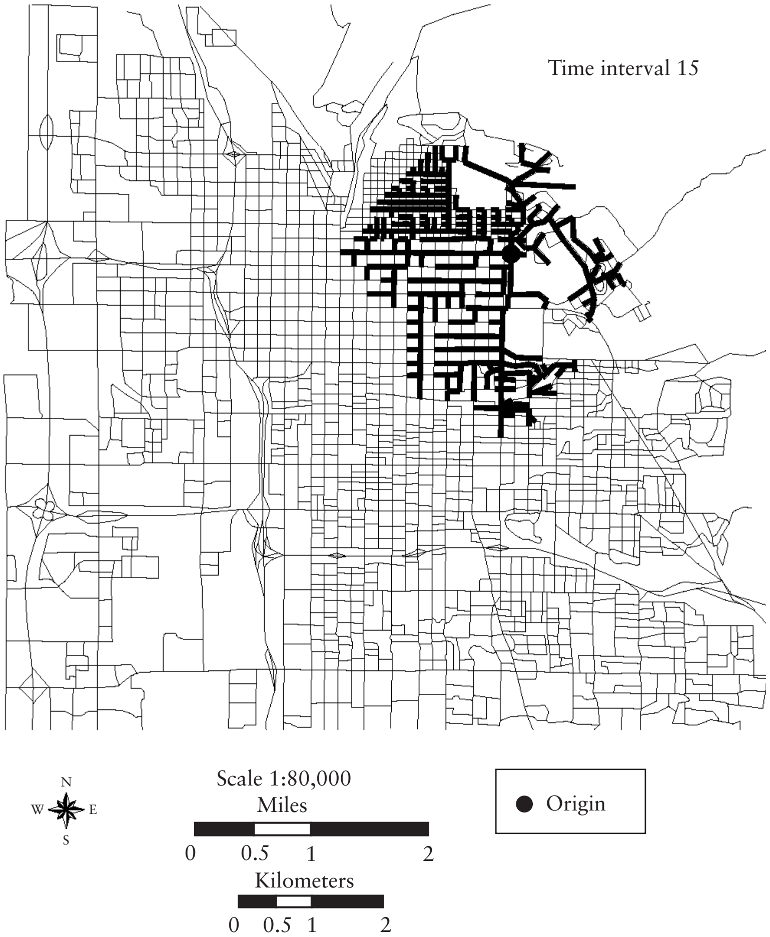

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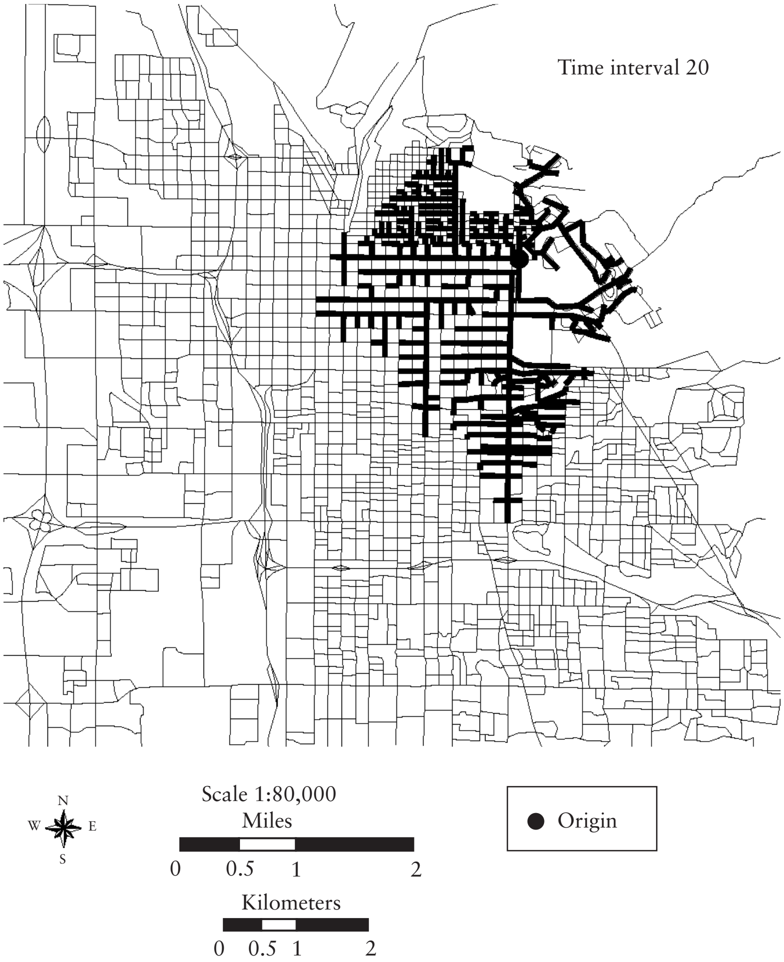
FIGURE 8 Dynamic Potential Path Tree in Salt Lake City, Given 10 Minutes Travel Time



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Accessibility: Concepts and Applications

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ABSTRACT

The character of accessibility as measuring the *situation* of a location in a region rather than its intrinsic qualities is emphasized throughout this paper. A brief characterization lays the basis for a sketch of data requirements, a specification of operational definitions, and a review of earlier findings. The idea of accessibility under competition is developed with several formulations, which are then compared through a synthetic example. Concluding comments suggest some guidelines and future directions.

INTRODUCTION

This paper will not attempt to serve as a general review of the literature on accessibility or of general practice in measuring and using it. Rather, it is an attempt to crystallize my own experience and thinking on the subject and to present a somewhat normative view of how the term accessibility should be defined and used. The ideas presented here are an extension of my much earlier "Notes on Accessibility" (Harris 1966). This note enjoyed limited circulation, but was never published in a journal. Here I also present a view of spatial competition approached through accessibility measures.

The following first three sections of the paper discuss the general nature of accessibility, the data requirements for its calculation, and possible exact

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definitions. Conclusions from earlier work are given. Then these definitions are expanded to deal with spatial competition, and a synthetic example is presented with some procedural suggestions. A concluding section discusses applications of these measures in a more general context.

THE NATURE OF ACCESSIBILITY

The *Oxford English Dictionary* defines access, a noun, as amongst other things: "the habit or power of getting near or into contact with. . . ." Clearly there is a mechanism governing ease of access. In dealing with locational matters, I focus on the influence of separation or distance in reducing access, which is thus universally applicable and of graded difficulty. Other impediments to access might require additional treatment.

Access is between entities, and most usually between actors, but we may conveniently in many cases replace entities with locations, usually assuming that these contain aggregates of entities and actors. The appropriateness of this aggregation must be constantly reviewed.

Accessibility is a measure of ease of access, which must be further defined. Generally, access is symmetrical: if A has access to B, then B has access to A; however, its measurement may be asymmetrical. Most common measures, scoring separation in space, define inaccessibility, or the opposite of ease of access. For the common-sense definition of accessibility I will focus on declining functions of separation and discuss them more fully in the second following section.

Access is not in general one-sided; we should not say that a given community has "good access" without specifying "access to what." For a pair of entities or locations we may define a measure of access, depending on their separation, but such a single quantity does not have much analytic power. A set of single measurements with one end fixed, such as the distance from the central business district (CBD), permits us to compare localities with respect to their centrality or their removal from some single center of interest. If we convert distance to some actual costs of access, we get a measure that may vary over time and may then provide a changed ranking of localities by centrality. If we aggregate the access measures to the CBD over the region, we can compare its centrality with that of other single facilities such as an airport, sports stadium, parks, or outlying recreational areas for which we might make similar aggregations.

These approaches help us understand the nature of accessibility, but they do not capture its essence. Most metropolitan locational decisions consider the variation across localities not only of immediate local conditions, or of the accessibility to single facilities, but also of situational variables related to the entire region. Thus there are many suburban communities with virtually identical local conditions, but with differing proximity to employment opportunities of different types and to other significant facilities. Useful and meaningful accessibility measurements provide a way to secure a synoptic view of locational qualities that result from nonlocal influences.

This view depends on three factors that our calculations will have to bring together. We imagine a beholder taking a view of the region from one location after another. First, we select a target being viewed as it is distributed over all locations in the region. Second, we identify those variations in cost of access between the viewing point and other locations that will influence choices. And third, we decide how a view will evaluate these costs as diminishing the importance of less accessible targets. I will propose that accessibility be measured, zone-by-zone, by a weighted average of access from each zone in the region to some target of opportunity in all other zones.

There are thus three essential elements needed to implement this conception: a distribution of one or more targets, a measurement of separation between zones, and a definition of the functional form of this weighted moving average that can reflect variations in attitudes toward interaction. In the next two sections I discuss the data required to support these ideas and the formal statement of a functional relationship.

DATA REQUIREMENTS

As to data, measuring and computing accessibilities requires: first, a system of subareas that subdivide a larger defined region (preferably exhaustively); second, one or more sets of measurements of the pairwise separation of the subareas; and third, areally distributed data sets of people, activities, and entities of interest. I will limit the possible choices in this discussion, but many changes and extensions are possible.

Conventional analysis focuses principally on metropolitan regions, divided into traffic analysis zones, census tracts, or aggregations of these. Valid measurements of separation include airline distance, route distances, travel time, cost, lack of safety or convenience, amenity, and weighted combinations of these. These measurements may vary by mode and time of day, and according to personal choice procedures for routes. (Measuring these quantities between the centroids of subareas introduces virtually unavoidable error. A special and important case is within-area travel; its nominal zero cost is often replaced by an estimated average.)

Data needed by subarea may include at least one of the following: jobs, establishments, workers at their residences, households, dwellings, vacant land, or facilities serving shopping or recreation, as well as those serving public health and safety. These categories can, and often should, be subdivided into more narrowly defined strata, including those defined by race, income, gender, family size, and the like.

Much of the foregoing information is readily available in transportation studies, but in both these and land-use studies very few items of data are deployed in any significant detail, even when most or all of it is stored in a geographic information system (GIS). Most land-use studies make limited use of large matrices of zone-to-zone time and cost. Transportation analysis pays little attention to details of housing types and probably too little attention to detailed aspects of ridership. Yet with increasing frequency these two types of studies are becoming more interdependent, and demands of equity are side-by-side with those of pollution control in calling for more detailed analyses.

Given the very large computational load in both transportation analysis and accessibility computations, it is desirable to focus on relatively few variables for these particular activities. More work will be needed to determine what accessibility computations capture all the variables that differentially affect locational choices. Analysis of those choices, in turn, may influence the way in which transportation demand analysis interprets travel behavior. After a reasonable period of further study, the scope and detail of accessibility calculations may possibly be reduced without impairing its potential power.

FORMALIZING THE CONCEPTS

The idea of accessibility as a weighted moving average of access to targets or “opportunities” may be illustrated in a very simple way, which incidentally defines a technique that can easily be adapted to the use of GIS.

Suppose that we are talking about the accessibility of various locations to retail trade customers. Imagine that we have a circular disc with a radius of one mile. We place the center of that disc on the map centroid of a zone of concern. We tally up all the customers in locations on the map within the circle. This tally represents the total accessibility to customers of that location. If we divide by the total of all customers in a relevant region, we have an average accessibility which is defined by the proportion of all customers who are within one mile of the center under study. If we were to use a larger circle, we would have a different average, the first perhaps applicable to food shopping and the second to apparel. (The graphic illustration of a circle can have as a radius only a map distance, but calculations could be based on actual time or cost.)

What we have described is a simple weighted average: every customer, in or out of the circle, is a weight; the accessibilities of customers within the circle are all 1 and those outside are all 0. The weighted sum is simply the count of those customers within the circle, and the sum of the weights is all customers. This generalizes to a series of concentric rings, to which the center has declining accessibilities, measured by their inverse radii and weighted by their populations. It can also be extended to deal with, say, purchasing power instead of customers. In each case, the result, when the weighted sum has been divided by the total target, which is the sum of the weights, including these with 0 access, is a kind of proportionate accessibility to the total “market.”

We can now move the disc in any direction, centering it on another zone centroid, and we get a new average. The reader may object, and rightly, that there is a likelihood of error when we deal with areas and their centroids, rather than with the "precise" location of individuals or houses. With millions of houses in large cities, the aggregation by area is a practical necessity that may be mitigated but not eliminated.

I now seek a more flexible measure of access between pairs of locations, which as I have suggested ought to be a declining function of their separation. Unlike the GIS approach just discussed, this function should be continuous. Accessibility has a close connection with the earlier gravity models, which with their implicit connection to Newtonian gravitation used first an inverse square of distance and later a general negative power of distance. Distance itself was generalized to a composite cost, which might become route distance, time, or monetary cost, or some combination of such variables as impede access. This definition of access has been modified in later practice to a negative exponential function, which I will use. The two definitions are equivalent, because if we use the logarithm of composite cost in the exponential function, it reduces to the negative power function. (The negative power function has a singularity when the cost equals 0, while the negative exponential varies from 0 to 1.) More complicated functions may be employed.

Once we have chosen a measure of access between pairs of points, it remains to define the measure of accessibility as a weighted sum or average of these measures. For any future behavioral analysis that we may attempt, the appropriate weights would be the targets of behavioral interest—such as jobs or shops for resident workers or shoppers, or workers or customers for business establishments. Behavioral considerations such as willingness to travel or completeness of information influence the choice of parameters for any declining function of distance, but the analysis of behavior itself goes beyond the measurement of accessibility.

I will now examine in some more detail the relation of accessibility to some other behavioral concepts used in land-use and transport analysis, at the same time providing a more precise definition of accessibility itself.

Let's first set out a useful example of a definition of accessibility, designated by Wilson as "Hansen Accessibility," from Hansen's seminal paper on "How Accessibility Shapes Land Use" (1959). Hansen accessibility for a given subarea *i*, to all other subareas *j*, each containing a sub-population W_{kj} of some total population of opportunities W_k, is given by:

$$A_{ik} = \sum_j W_{kj} f_{ij} \tag{1}$$

Where the impedance function *f* is now usually specified, with *C* a generalized cost and *b* a non-negative parameter, by:

$$f_{ij} = \exp(-bC_{ij}) \tag{2}$$

When *b* is small there is little impediment to access, so that accessibility is high, and vice versa.

The foregoing may be modified in a simple way that facilitates both computations and interpretation. We define the population or target of interest in each subarea as a proportion of the total population. Hence using lower case variables:

$$w_{kj} = W_{kj}/W_k \tag{3}$$

and

$$\sum_j w_{kj} = 1 \tag{4}$$

$$a_{ik} = \sum_j w_{kj} f_{ij} \tag{5}$$

The *a*'s now represent an average accessibility and correspond inversely to a kind of average cost, which can be readily calculated as an average cost incurred in accessing activity *k* from location *i* under the current value of *b*:

$$c_{ik} = -\ln(a_{ik})/b \tag{6}$$

This average approaches 0 as *b* becomes very large, and becomes larger as *b* approaches 0. This result corresponds with the fact that *b* represents a measure of unwillingness to travel.

It should be clear that using a normalized population involves only a change of scale in the accessibilities and does not, in a behavioral analysis, affect most comparisons between locations of the results from computing the values of *a* with the same *b, k,* and set of costs.

It is also important to note the relation between Hansen accessibility as in either definition above, and the logit or multinomial logit model of discrete choice theory. Discrete choice is based on a concept of utility, either as a weighted sum of the logarithm of variables contributing to utility or as the product of the exponentiated variables. These are equivalent as measurements of utility, but the exponential form leads to more appropriate definitions of the probability of choice. (This form has some similarity with the Cobb-Douglas production function.) Since *C* is a measure of disutility, it carries a negative coefficient (-*b*) that would be reweighted if a specific accessibility variable were used in a behavioral analysis.

With a view to further exploration, this definition of accessibility can be related to the singly constrained gravity model, as discussed by Wilson (2000) in a limited context. This model derives the number of trips *T* between subareas *i* and *j* by allocating the number of originating trips at *i*, O_i, in proportion to the number of destinations at *j*, D_j, and in inverse proportion to the impedance or cost separating the two zones. In order to ensure that the correct number of trips is distributed from each origin, a proportionality factor (call it *G*) is introduced:

$$T_{ij} = G_i O_i D_j f_{ij} \tag{7}$$

with

$$G_i = 1 / \sum_j D_j f_{ij} = 1 / A_i \tag{8}$$

so that

$$P_{j \mid i} = D_j f_{ij} / A_i \tag{9}$$

Thus the proportion of trips leaving *i* for *j* is exactly *j*'s share of the total Hansen accessibility of *i*.

EARLIER SUBSTANTIVE CONCLUSIONS

Up to this point I have summarized, with some elaboration, the basic ideas of my earlier Note. There are two empirical findings of which we may also take account. First, I found that for fixed *k* and *C,* the results of measuring Hansen accessibilities over different *b*-values were closely related. Accessibilities calculated with intermediate values could be expressed with great accuracy as linear combinations of more extreme values. This finding merits further theoretical and empirical investigation.

The second finding was based on a brief exploration of accessibility in Hartford, Connecticut, at the census tract level, using five classes of employment, two modes of travel, and two values of *b,* corresponding to short and long trips. These 20 measures of accessibility for over 100 tracts were subject to principal component analysis. The first component defined a general accessibility that accounted for over 80 percent of the variance. Three other much smaller components accounted for nearly all the rest of the variance. They measured the difference between auto and transit accessibility, accessibility for short and long trips, and accessibility to manufacturing employment verses all other employment. This analysis is carried out for populations in an urban area and is shown in tables 1 and 2.

These two findings suggest that, although in principle scores or hundreds of measures of Hansen accessibility can be defined, the intrinsic structure of urban activity distributions and their transportation connections limits the dimensionality of its significant variation, perhaps to as few as 5 or 10 composite measures. This possibility could be explored not only in its own right in connection with locational modeling, but as a powerful means of defining and comparing different urban structures.

ACCESSIBILITY UNDER COMPETITION

Anticipating the behavioral applications of these measures, I now discuss a subtle but crucial modification. In many instances, accessibility is not measured correctly if we fail to take into account the competition from other subareas for access to the target population. For instance, when considering locating a new shopping center, a developer will measure the accessibility to customers—yet if a location has high accessibility to customers, but is well served by other nearby centers, it will not be attractive. In some sense, the most attractive

TABLE 1 Mapped Hypothetical Distributions of Strata and Totals of Number of Workers (In thousands; components may not sum to totals because of rounding.)

At place of residence							At place of work						
Low income													
13	11	9	8	6	5	3	4	4	3	4	4	6	4
12	10	9	7	5	4	2	5	4	5	4	7	7	5
16	14	13	11	7	3	2	18	7	8	6	5	6	4
24	12	24	27	20	8	4	32	18	14	14	14	7	4
24	8	39	4	31	4	3	22	14	22	72	22	14	9
Middle income													
18	16	14	13	11	9	7	3	3	4	5	14	5	4
7	16	22	20	18	16	14	5	5	4	8	19	22	5
7	7	11	14	18	14	11	22	4	4	5	6	6	5
7	4	4	6	7	7	7	32	27	11	14	11	5	6
7	11	11	11	11	14	11	27	14	16	54	11	8	4
High income													
4	5	6	7	8	12	12	0	0	0	2	14	5	1
2	4	5	6	7	9	12	0	0	0	5	18	14	7
1	2	3	3	5	5	6	5	2	2	3	8	7	5
1	1	1	1	2	5	7	2	2	5	5	9	5	2
5	12	9	5	2	12	12	2	2	5	46	9	5	3
Total													
34	32	30	27	25	25	22	6	8	7	11	31	16	10
21	30	35	33	31	30	29	11	9	9	16	44	43	17
24	24	26	29	30	23	19	44	14	14	15	19	19	15
32	17	28	35	29	20	18	67	47	30	33	34	17	12
35	30	59	19	44	30	26	51	30	42	172	42	28	16

Correlations among the eight distributions displayed above

1.000	–.364	–.499	.706	.281	.198	–.166	.149
–.364	1.000	.255	.291	–.287	–.262	.051	–.207
–.499	.255	1.000	.035	–.206	–.190	.053	–.144
.706	.291	.035	1.000	.058	–.014	–.136	–.018
.281	–.287	–.206	.058	1.000	.886	.720	.959
.198	–.262	–.190	–.014	.886	1.000	.705	.948
–.166	.051	.053	–.136	.720	.705	1.000	.849
.149	–.207	–.144	–.018	.959	.948	.849	1.000

Principal components analysis of correlations: five eigenvalues and eigenvectors

Trace and cumulative proportions:

3.675456	1.951240	1.358312	.711515	.201458
.459432	.703337	.873126	.962065	.987247

Principal components or loadings:

.140507	–.680508	.073444	.114835	–.180187
–.166218	.215088	.639869	–.582576	.221978
–.135377	.397800	.375140	.779367	.051789
.001011	–.472908	.635321	.143169	–.052576
.502884	–.017996	.045421	.059499	.149829
.494478	.034554	.018589	.025862	.559322
.414416	.314258	.180428	–.123674	–.757517
.514936	.092106	.076467	.001820	.060758

TABLE 2 Illustrative Set of Simple Accessibilities: $b = 1.0$

Accessibilities to 4 residence and 4 workplace distributions over 35 zones

.088	.103	.054	.087	.045	.045	.016	.039
.103	.132	.081	.110	.056	.057	.029	.051
.100	.143	.105	.118	.057	.068	.053	.060
.088	.141	.127	.117	.058	.082	.102	.077
.071	.130	.149	.110	.058	.103	.166	.097
.052	.110	.166	.098	.055	.084	.133	.082
.033	.079	.143	.073	.041	.055	.082	.055
.117	.100	.058	.098	.079	.082	.030	.071
.139	.150	.088	.134	.092	.094	.048	.084
.138	.181	.116	.151	.095	.099	.080	.093
.124	.187	.141	.152	.091	.117	.145	.112
.099	.178	.166	.144	.091	.141	.223	.138
.069	.154	.182	.126	.080	.130	.199	.124
.042	.113	.163	.095	.056	.075	.127	.078
.144	.089	.054	.104	.135	.145	.057	.124
.173	.123	.082	.135	.142	.139	.077	.128
.180	.153	.104	.154	.144	.133	.113	.134
.167	.172	.123	.160	.139	.137	.162	.143
.132	.176	.146	.152	.123	.134	.204	.144
.087	.154	.158	.128	.098	.112	.182	.120
.049	.111	.140	.092	.065	.074	.125	.081
.161	.075	.058	.106	.178	.187	.058	.158
.184	.096	.084	.129	.189	.200	.092	.174
.217	.114	.096	.152	.200	.178	.151	.181
.213	.130	.104	.158	.208	.179	.207	.196
.172	.135	.120	.147	.175	.147	.212	.171
.106	.124	.141	.120	.120	.104	.158	.121
.057	.094	.131	.087	.072	.069	.100	.076
.137	.059	.067	.092	.144	.157	.050	.130
.152	.083	.109	.116	.169	.164	.086	.150
.207	.095	.110	.143	.211	.178	.160	.188
.160	.103	.096	.124	.288	.225	.311	.267
.165	.106	.096	.128	.193	.140	.202	.173
.091	.104	.135	.105	.126	.091	.131	.113
.049	.078	.124	.076	.074	.054	.079	.067

Corresponding simple correlations:

1.000	.059	–.530	.718	.831	.792	.184	.747
.059	1.000	.438	.709	–.193	–.074	.341	–.028
–.530	.438	1.000	.073	–.356	–.243	.534	–.118
.718	.709	.073	1.000	.490	.553	.486	.575
.831	–.193	–.356	.490	1.000	.912	.482	.954
.792	–.074	–.243	.553	.912	1.000	.491	.947
.184	.341	.534	.486	.482	.491	1.000	.687
.747	–.028	–.118	.575	.954	.947	.687	1.000

Principal components analysis of correlations: five eigenvalues and eigenvectors

Trace and cumulative proportions:

4.415775	2.160169	1.140605	.155717	.102185
.551972	.821993	.964569	.984033	.996806

Components or loadings:

.418009	–.176421	–.344916	.122811	.441656
.056761	.562616	–.492121	–.215538	–.396866
–.100144	.580724	.376128	.596376	.312132
.351189	.317475	–.446917	.154137	.243516
.446447	–.178123	.158879	–.147357	.243650
.446582	–.099333	.131797	.472199	–.645353
.281951	.415457	.441514	–.558792	.049976
.458735	–.010425	.245144	–.045879	–.111209

locations will have the greatest difference between accessibility to customers and accessibility to other shopping locations. The reverse case in this instance is not so clear. A residential area accessible to shops will not be so adversely affected by the closeness of other residences unless this leads to egregious overcrowding in the shops. Other cases are more symmetrical. The value of accessibility to jobs from home is diminished by the accessibility of the same jobs to other residents. Conversely the value to an employer of accessibility to workers is diminished insofar as the nearest workers have access to many other jobs.

In the event that a market and source of supply are in perfect spatial balance, the accessibilities to each should be similar in every location, and no site would offer opportunities for greater competitive advantage than other sites to either suppliers or demanders. (It is not clear that this concept of balance would apply under all definitions of impedance or cost, or to all levels of unwillingness to travel, as indicated by the level of the parameter *b*.) I distinguish three basic approaches for operationalizing this concept, all giving somewhat similar results.

First, we may directly compare the accessibilities, forming either their difference or their ratio. A particular new location is more advantageous to the supplier or the market, depending on which has the lower accessibility from this location. The behavior of locators following this rule would modify the relative accessibility in this location so as move the two sides of the market toward spatial balance. Considering only the accessibilities applying to these two activities, an area favorable for the location of one is unfavorable for the other. We may thus define two new accessibility variables. (From this point, we will usually assume that all accessibilities and target populations are normalized, without using the lower case representation.) The first of these new variables is the accessibility to population 1, discounted by the proximity of population 2, while the second is the inverse of this:

$$A_{i3} = A_{i1}/A_{i2} \tag{10a}$$

$$A_{i4} = A_{i2}/A_{i1} \tag{10b}$$

The second approach is one developed by Shen (1998). He calculates the accessibility of each of two activities, which we again designate as 1 and 2, from every subarea. He then recalculates the accessibility on the basis of one of the two new variables defined by

$$W_{3j} = W_{1j}/A_{j2} \tag{11a}$$

$$W_{4j} = W_{2j}/A_{j1} \tag{11b}$$

Call activity 1 employment and activity 2 workers at home. Then activity 3 will be employment discounted for access to workers at home, with activity 4 being workers at home, discounted by their proximity to employment. If we are to treat the two possible new accessibilities as a weighted average access, then the new activity variables must be normalized to sum to 1, but it is perhaps preferable to use an unnormalized variable in this case. The result would be a new measure that would vary around unity as does the first approach. This general approach may be extended to other pairs of variables, so long as the universes' activity totals are equal, which is true if both are normalized.

As a third approach, we can use the two balancing factors of a doubly constrained gravity model, as defined by Wilson (1970). In this model, trips between (say) home locations and work locations are to be distributed in proportion to the number of workers at each type of location, and in inverse proportion to the impedance between locations. However, ensuring that the totals at each location are exactly satisfied by the sums of trips requires two sets of balancing factors. We define these using a modification of the standard notation with *H* and *B* replacing *A* and *B,* and with trips, origins, destinations, and impedance factors as above:

$$T_{ij} = H_i O_i B_j D_j f_{ij} \tag{12a}$$

$$H_i = 1/\sum_j B_j D_j f_{ij} \tag{12b}$$

$$B_j = 1/\sum_i H_i O_i f_{ij} \tag{12c}$$

The balancing factors *H* and *B* are vectors unique to a multiplicative factor and are not readily comparable in raw form; I adjust them so that their geometric means are equal. The reciprocals of the balancing factors are modified accessibilities of the types discussed in the two previous possible procedures, in which two distributions interact. Indeed, as pointed out by a referee, the previous method as proposed by Qing is equivalent to the first iteration of one way of determining *H* and *B*. In practice, such modified accessibilities fall on both sides of unity, and their interpretation as average costs requires a special approach. In every case, they may be taken to be costs, either positive or negative, that modify the measured average cost of separation. This economic interpretation is clarified below, and may be extended by analogy to the second procedure above.

We may define two new variables, *U* and *V*, as follows:

$$U_i = \ln(H_i)/b \tag{13a}$$

$$V_j = \ln(B_j)/b \tag{13b}$$

These variables, when used in the calculation of *T*, show how *U* and *V* modify the costs, *C*, and illustrate the relation between the doubly constrained gravity model and the transportation problem of linear programming, or the Hitchcock Problem:

$$T_{ij} = O_i D_j \exp[-b(C_{ij} - U_i - V_j)] \tag{14}$$

We may interpret *U* and *V* as offsets to interaction costs, in the metric of *C;* these are analogous to the dual variables required to clear the market under the behavioral assumptions of this model. Trips from one origin are distributed over many destinations, unlike the case in linear programming, where the number of different active origin-destination pairs is strictly limited. If *U* or *V* is negative this indicates a locational disadvantage and if positive an advantage. With some stretch of the imagination, we may regard the *H*'s and *B*'s as inverse Hansen accessibilities, so that, for example, a low balancing factor corresponds to high competitive accessibility, which leads to a high positive offset.

In computing the doubly constrained gravity model, I find it useful to normalize both *O* and *D*, each to sum to unity. (An adjustment akin to normalization is necessary whenever the two populations are originally unequal in size.) Then as a result *T*, which does not enter directly into their definition, would in fact be normalized so that its double summation over *i* and *j* is also unity. The computation of the doubly constrained model is degenerate if any of the *O*'s and *D*'s are nonpositive.

TESTING RELATIONS OF ACCESSIBILITY AND COMPETITION

The previous formulations of accessibility and the effects of competition were examined in a series of computations based on a simple hypothetical metropolitan area. I assumed an array of 35 square zones, 5 rows by 7 columns, with the central business district in the center of the lowest row of zones. Most data reported below are presented as if mapped in this array. Costs or impedances were computed as the Euclidean distances between zone centroids; no effects of congestion or mode choice were examined. The unit of distance or impedance in the computations is the separation of two adjacent zones. This seems to correspond with an actual distance of about three miles. I arbitrarily assigned three classes of workers—400,000 low income, 400,000 middle income, and 200,000 high income—to places of employment and residence, according to a pattern that was intended to be somewhat realistic. Calculations were all done with normalized employment, so that accessibility measures correspond directly with average impedances or costs. Values of *b* in the 0.25 to 3.0 range were employed, and results for selected values are reported in detail.

The following was the general scheme of the accessibility calculations. There are eight populations located in the model metropolis: home and workplace for each of three classes and for their totals. These populations were examined in pairs for each given *b*-value; there are 28 pairs, a few are of more substantive interest than the rest, but most showed similar behavior. For each pair of populations eight measures were calculated: simple accessibility and each of the three competitive measures—all of these four with respect to each member of the pair, three of them in competition that was felt through the other member. The corresponding average impedances were calculated for each accessibility measure. These calculations were the basis for a simple statistical analysis. The total output of these computations involved 5 *b*-values, 28 pairs of populations, and 8 types of accessibility in 2 forms, always for 35 zones: or a total of 78,400 "observations" or numbers. There was limited redundancy but a great deal of collinearity.

From the design of this experiment, it is not possible to examine the relationship of measures across modes of travel or types of impedance measures. I will ignore the relationships of accessibilities to a given population under different *b*-values, which tend to be linearly dependent. Similarly, I do not examine the relationships between accessibilities to different populations under various *b*-values, where a principal component analysis would show a somewhat less striking collinearity, but a strong dominant component with a variety of modifying factors based on different locational patterns (see Harris 1966). My principal focus is on the relationships among the three measures of accessibility under spatial competition and the stability or instability of these relations across pairs of populations. The results of this investigation lead to tentative recommendations as to the practical treatment of spatial competition in the broader context of a more extensive spatial analysis.

The process of analysis and the results are illustrated in the following tables:

- Table 1: Eight arrays, similar to maps, showing the hypothetical distribution of workers by place of residence and place of work. Pairwise correlations between these distributions of workers by places of residence and work are displayed, with a principal component analysis.
- Table 2: Area accessibilities to each of eight populations, with $b = 1.0$, correlations between pairs of these measures, and the principal components of the correlations.
- Table 3: Area values of four different accessibility measures, with $b = 1.0$. Three measures reflect spatial competition, and all are provided for each of a single pair of activities—total workers at home and at workplaces. Also shown are the pairwise correlations of these eight measures.
- Table 4: Selected pairwise correlations between accessibility measures for each of 28 pairs of locational patterns and 3 *b*-values to analyze the mutual substitutability among them.

The basic analysis is supported principally by data in table 4, but the features of the analysis will be outlined by considering all the tables consecutively.

- Table 1. The presentation of the distributions in table 1 is intended to convey a sense of the residential and employment composition of the city. It is roughly intended to resemble the Chicago area, but with the lakefront to the south, and is similar to Toronto or an upside-down Cleveland. The zones would be numbered consecutively from left to right across the rows, with 1 in the upper left and 35 in the lower right. The central business district is in zone 32, in the middle of the bottom row. The correlations between these distributions show that residential types are less highly correlated (perhaps more segregated) than employment types, while residence and workplace by class is associated positively for low- and middle-income workers, but not for high-income workers.
- Table 2. Simple accessibilities are presented for eight classes of locators, with $b = 1.0$. In general, these accessibilities are positively correlated but not highly so. Other *b*-values, not shown, display similar patterns: but as *b* increases, the proportion of the target easily reached falls, while the implied average trip length rises. (Values of *b* of 0.5, 1.0, and 3.0 correspond roughly to trips with average lengths of 3, 2, and 1 grid units.)
- Table 3. This table is designed to show how the basic data for the analysis were derived. For each of a pair of classes of locators we calculate simple accessibility and three accessibilities reflecting competition with the other member of the pair. These eight measures are correlated pairwise. The upper left and lower right 4 X 4 submatrices reflect the relations among measures for the two paired locator classes, and are abstracted for all pairs and *b*-values in table 4. The upper right submatrix shows the relations between pairs of measures for the pair of locator classes.
- Table 4. The main table consists of three subparts, each for a different *b*-value. Each subtable

TABLE 3 Illustrative Computation of Competitive Accessibilities and Average Costs

b = 1.0 Comparison between total of residences and total of jobs, over 35 zones; includes accessibilities and derived average costs.

Accessibilities							
Accessibility to employment				Accessibility to residents			
Simple	Ratio	Discounted	Gravity	Simple	Ratio	Discounted	Gravity
.045	.515	.371	.087	.088	1.942	1.332	.657
.056	.541	.448	.112	.103	1.847	1.414	.663
.057	.565	.472	.131	.100	1.770	1.309	.557
.058	.653	.549	.164	.088	1.532	1.129	.419
.058	.805	.672	.209	.071	1.242	.926	.291
.055	1.057	.829	.262	.052	.946	.719	.189
.041	1.232	.766	.244	.033	.811	.511	.115
.079	.675	.567	.159	.117	1.481	1.292	.614
.092	.658	.643	.192	.139	1.520	1.449	.659
.095	.683	.681	.220	.138	1.463	1.377	.575
.091	.740	.738	.255	.124	1.351	1.215	.449
.091	.922	.899	.317	.099	1.084	.999	.319
.080	1.147	1.012	.359	.069	.872	.768	.209
.056	1.333	.903	.320	.042	.750	.527	.124
.135	.941	.893	.287	.144	1.063	1.160	.526
.142	.817	.897	.312	.173	1.224	1.348	.586
.144	.799	.914	.348	.180	1.251	1.348	.543
.139	.831	.955	.389	.167	1.204	1.242	.450
.123	.931	1.003	.416	.132	1.074	1.030	.329
.098	1.129	1.028	.423	.087	.886	.760	.211
.065	1.318	.880	.357	.049	.759	.502	.123
.178	1.107	1.127	.407	.161	.904	1.064	.458
.189	1.031	1.146	.446	.184	.970	1.175	.486
.200	.919	1.181	.510	.217	1.088	1.308	.506
.208	.978	1.297	.602	.213	1.022	1.266	.445
.175	1.019	1.251	.592	.172	.981	1.099	.344
.120	1.128	1.107	.518	.106	.886	.795	.218
.072	1.258	.870	.397	.057	.795	.524	.125
.144	1.051	.944	.363	.137	.951	.890	.364
.169	1.106	1.040	.434	.152	.904	.910	.361
.211	1.020	1.241	.578	.207	.980	1.125	.419
.288	1.803	1.809	.904	.160	.555	.890	.306
.193	1.168	1.334	.678	.165	.856	.957	.292
.126	1.394	1.160	.584	.091	.718	.616	.169
.074	1.527	.940	.460	.049	.655	.412	.097

Correlations among eight accessibility measures, four in each of two groups

1.000	.351	.856	.823	.832	–.393	.224	.139
.351	1.000	.731	.736	–.192	–.937	–.797	–.789
.856	.731	1.000	.974	.476	–.769	–.257	–.363
.823	.736	.974	1.000	.437	–.737	–.287	–.390
.832	–.192	.476	.437	1.000	.080	.669	.576
–.393	–.937	–.769	–.737	.080	1.000	.768	.804
.224	–.797	–.257	–.287	.669	.768	1.000	.964
.139	–.789	–.363	–.390	.576	.804	.964	1.000

continues

TABLE 3 Illustrative Computation of Competitive Accessibilities and Average Costs (*continued*)

Derived average costs							
Accessibility to employment				Accessibility to residents			
Simple	Ratio	Discounted	Gravity	Simple	Ratio	Discounted	Gravity
3.090	.664	.992	2.440	2.427	–.664	–.287	.420
2.886	.613	.803	2.187	2.272	–.613	–.347	.411
2.870	.571	.751	2.031	2.299	–.571	–.269	.585
2.852	.427	.599	1.810	2.426	–.427	–.122	.869
2.856	.217	.398	1.564	2.639	–.217	.077	1.234
2.897	–.056	.188	1.341	2.952	.056	.329	1.664
3.205	–.209	.267	1.412	3.414	.209	.671	2.165
2.539	.392	.567	1.842	2.146	–.392	–.256	.487
2.390	.419	.442	1.652	1.971	–.419	–.371	.418
2.358	.381	.384	1.513	1.978	–.381	–.320	.554
2.392	.301	.303	1.366	2.091	–.301	–.195	.800
2.397	.081	.107	1.149	2.316	–.081	.001	1.143
2.530	–.137	–.012	1.025	2.667	.137	.264	1.566
2.885	–.287	.102	1.139	3.172	.287	.641	2.087
2.000	.061	.113	1.249	1.939	–.061	–.149	.642
1.955	.203	.109	1.165	1.753	–.203	–.299	.534
1.937	.224	.090	1.056	1.712	–.224	–.299	.610
1.973	.185	.046	.945	1.787	–.185	–.216	.798
2.099	.071	–.003	.876	2.027	–.071	–.029	1.113
2.326	–.121	–.027	.860	2.447	.121	.275	1.555
2.737	–.276	.128	1.031	3.013	.276	.689	2.100
1.725	–.101	–.120	.900	1.826	.101	–.062	.781
1.664	–.031	–.136	.808	1.694	.031	–.161	.722
1.610	.084	–.167	.673	1.526	–.084	–.269	.682
1.570	.022	–.260	.507	1.548	–.022	–.236	.809
1.742	–.019	–.224	.524	1.760	.019	–.094	1.068
2.121	–.120	–.102	.658	2.242	.120	.230	1.524
2.634	–.230	.139	.923	2.864	.230	.647	2.079
1.937	–.050	.058	1.014	1.987	.050	.116	1.011
1.780	–.101	–.040	.834	1.881	.101	.094	1.020
1.556	–.020	–.216	.549	1.576	.020	–.117	.869
1.244	–.589	–.593	.101	1.833	.589	.116	1.184
1.645	–.155	–.288	.389	1.800	.155	.043	1.232
2.069	–.332	–.149	.538	2.401	.332	.484	1.780
2.602	–.424	.062	.776	3.025	.424	.887	2.330

contains 28 lines, for the possible pairs of 8 locator classes. Each line contains six *r*-values for each of the upper left and lower right submatrices. This arrangement, although unconventional, permits more ready comparison for patterns across pairs of locators and between *b*-values. Several observations on these comparisons follow.

1. The correlations presented are for different measures for each member of the pair. The correlations between accessibility measures for different members of the pair were not examined in detail here and no data are presented. Correlations between the same two simple accessibility measures for different locators are frequently positive, but adventitious in size, as shown in table 2. Correlations between the same competitive measures for paired populations are almost invariably negative. (See the upper right submatrix in table 3.)
2. In general simple accessibility (variable 1) is weakly correlated with the competitive accessibilities (variables 2, 3, and 4). This indicates that competitive accessibilities are distinctively different from the conventional

TABLE 4 Correlations Between Pairs of Accessibility Measures, Within Viewpoints, Across Zones

Each line identifies paired distributions and pairwise correlations of measures by viewpoints

Column 0: paired activities; cols. 1 to 6, and 7 to 12: *r*'s for paired measures as noted

b = 0.5

0	Accessibilities to 2nd member of pair competitively modified by 1st						Accessibilities to 1st member of pair competitively modified by 2nd					
	1–2	1–3	1–4	2–3	2–4	3–4	1–2	1–3	1–4	2–3	2–4	3–4
1 2	.207	.884	.831	.618	.681	.994	.742	.981	.964	.852	.880	.997
1 3	.629	.935	.914	.856	.879	.998	.768	.963	.926	.905	.940	.993
1 4	–.352	.780	.696	.297	.406	.990	.811	.993	.979	.866	.901	.996
1 5	.282	.976	.969	.430	.468	.998	.122	.954	.948	.400	.420	.997
1 6	–.223	.924	.926	.074	.079	.998	.504	.982	.979	.628	.643	.997
1 7	.557	.945	.928	.774	.804	.998	.425	.884	.870	.783	.801	.998
1 8	–.018	.924	.906	.301	.353	.996	.429	.962	.951	.640	.670	.996
2 3	.519	.976	.957	.667	.727	.992	.219	.878	.813	.646	.730	.991
2 4	.057	.959	.944	.327	.372	.998	.456	.992	.984	.551	.600	.998
2 5	.803	.987	.980	.877	.892	.999	.356	.925	.901	.680	.716	.995
2 6	.689	.968	.947	.829	.855	.997	.378	.957	.927	.622	.670	.989
2 7	.797	.991	.991	.848	.860	.998	–.024	.737	.722	.619	.638	.999
2 8	.699	.974	.964	.819	.840	.999	.349	.945	.933	.623	.654	.994
3 4	.279	.862	.773	.718	.810	.988	.666	.980	.954	.796	.850	.994
3 5	.790	.964	.933	.914	.943	.995	.600	.937	.918	.835	.857	.996
3 6	.694	.933	.880	.899	.941	.992	.621	.960	.932	.808	.847	.995
3 7	.787	.977	.975	.895	.899	.999	–.341	.947	.943	–.116	–.051	.993
3 8	.671	.935	.886	.879	.924	.993	.554	.959	.936	.760	.798	.995
4 5	.835	.996	.991	.872	.889	.998	–.182	.815	.771	.409	.466	.996
4 6	.718	.993	.978	.785	.821	.994	–.153	.917	.874	.228	.296	.992
4 7	.832	.997	.991	.869	.889	.998	–.173	.710	.669	.556	.598	.998
4 8	.748	.996	.990	.794	.817	.998	–.164	.905	.883	.254	.295	.998
5 6	–.437	.913	.937	–.094	–.136	.997	.677	.994	.997	.689	.713	.998
5 7	.497	.915	.896	.786	.816	.998	.359	.887	.865	.720	.755	.998
5 8	–.408	.918	.924	–.039	–.050	.998	.632	.995	.993	.643	.692	.997
6 7	.659	.969	.945	.803	.849	.996	.222	.856	.818	.682	.733	.996
6 8	.270	.976	.978	.384	.420	.998	–.007	.980	.983	.098	.161	.993
7 8	.065	.848	.804	.559	.630	.995	.606	.962	.942	.778	.823	.997

b = 1.0

0	Accessibilities to 2nd member of pair competitively modified by 1st						Accessibilities to 1st member of pair competitively modified by 2nd					
	1–2	1–3	1–4	2–3	2–4	3–4	1–2	1–3	1–4	2–3	2–4	3–4
1 2	.256	.638	.457	.884	.931	.969	.812	.942	.822	.956	.971	.960
1 3	.730	.887	.833	.951	.966	.991	.828	.926	.739	.968	.934	.924
1 4	–.459	.043	–.118	.844	.906	.978	.892	.977	.884	.959	.969	.955
1 5	.351	.856	.822	.730	.736	.974	.083	.671	.577	.768	.804	.964
1 6	.000	.582	.482	.717	.770	.982	.390	.825	.793	.804	.801	.974
1 7	.552	.822	.706	.898	.946	.977	.246	.539	.555	.922	.867	.962
1 8	.090	.642	.514	.749	.804	.962	.319	.739	.654	.845	.862	.967
2 3	.600	.877	.851	.888	.854	.946	.333	.666	.385	.901	.942	.929
2 4	.080	.693	.534	.760	.863	.971	.632	.949	.883	.828	.899	.974
2 5	.888	.967	.932	.968	.979	.990	.492	.798	.686	.907	.916	.945
2 6	.823	.931	.848	.958	.966	.980	.453	.796	.739	.880	.794	.874
2 7	.876	.966	.944	.955	.954	.988	.037	.278	.257	.939	.942	.999
2 8	.827	.938	.898	.955	.965	.990	.427	.744	.745	.898	.877	.950
3 4	.352	.638	.320	.921	.936	.924	.790	.946	.879	.938	.952	.977
3 5	.868	.937	.800	.976	.943	.947	.710	.871	.830	.949	.929	.967
3 6	.803	.889	.736	.972	.941	.951	.650	.879	.860	.915	.857	.952
3 7	.862	.931	.883	.980	.976	.986	–.327	–.022	.359	.891	.684	.876

continues

TABLE 4 Correlations Between Pairs of Accessibility Measures, Within Viewpoints, Across Zones (*continued*)

4 5	.921	.989	.970	.965	.967	.989	–.210	.249	.069	.872	.900	.951
4 6	.865	.980	.907	.941	.931	.957	–.194	.405	.207	.772	.736	.882
4 7	.921	.993	.967	.959	.969	.985	–.235	.075	.037	.925	.920	.993
4 8	.883	.986	.960	.943	.937	.978	–.189	.339	.215	.826	.854	.971
5 6	–.256	.459	.403	.674	.737	.994	.608	.961	.972	.748	.763	.988
5 7	.510	.736	.631	.937	.968	.981	.223	.585	.569	.874	.846	.986
5 8	–.276	.491	.358	.657	.756	.970	.550	.967	.937	.671	.735	.978
6 7	.692	.904	.759	.904	.945	.960	.159	.595	.566	.854	.863	.994
6 8	.316	.902	.860	.545	.710	.968	–.012	.875	.835	.319	.506	.908
7 8	–.036	.465	.413	.815	.838	.992	.637	.870	.737	.901	.954	.969

b = 3.0

	Accessibilities to 2nd member of pair competitively modified by 1st						Accessibilities to 1st member of pair competitively modified by 2nd					
0	1–2	1–3	1–4	2–3	2–4	3–4	1–2	1–3	1–4	2–3	2–4	3–4
1 2	.469	.485	–.086	.998	.462	.466	.893	.917	.303	.997	.362	.374
1 3	.805	.818	.442	.999	.603	.608	.787	.814	.354	.998	.484	.493
1 4	–.354	–.332	–.252	.997	.517	.530	.907	.929	.366	.995	.411	.421
1 5	.726	.763	.136	.996	.470	.461	.229	.263	–.015	.997	.657	.664
1 6	.621	.650	–.083	.996	.467	.453	.416	.451	.013	.996	.669	.671
1 7	.824	.848	.061	.998	.478	.459	.018	.021	.239	.999	.541	.554
1 8	.696	.728	–.114	.997	.439	.416	.327	.353	.004	.998	.669	.668
2 3	.838	.879	.536	.995	.652	.649	.224	.318	.201	.991	.377	.405
2 4	.333	.422	.258	.991	.467	.511	.862	.899	.416	.996	.568	.574
2 5	.921	.938	.461	.998	.502	.515	.795	.816	–.037	.998	.195	.185
2 6	.886	.900	.386	.998	.451	.462	.667	.688	.035	.998	.149	.132
2 7	.947	.958	.856	.998	.903	.913	.332	.337	.214	.999	.871	.874
2 8	.897	.914	.722	.998	.688	.707	.659	.675	.239	.999	.583	.567
3 4	.278	.318	–.046	.997	.607	.616	.927	.941	.508	.999	.633	.629
3 5	.764	.792	.363	.997	.542	.565	.734	.749	.425	.999	.542	.543
3 6	.743	.766	.478	.997	.571	.592	.716	.741	.449	.998	.583	.582
3 7	.845	.876	.838	.995	.810	.845	–.117	–.128	–.068	.999	.918	.916
3 8	.731	.759	.342	.997	.565	.585	.651	.675	.432	.998	.595	.590
4 5	.961	.974	.815	.998	.784	.791	.011	.024	–.249	.998	.276	.273
4 6	.957	.971	.503	.998	.407	.416	.096	.108	–.276	.998	.389	.377
4 7	.981	.987	.900	.999	.917	.920	.095	.092	.037	.999	.830	.834
4 8	.964	.977	.898	.998	.915	.920	.096	.106	–.007	.999	.855	.855
5 6	.125	.175	.032	.996	.816	.803	.297	.403	.810	.986	.507	.593
5 7	.461	.479	.142	.998	.475	.481	–.157	–.155	.308	.999	.072	.082
5 8	.020	.078	–.041	.994	.820	.827	.247	.374	.484	.980	.280	.363
6 7	.541	.603	.088	.991	.532	.529	–.184	–.170	.468	.999	.160	.186
6 8	.147	.377	.137	.934	.701	.763	.135	.333	.361	.956	.561	.586
7 8	–.242	–.235	.266	.999	.113	.132	.534	.587	.138	.992	.544	.546

concept and potentially influential in locational analysis.

3. The latter three variables as a group are all closely correlated, sometimes very highly so. To an extent, this suggests that any of these three may be taken as a substitute or proxy for the other two.
4. There are important systematic variations among the pairwise correlations of these three variables. The second of them, as proposed by Shen (1998), plays an intermediate role in their relationships. For low *b*-values, implying a high willingness to travel, the correlation between the first and second competitive formulations is lower than that between the second and third, which may be high. The same variation becomes more marked as the correlation between the two populations becomes weaker, as indicated in table 1. When the *b*-values are very high, the

correlation between the first and second competitive models is tight, and the correlation between the second and third may be weaker.

Thus the most interesting finding to emerge here is the fact that the first measure of competitive accessibility, despite its lack of attention to explicit structure, may be adequate in many analyses. This would prove to be a significant advantage, because it makes it possible to bypass the very large number of pairs of populations whose competitive interaction might be considered important in location. Using either the Shen method or the doubly constrained gravity model requires calculating a new set of measures for relevant *pairs* of activities, and in the second of these cases, many iterations may be required. Identifying the most important pairs of locators, computing numerous competitive accessibilities, and using them in a large-scale analysis present formidable difficulties.

If an analysis is made using methods based on the theory of discrete choice in a multinomial logit model, the variable influencing utility might be the ratio of two other variables. In the actual fitting, a log-linear model is used. Thus the ratio of competitive accessibilities does not appear, and the influence of the difference of the logarithms of simple accessibilities is merged across pairs. Ten different accessibilities generate 45 different pairs, but all 55 variables can be represented by the logarithms of the 10 original accessibilities.

Stated differently, variables that might not be expected to influence some particular behavior will in fact influence it because of indirect effects. If it is desired to separate direct and indirect effects, at least in part, then a more explicit form of spatial competition must be introduced. This is only the beginning of a far more intricate process, owing to the collinearity of many important influential variables in spatial analysis.

CONCLUDING SUGGESTIONS

The analysis of location involves far more than the examination of sites and their immediate vicinities—contrary to the suggestion of much planning practice and of the customary applications of GIS. The specification of location within an urban region can be accomplished with the designation of rings and sectors. However, this is vacuous to anyone (like a computer) who cannot immediately associate these designations with the contents of these segments, and with their connections with the rest of the region, and is consequently invariant over time and circumstance. The character of these subregions may be specified by variables like density and population composition, but these are again local and are in fact the result of the connections within the region interacting with local conditions.

Accessibility is a set of measures of varied form and content that makes it possible to overcome local myopia. For this, it must be defined clearly and used carefully. Accessibility is a quality of places that varies from place to place independent of any local conditions except connections with the rest of the region. It is not an intrinsic attribute or property of actors or classes of people and activities. For example, the accessibility of an area to jobs does not depend on the fact that some or most of its residents are discriminated against in employment. This dependency is defined by the class of jobs being examined. Thus accessibility's fundamental source is the distribution of properly specified activities over the region, but it also depends on the costs of the means of interaction between places, on the assumed willingness or actual capacity to employ those means, and on the separation from the place of measurement from the target activity to be accessed.

Important issues of equity and discrimination can be addressed purely through considerations of accessibility. For example, we might want to study the ability of low-income families to access low- and middle-income employment. Every zone has a measurable accessibility to these targets. We could form an average accessibility, weighted by the low-income population of each zone. Then what? The same measurement for high-income families' access to high-income jobs might show a lower average accessibility, because members of these families travel further to their jobs. A more sophisticated analysis is needed, showing the relative importance of accessibility in residential choice and the role of discrimination or the lack of transport alternatives (following Shen) in making these choices.

There is a danger in confounding the effects of accessibility and related variables. For example, density is closely correlated with accessibility, yet often one cannot be used as a proxy for the other. When accessibility runs ahead of this expected relationship, growth may be anticipated, and vice versa. Thus in a more complex model, with many locational decisions, these two variables may play different roles, and these roles may seem to shift over time as other variables change. This is only one example of the complexities of collinearity in urban analysis.

Special attention must be paid to the relationship between accessibility and actual place of work in residential location choice. Some working-class neighborhoods are concentrated like company towns around employment opportunities, and generalized accessibility plays little part in the locational choices of its residents. Conversely, many upper-income residential areas are far from employment in the CBD, with low accessibility. There is, however, a large population that seems to make location choices on the basis not only of housing prices and neighborhood variables, but on a mixture of accessibility and closeness to an actual job. Aggregated and cross-sectional studies are not adequate to sort out these decision processes, and suitable detailed longitudinal studies are required, with analyses that include accessibility.

All of these examples suggest the importance of a new and more flexible and imaginative use of accessibility measures, to which this paper has attempted to make one of many possible contributions.

ACKNOWLEDGMENT

Part of this research was supported through a contract from the U.S. Department of Housing and Urban Development (HUD) with the University of Pennsylvania. The author appreciates the help of HUD and wishes to thank the referees for many helpful suggestions.

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Performance of Accessibility Measures in Europe

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ABSTRACT

Although there is no universally acknowledged definition of accessibility, various indicators with different theoretical backgrounds and complexities have been proposed and implemented in empirical investigations. Consequently, results from these models are widespread and reflect more or less the modeler's aim and point of view. Given the importance of accessibility measures as tools in planning, the aim of this paper is to elicit an understanding of the mechanism behind their diversity. In this paper, accessibility measures are classified according to their underpinning theories, complexity in constructions, and demand on data. The classifications comprise travel-cost, gravity, constraints-based, utility-based, and composite approaches. While simpler models are less demanding on data, they fail to address the subject in a theoretically rigorous manner. The paper also summarizes issues that are important in modeling accessibility. We compare the performance of some conferred accessibility measures in a European context and examine the effects of functional forms of the deterrence variable and agglomeration effect.

INTRODUCTION

Trade and flows of commodities and information are recognized as important factors behind

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economic growth and increased welfare. It is in this context that various researchers have related accessibility between supply and demand of goods and services to economic growth (see Lundqvist 1978; Bruinsma and Rietveld 1998). As a result, accessibility indices are among the most prevailing measures used by planners and politicians to bolster their everyday propositions. Attempts to foster accessibility from national governments, policymakers, and planners have mostly been limited to local or nationwide improvement of the transportation infrastructure. Less attention and resources have been offered to border regions and international accessibility because of geographical and political borders between countries.

After introduction of the European Economic Community (EEC) in the 1960s, more and more countries entered the common market. Furthermore, the Maastricht Treaty of 1991[1] intensified economic activities between member states and transformed Europe into a huge market. Inspired by the principles of equity and efficiency, which require that all member countries benefit from the new common market, incentives to improve the European transportation infrastructure and accessibility have grown (Vickerman 1995). Clear evidence of this is development of the Trans-European Network (TEN) projects. It is hoped that construction of new highways and high-speed railroads will overcome disparities between the EEC member states, but an evaluation of the present level of accessibility indicators in Europe is needed to gauge the impact of these measures.

Gould (1969, 64) states "accessibility . . . is a slippery notion . . . one of those common terms which everyone uses until faced with the problem of defining and measuring it." Although there is no universally acknowledged definition of accessibility, various indicators with different theoretical backgrounds and complexity have been proposed and implemented in empirical investigations (see, e.g., Ingram 1971; Morris et al. 1978; Handy and Niemeier 1997). Recognizing the value of accessibility measures as planning tools, it is important to understand the mechanism behind their diversity. This paper first presents a summary of different accessibility indicators and clarifies their underpinning theories and corresponding properties. It then addresses issues important in measuring accessibility. The following section discusses some conferred measures applied to major European cities. Similarities and differences between these measures are then evaluated in the Analysis of Results section. Finally, some conclusions are presented.

A REVIEW OF ACCESSIBILITY INDICATORS

The two most fundamental questions concerning accessibility measures are for whom and for what, and the most straightforward description of accessibility is the state of connectivity. A location is assumed to be accessible if it is connected to other locations via a link to a road or railroad network (see, e.g., Bruinsma and Rietveld 1998) or to an airport or harbor. Accessibility described as connectivity does not need to have a binary form (that the location is connected or not). The extent of accessibility can also be calculated as the number of different links and modes to which the specific location has access. Despite the simplicity of the outline of such indicators, the obscurity of accessibility as a measure of connectivity is apparent.

Different accessibility indicators can be employed to describe and summarize characteristics of the physical infrastructure (e.g., accessibility to certain links, the network, or specific mode or modes). These conventional indicators, often referred to as objective or process indicators, reveal the level of service of the infrastructure network from the suppliers' perspective, regardless of their utilization. On the other hand, the importance of recognizing perceived accessibility by individuals as the real determinant of behavior is emphasized by many researchers, and it is argued that proof of access lies in the use of services. The inherent conflict between the choice of process indicators (objective indicators) and outcome indicators (perceived measures that reflect behavior) gives rise to a great range of indicators with different degrees of behavioral components.

Comprehension of differences between accessibility indicators necessitates classification. The criteria adopted for such classification is based on the discussion above, starting with the group of meas-

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[1] For more information, go to http://www.facts.com/cd/v00087.htm.

ures that address the supply side. The other groups of measures are perceived measures that represent the behavioral component. This approach to the classification of accessibility measures has been used by many researchers (see, e.g., Koenig 1977; Morris et al. 1978). Five major theoretical approaches for measurement of accessibility indicators can be found in the literature:

1. travel-cost approach,
2. gravity or opportunities approach,
3. constraints-based approach,
4. utility-based surplus approach, and
5. composite approach.

Approaches 1 to 3 have been acknowledged by Arentze et al. (1994) and others, while Miller (1998; 1999) and Miller and Wu (1999) categorize approaches 3 and 4 and derive a new composite indicator (5).

Travel-Cost Approach

The first class of accessibility indicators embodies those measuring the ease with which any land-use activity can be reached from a location using a particular transportation system (Burns and Golob 1976). These indicators have been utilized to indicate performance of the transportation infrastructure (Guy 1977; Breheney 1978). The common aspect for this class of accessibility indicators is determined by their configuration, where the indicator is simply some proxy of transport cost (network or Euclidean distance, travel time, or travel cost). A simple functional form for this class of measures is presented by equation 1.

$$A_i = \sum_{j \in L} \frac{1}{f\left(c_{ij}\right)} \tag{1}$$

where

A_i is the measure of accessibility at location *i*,

L is the set of all locations, and

f(c_{ij}) is the deterrence function and c_{ij} is a variable that represents travel cost between nodes *i* and *j*.

This class of measures has a number of advantages. They are

- easy to understand because of the simplicity of model construction,
- quite easy to calculate, and
- less demanding on data than other indicators.

The following are the most critical disadvantages of indicators within this class:

- they neglect variations in the quality of locations,
- they neglect variations in the value of time among travelers,
- they are highly sensitive to the choice of demarcation area (see, e.g., Bruinsma and Rietveld 1999), and
- they do not consider the behavioral aspects of travelers (see Hensher and Stopher 1978).

Gravity or Opportunities Approach

Indicators based on spatial opportunities available to travelers are among the first attempts to address the behavioral aspects of travel. A great number of accessibility indicators are in this class. The *potential to opportunities* or the *gravity* approach is undoubtedly the most utilized technique among accessibility indicators (see, e.g., Dalvi and Martin 1976; Linneker and Spence 1991; Geertman and Ritsema Van Eck 1995; Bruinsma and Rietveld 1998; Brunton and Richardson 1998; Kwan 1998; and Levinson 1998). An early attempt was made by Hansen (1959), who claimed that accessibility is the "potential of opportunities for interaction" or literally "a generalization of population-over-distance relationship" (p. 73). The concept of potential to opportunities is closely associated with the gravity models based on the interaction of masses and has been extensively discussed by Rich (1978). Equation 2 shows a simple form for this class of accessibility indicators.

$$A_i = \sum_{j \in L} \frac{W_j}{f\left(c_{ij}, \beta\right)} \tag{2}$$

where

W_j represents the mass of opportunities available to consumers, regardless of if they are chosen or not,

$f\left(c_{ij}, \beta\right)$ is the deterrence function,

c_{ij} is a variable that represents travel cost between nodes *i* and *j*, and

β is the travel-cost coefficient usually estimated from a destination choice model.

Advantages of this class of accessibility measures are

- ease of comprehension,
- ease of calculations,
- they are less demanding on input data than other indicators that reflect behavioral aspects, and
- the ability differentiate between locations.

Some disadvantages of this class of indicators are their

- sensitivity to the choice of demarcation area,
- deficiency in treatment of travelers with dispersed preferences, and
- ambiguity in what the magnitude of indicators express (dimension problem).

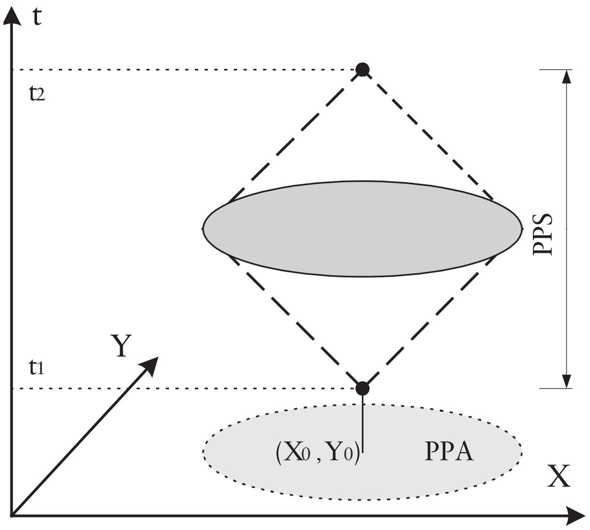
Constraints-Based Approach

Despite the popularity of potential accessibility indicators, they have some weak points. One weak point with gravity models is that they do not address time constraints facing individuals. The constraint-oriented approach was developed by Hagerstrand (1970) within the *space-time* framework and is based on the fact that individual accessibility has both *spatial* and *temporal* dimensions. Opportunities or potential to opportunities for an individual are not only constrained by the distance between them, but also by the time constraints of the individual.

Miller (1999, 2) defines Potential Path Space (PPS) by stating that: "The space-time prism delimits all locations in space-time that can be reached by an individual based on the locations and duration of mandatory activities (e.g., home, work) and the travel velocities allowed by the transportation system." Assume an individual located at time t_1 in node (X_0, Y_0). Again assume that at time t_2 the individual has to be back at the same node. Then the available time for all activities is given by $t = t_2 - t_1$. Figure 1 shows the contained volume by two cones that represents the space-time prism or PPS.

The projection of PPS on the two-dimensional XY-space represents the *potential path area* (PPA) that corresponds to the potential area that an individual can move within, given the time budget.

FIGURE 1 Demonstration of PPS and PPA



Lenntorp (1976; 1978) developed a so-called *program evaluating the set of alternative sample paths* (PESASP) to calculate the number of feasible paths between nodes, given the activity schedules and space-time constraints. The number of feasible activity schedules simulated by the program represents a measure of accessibility. In other studies, modified space-time prisms have been employed to indicate the individual accessibility based on various travel speeds, multistop trip chaining, and changes in activity schedules (see Hall 1983 and Arentze et al. 1994).

A frequently adopted indicator within this class is the cumulative opportunity measure or the so-called *isochronic* indicators that estimate accessibility in terms of opportunities available within predefined limits of travel cost, C (Dunphy 1973; Sherman et al. 1974; Breheny 1978; Hanson and Schwab 1987).

This class of indicators addresses some of the limitations of the earlier models by:

- consideration of the temporal dimension of human activities, which leads to indicators that account for the individuals time constraints, and
- the recognition of multipurpose activity behavior by a space-time prism.

Wang (1996) points out four weak points with this approach:

- assuming a constant speed in all directions is not realistic and variable speed makes the model exceedingly burdensome to handle;
- the planar space defined as PPA is too abstract—a large PPA is not necessarily better than a small

one, if the smaller PPA contains more potential locations;

- the activity schedules are usually incomplete and do not cover the whole spectrum of activities; and
- even though a time budget is introduced, the individual's travel behavior is not fully addressed in this class of measures.

Utility-Based Surplus Approach

This class of accessibility indicators is another attempt to include individual behavior characteristics in accessibility models. Utility-based indicators have their roots in travel demand modeling. Ben-Akiva and Lerman (1979, 654) states: "accessibility logically depends on the group of alternatives being evaluated and the individual traveler for whom accessibility is being measured." In that sense, the shortcoming of gravity-based indicators becomes obvious, as all individuals within the same zone will experience the same amount of accessibility, regardless of the differences between their perceived utility of alternatives. Ben-Akiva and Lerman (1979, 656) continue: for any single decision, the individual will select the alternative which maximizes his/her utility," $U^n_{j|i}$. Thus a simple definition of accessibility A^n_i is:

$$A^n_i = \max_{i,j \in L} U^n_{j|i} \qquad (3)$$

where

n is a mutually exclusive and collectively exhaustive individual member of I,

j is the destination $\{j = (1,2,\ldots,j,\ldots,l); \forall j \neq i\}$ and

i is the node for which the accessibility is calculated;

and

$$U^n_{j|i} = v^n_j - c^n_{ij} + \varepsilon_{ij} \qquad (4)$$

where

v_j is some measure reflecting the attraction of the alternative j, observable to the modeler,

c_{ij} is the cost of travel between i and j, and

ε_{ij} is the stochastic, random, and unobservable part of the utility ($\varepsilon = 0$ for the individual but unknown for the modeler).

By assuming that the random variables are independent and identically distributed according to the extreme value distribution, the accessibility of location i for individual n is:

$$A^n_i = \max_{i,j \in L} U^n_{j|i} = \frac{1}{\mu} \ln \sum_{j \in L} e^{\mu\left(v^n_j - c^n_{ij}\right)} \qquad (5)$$

where μ is a positive scale parameter.

The measure of accessibility defined in this way is in monetary units, which enables the comparison of different scenarios. Williams (1977) noted that utility-based accessibility is linked to consumer welfare. McFadden (1975) and Small and Rosen (1981) showed how this measure can be derived in the discrete choice situation for the multi-nomial logit (MNL) model when income effect is not present. For examples of investigations on utility-based accessibility measures see papers by Niemeier (1997) and Handy and Niemeier (1997).

The advantage of this class of indicators is that they are supported by relevant travel behavior theories. Some disadvantages of this class of indicators are:

- modeling of utility-based accessibility indicators demands extensive data on locations and individuals' travel behavior and their choice sets, and
- the assumption of nonpresence of an income effect is restrictive.

Composite Approach

Representation of the multiple-purpose property of trips is lacking in the utility-based measures. These drawbacks have been discussed by some researchers. Among them Miller (1998; 1999) summarizes the disadvantages of these measures and derives new measures by combining the space-time and the utility-based models into a composite model. Miller's work has Weibull's (1976) axiomatic approach as its starting point. Miller calls these models space-time accessibility measures

(STAMs), which are based on the assumption of uniform travel speed.

STAMs are based on the utility of performing a series of discretionary activities (e.g., shopping, visiting), given the mandatory activities (e.g., work). The following utility function, $u(.)$, defined by Burns (1979) and Hsu and Hsieh (1997), is employed as the base:

$$u_{ij}\left(a_k, T_k, t_k\right) = a_k^{\alpha} T_k^{\beta} e^{-\lambda t_k} \tag{6}$$

where

a_k = attractiveness of discretionary activity location k,

α is the parameter for the attraction mass,

$T_k = \begin{cases} t_j - t_i - t_k \text{; if} > 0 \\ 0 \text{ else} \end{cases}$ is the available time for participation in activities [$T = f(t)$],

t_i,t_j = stop times for mandatory activity i and start time for mandatory activity j,

$t_k = [d(x_i, x_k) + d(x_k, x_j)]/s$ is the required travel time from/to the mandatory activities,

x_i = location vector of mandatory activity i,

$d(x_i,x_k)$ = distance from activity location i to activity location k,

s = constant velocity of travel,

β is the coefficient for available time, and

λ is the travel time coefficient.

Based on these formulations Miller (1999) defines three different STAMs as:

$$AM_1 = \frac{1}{\lambda} \ln \sum_{k \in L} \exp\left(a_k^{\alpha} T_k^{\beta} e^{-\lambda t_k}\right) \tag{7}$$

$$AM_2 = \sum_{k \in L} b_k \tag{8}$$

$$AM_3 = \max_{\{k\}} \left[b_k\right] \tag{9}$$

where

$$b_k = \begin{cases} 0 \text{ if } a_k \text{ or } T_k = 0 \\ \exp\left[\lambda\left(\frac{\alpha}{\lambda} \ln a_k + \frac{\beta}{\lambda} \ln T_k - t_k\right)\right] \text{ else} \end{cases} \tag{10}$$

AM_1 corresponds to the user-benefit approach while AM_2 and AM_3 correspond to the locational benefits approach. AM_2 considers the whole choice set while AM_3 assumes that an individual only considers the choice that maximizes her utility. Miller and Wu (1999) develop this approach further to incorporate a departure-based, discrete time network flow model. While this approach aims at avoiding the problems of the other accessibility measures, its main disadvantage is related to the vast data requirement.

FURTHER ISSUES IN ACCESSIBILITY MODELS

The following discussion summarizes a chapter in Bruinsma and Rietveld (1999), in addition to some further issues.

Measurement of Spatial Separation

The degree of spatial separation between locations can be measured several ways. Common proxies are travel distance, travel time, and generalized travel cost. Travel distance and travel time are usually easy and straightforward to calculate, while operation with generalized travel cost is more cumbersome. In the case of generalized travel cost, other than the calculation of distance-dependent costs, information associated with costs of vehicle use, fares, taxes, and so forth, are needed. Since such data is not readily available at the disaggregate level, mean values must be used, which implies further assumptions.

The calculation of travel time is usually based on a shortest path algorithm. A more precise method is use of a route choice simulation procedure, which is especially necessary for congested networks. However, the procedure is data demanding and requires trip-matrices as well as volume-delay functions. In the case of public transport, waiting, transfer, and auxiliary times are also relevant in addition to in-vehicle time and fares.

The functional form of the deterrence variable is also important. For instance, we know that the perception of utility (disutility) derived from waiting time is not equal to the in-vehicle time.

Furthermore, the deterrence variable does not necessarily have to be linear in construction.

Measurement of Attraction Masses

Earlier in this paper, two important questions were raised, accessibility for whom and to what. While the first question is answered by the choice of the model (e.g., individual or aggregate), the choice of attraction mass responds to the second question. The mass of attraction in accessibility models represents the potential utility for opportunities at a destination,[2] or in other words, the utility an individual can derive by visiting a specific location or a set of locations. The choice of appropriate interaction mass is crucial for the determination of accessibility. In large-scale accessibility studies and in the absence of other attributes, population is often used as the interaction mass variable. Other possible proxies are percentage of gross domestic product, number of employees, volume of sales, etc.

Choice of Demarcation Area

Arbia (1989) divides the problems related to choice of demarcation area into two subproblems. The first is related to the effects of scale while the second corresponds to zoning problems.[3] A third problem arises as a consequence of the choice of total study area.

The scale problem is related to the number of units represented in the study area. Inclusion or exclusion of units will affect the results of the accessibility model. The zoning problems relate to the way locations are presented. Expressing locations as nodes that correspond to urban centers will cause aggregation problems, that is, all individuals in the same zone will have the same level of accessibility (Ben-Akiva and Lerman 1979). Furthermore, the underlying assumption is that all locations presented by that node have similar accessibility measures (Bruinsma and Rietveld 1998). That also complicates the calculation of internal accessibility measures. However, the use of geographic information system (GIS) and disaggregated census data can reduce these difficulties. In this case other problems might arise, like definition problems concerning the grid resolution and issues related to the modifiable areal unit problem.

The choice of total study area is also an important problem that needs attention. With the determination of the study area, one will consequently decide which areas should be excluded. The choice of a closed study area will ignore the effects from outside, which in many cases can be questionable (Bruinsma and Rietveld 1998).

Unimodality versus Multimodality

Uni- versus multimodality is also a relevant consideration in modeling accessibility. For instance, for a work trip, a range of travel modes can be appropriate. In case of trips by air, we can easily imagine that the traveler actually faces two additional mode choices. One has to determine travel modes to the airport of departure and from the airport of disembarkation. Multimodality can partially be handled in accessibility models. In a travel-cost approach or gravity approach, multimodality can be embedded in the calculation of travel time or cost for all modes. These can be presented separately or by the assumption that the traveler might choose the fastest or the least expensive among alternative modes. In the case of utility-based and composite accessibility models, multimodality can be brought to the model by the construction of a nested destination/mode choice model.

Time of Day

Differentiation between accessibility measures at different times of day is necessary when the level of service varies during the day or when traffic congestion is a factor. The variation in accessibility for different times of day can be reproduced by the construction of separate accessibility models for different time periods. However, in many cases, especially in the case of long-distance trips, these variations could be small and may have only a minor impact on accessibility measures.

Agglomeration Effects

The magnitude of opportunities offered at a location also encompasses opportunities available in surrounding locations within the individuals' travel

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[2] In the case of potential, time-space, utility-based, and composite accessibility indicators.

[3] The spatial arrangement of units or the modifiable areal unit problem.

constraints. Inclusion of agglomeration effects is a complicated task. However, since agglomeration effects have a direct impact on the utility derived from the opportunities, the easiest way of approximating these effects is through transformation of the attraction mass variable.

A pre-set degree of spatial dependence can be embedded in a variable by means of spatial transformation. Different techniques can be used to realize these transformations, which can simply be called spatial averaging (see Anselin 1992). One transformation technique is termed the *spatial window average*.

$$W_i^* = \frac{W_i + \sum_{j \in L} \Psi_{ij(d)} W_j}{1 + \sum_{j \in L} \Psi_{ij(d)}} \qquad (11)$$

where W_i^* is the transformed mass variable representing the attraction mass of node i (agglomeration effects included) compared with W_i the mass variable at node i and $\Psi_{ij(d)}$ is a spatial weight from a contiguity matrix[4] up to distance d. This formulation is not suitable when the mass is in monetary units.

The above formulation is highly sensitive to the definition of contiguity. As an example, if we define contiguity by masses within a distance d from a location, then the above formulation will underestimate a large agglomeration with many surrounding settlements compared with another with few surrounding settlements. An approach to correct for this problem is to average the mass of agglomeration (nominator) by a fixed number, K, for all locations i. This implies all nodes have the same degree of neighborhood (K–1).

$$W_i^* = \frac{W_i + \sum_{j \in L} \Psi_{ij(d)} W_j}{K} \qquad (12)$$

Dimension Problem

The dimension problem arises because almost all accessibility indicators (except utility-based and composite measures) present the accessibility of locations as nondimensional values that are not comparable with each other. These nonmonetary values complicate the evaluation of infrastructure improvements. A method that can be used for comparison of different accessibility measures is *ranking*. By dividing each accessibility measure by the highest accessibility measure, indicators will become normalized in a way that makes them suitable for comparison.

A STUDY OF ACCESSIBILITY MEASURES OF EUROPEAN CITIES

The aim of our study is to understand the built-in mechanism of some of the accessibility models discussed earlier, while looking at accessibility measures of European cities with road infrastructure. Even though the discussed accessibility models are operational, not many of them have been applied in large-scale studies. In large-scale accessibility studies, the unavailability of illustrative and homogeneous data is always a limiting factor. Consequently, one's choice is limited to more simple and straightforward models. For this reason, the empirical study presented here is based on the first and the second class of the models (travel-cost and gravity type), with consideration of the agglomeration effect. Furthermore, variations in accessibility caused by different assumptions about the deterrence variable will be examined.

Data

To decrease the problems associated with the choice of the demarcation area, all of Europe was chosen as the study area (except for Turkey due to the absence of appropriate data). Accessibility indicators are calculated for more than 4,500 cities with a population greater than 10,000, located in 44 European countries connected to each other by the road infrastructure. The data source is a modified GIS data layer containing urban centers in Europe[5] that includes population data. Travel distance and travel time variables are used as proxies to the spatial separation variable. These are calculated using a digitized road network from three dif-

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[4] A contiguity matrix represents the degree of neighborhood of a location with its surrounding locations.

[5] The source for urban centers data is CEC-Eurostat/GISCO.

ferent sources implemented in a GIS-database. The sources for the road network data are:

1. the IRPUD road network,[6]
2. the digitized road network for Sweden,[7] and
3. the digitized road network for Finland.[8]

Travel distance and travel time are calculated using the shortest path algorithm in TransCAD.[9] The calculation of travel distance is based on the length attributes of the links, while travel time is based on different link speeds, commonly assumed for different link categories. Hence, the effect of congestion is not taken into account in this study. Car ferry links are penalized by an additional travel time of 45 minutes.

The calculation of internal accessibility measures is necessary. In the absence of appropriate data, the internal travel distances and travel times are calculated with the assumption that cities are circular,[10] based on the following equations:

$$t_{ii} = \frac{d / 4}{40} \tag{13}$$

where

$$d = \frac{\sqrt{O / \pi}}{2} \tag{14}$$

and

$$O = \frac{Population}{Density} \tag{15}$$

where d is the diameter of the city. An average travel speed of 40 kilometers per hour has been assumed for all internal trips.

Selected Accessibility Models

One group of accessibility models based on the travel-cost approach and two groups of gravity-based models will be examined in this work. In all model groups, an internal accessibility measure is included. For each model group, three deterrence functions will be examined:

1. linear in travel time (t),
2. exponential in travel time, and
3. Box-Cox transformed travel time.[11]

The first group of measures is based on the travel-cost approach where the measure of accessibility can be interpreted as the level of connectivity of the nodes as:

$$a_1 = \frac{1}{t_{ii}} + \sum_{j \in L} \frac{1}{t_{ij}}, \quad i \neq j \tag{16}$$

$$a_2 = \frac{1}{e^{\beta t_{ii}}} + \sum_{j \in L} \frac{1}{e^{\beta t_{ij}}}, \quad i \neq j \tag{17}$$

$$a_3 = \frac{1}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{1}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, \quad i \neq j \tag{18}$$

where

t_{ii} is the internal travel time at i, and
t_{ij} is the travel time between locations.

The second group of measures is based on the gravity approach models (Hansen type) and are:

$$b_1 = \frac{p_i}{t_{ii}} + \sum_{j \in L} \frac{p_j}{t_{ij}}, i \neq j \tag{19}$$

$$b_2 = \frac{p_i}{e^{\beta t_{ii}}} + \sum_{j \in L} \frac{p_j}{e^{\beta t_{ij}}}, i \neq j \tag{20}$$

$$b_3 = \frac{pi}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{p_j}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, i \neq j \tag{21}$$

where p is population.

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[6] This digitized road network is developed by the Institute of Spatial Planing in Dortmund, Germany.

[7] The source of this network is the Swedish National Road Administration (Vagverket).

[8] The source of this network is the Finnish National Road Administration (VTT).

[9] TransCAD is a transportation-GIS software from Caliper Corp. (www.caliper.com).

[10] This formulation of internal distance has been discussed by Rich (1980) and also by Bruinsma and Rietveld (1998).

[11] Box-Cox transformation implies: $y = \frac{x^{\theta} - 1}{\theta}$

The last group of measures also belongs to the gravity type with the agglomeration effect included as:

$$c_1 = \frac{p_i^*}{t_{ii}} + \sum_{j \in L} \frac{p_j^*}{t_{ij}}, i \neq j \tag{22}$$

$$c_2 = \frac{p_i^*}{e^{\beta t_{ii}}} + \sum_{j \in L} \frac{p_j^*}{e^{\beta t_{ij}}}, i \neq j \tag{23}$$

$$c_3 = \frac{p_i^*}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{p_j^*}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, i \neq j \tag{24}$$

where p_i^* is the transformed population of location calculated as:

$$p_i^* \Big| \left(t_{ij} \leq 1\, hour\right) = \frac{p_i + \sum_{j \neq i} \Psi_{ij(d)} p_j}{K} \tag{25}$$

A location *j* is assumed to be a neighbor of location *i* if t_{ij} is less than or equal to one hour. The choice of one hour as the threshold is related to the time constraint a traveler faces making a roundtrip during a working day.[12]

Conventionally, parameters in the models of accessibility should be estimated, but due to the absence of appropriate data for the whole study area, parameters from a Swedish study are used[13] (Baradaran 2001). These are:

$$\beta = 0.00329,$$
$$\delta = 0.07014, \text{ and}$$
$$\theta = 0.545.$$

ANALYSIS OF RESULTS

Relationships between different aspects of the selected measures are analyzed by examination of correlations and other deviation measures and by comparisons of accessibility maps.

TABLE 1 Correlation Table for the Calculated Accessibility Measures

	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3
a_1	1								
a_2	.84	1							
a_3	.86	.99	1						
b_1	.99	.82	.85	1					
b_2	.84	1.0	.99	.82	1				
b_3	.90	.98	.96	.88	.98	1			
c_1	.53	.23	.28	.54	.23	.28	1		
c_2	.36	.09	.12	.35	.09	.12	.95	1	
c_3	.42	.15	.18	.42	.15	.18	.98	.99	1

Examination of Correlations and Other Deviation Measures

The similarities and differences between models are investigated by construction of the correlation[14] table (see table 1).

Examination of the correlation table shows that measures in the third group of models (group *c*, which includes the agglomeration effect) are quite different from the first two groups (group *a* and *b*). Within the first two groups, measures based on linear construction of the deterrence variable (*a*1 and *b*1) are highly correlated with each other, while having lower correlation with other measures based on nonlinear construction of the deterrence variable. Similarly, measures based on nonlinear construction of the deterrence variable are highly correlated with each other, while they have lower correlation with measures based on linear construction of the deterrence variable. Group *c* measures that includes agglomeration effects have higher correlation with the linear measures (*a*1 and *b*1).

Similarities and differences between the models have also been analyzed using dispersion and skewness statistics shown in table 2. The second column in table 2 represents a dispersion measure, φ, which is constructed as follows:

$$\varphi = \frac{standard\ deviation}{\text{mean accessibility}} \tag{26}$$

This measure describes the degree of dispersion of the calculated accessibility measures. This measure is of course dependent on the area of the study.

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[12] One should indeed conduct a sensitivity test to evaluate the importance of the threshold.

[13] These parameters are estimated by using a multinomial-logit model with disaggregate data for long-distance trips in Sweden.

[14] Correlation: $corr\,[X,Y] = \frac{\mathrm{cov}[X,Y]}{\sqrt{var[X]var[y]}} \in [-1,1]$

TABLE 2 Dispersion and Skewness of Accessibility Measures

Model	φ	Skewness
a_1	0.307	0.39
a_2	0.018	(–0.80)
a_3	0.095	(–0.14)
b_1	0.405	0.76
b_2	0.041	(–0.80)
b_3	0.098	(–0.51)
c_1	1.51	3.01
c_2	1.61	3.09
c_3	1.49	2.93

Hence, it is not the magnitude of this measure that is crucial, but the degrees of similarity or dissimilarity among these measures that provides the necessary information. Table 2 shows that group *c* measures that include agglomeration have a much higher φ-value than other measures. This suggests that measures that include agglomeration are different from the rest. Among other measures, the nonlinear measures (*a*2, *a*3, *b*2, and *b*3) have the lowest φ-values, suggesting that a nonlinear transformation of the deterrence variable has a kind of smoothing effect on the accessibility measures.

The last column in table 2 represents the skewness[15] of measures estimated from different models. Skewness helps identify the degree of asymmetry of a distribution around its mean. Positive skewness indicates that the asymmetrical tail is protracted toward more positive values while negative skewness indicates the opposite. Again we can see that the skewness of the linear measures (*a*1 and *b*1) and group *c* measures represent cumulative processes (because they are positive) while the nonlinear measures (*a*2, *a*3, *b*2, and *b*3) show declining processes (because they are negative).

Differences among accessibility models can also be investigated by using a numerical taxonomy. Sneath and Sokal (1973, 116) state that "... a coefficient of similarity is a qualification of the resemblance between the elements in two columns of the data matrix representing the character state of two operational taxonomic units in question." Two different dissimilarity coefficients are calculated. These are

- *mean absolute difference (MAD)*, which is a variant of Minkowski metrics[16] adjusted for number of vector elements and specified as

$$MAD = \frac{1}{L}\sum_{i \in L}\left|\hat{A}_i - A_i\right| \tag{27}$$

where $\hat{A}_i$ is the accessibility measure for location *i* and *L* is the set of all locations.

- *dissimilarity index (DSI)*, also known as Leontief index (after multiplication by 100), specified as

$$DSI = \frac{1}{L}\sum_{i \in L}\left[\frac{\left|\hat{A}_i - A_i\right|}{\left(\hat{A}_i + A_i\right)}\right], \hat{A}_i \neq 0 \text{ or } A_i \neq 0 \tag{28}$$

The results are presented in the appendix. However, due to differences in their ranges, these metrics are not directly comparable. For comparison they are normalized in the following way:

$$\overline{M} = \frac{M - \min(M)}{\left[\max(M) - \min(M)\right]} \tag{29}$$

where *M* is the metric and $\overline{M}$ is its transformed form. The result of this transformation are metrics that vary from 0 to 1. To avoid zeros in the case of *DSI*-metric, zeros are replaced with 0.000001.

Figure 2 shows the differences between accessibility measures with respect to measure *a*1, using MAD and DSI metrics. The examination of different metrics points to 3 clusters for the 9 accessibility measures. One cluster is a linear deterrence variable (*a*1 and *b*1). The second cluster is a nonlinear deterrence variable (*a*2, *a*3, *b*2, and *b*3). The third cluster includes an agglomeration effect (group *c* measure).

The differences between the examined accessibility measures can be caused by either some key

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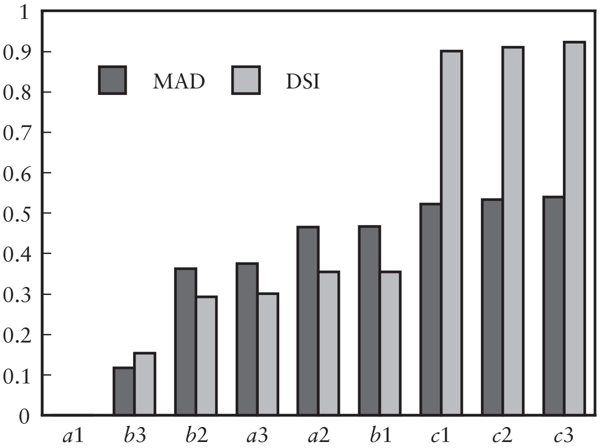
[15] A skewness coefficient is a measure of asymmetry of a distribution. $Skew = \sum_i \frac{(x_i - \mu)^3}{\sigma^3}$ where μ is the population mean and σ is the standard deviation.

[16] The Minkowski metric corresponds to the Minkowski inequality, specified as
$$\left[\Sigma_{i=1}^{l}\left|\hat{A}_i - A_i\right|^r\right]^{1/r} \leq \left[\Sigma_{i=1}^{l}\left|\hat{A}_i\right|^r\right]^{1/r} + \left[\Sigma_{i=1}^{l}\left|A_i\right|^r\right]^{1/r}$$

FIGURE 2 **Differences Between Accessibility Measures Using MAD and DSI Metrics with Respect to Model *a*1**



assumptions made in the calculation, such as parameters and internal travel time, or by the functional characteristics of the models.[17] The examination of relationships between the selected measures by use of correlation coefficients, measures of skewness and dispersion, and other metrics (MAD and DSI) support each other. The following are some general conclusions that can be drawn from the examination of different deviation measures.

- Differences in accessibility measures are better explained by the choice of functional form for the deterrence variable than by the choice of model approach.
- Various methods used to evaluate the differences between measures suggest that models based on linear functional forms of the deterrence variable are not the same as measures based on nonlinear designed models.
- Nonlinear specification of the deterrence variable decreases the level of dispersion among the measures.
- Corrections for the agglomeration effect produce results that are significantly different from the other examined approaches.

Comparisons of Accessibility Maps

Finally, different accessibility maps are constructed using a GIS-platform by construction of TIN-models.[18] Isochor polygons are the result of the TIN-model, where the magnitude of accessibility in each polygon will demonstrate its level comparable to the other polygons in its surrounding neighborhood. Each isochor surface is classified by its rank, where rank 0 corresponds to locations with the least accessibility and 100 corresponds to locations with maximum accessibility. The accessibility rank[19] of each city is used as the *Z*-value,[20] which differentiates the isochors. The dark colors represent highly ranked areas, while the bright areas are ranked lower for accessibility. The continuous range of accessibility ranks is divided into 10 equal segments. This, however, makes a visual examination of small changes on the accessibility maps difficult. For the comparison of minor differences of two accessibility maps, one can zoom in areas of interest and use finer segments.

Figure 3 shows an accessibility map of Europe based on model *a*1 (travel-cost approach and linear deterrence variable), while figures 4 and 5 show corresponding maps based on model *a*2 (travel-cost approach and nonlinear deterrence variable) and model *b*2 (gravity approach and non-linear deterrence variable). A comparison of these figures suggests that the accessibility maps of Europe are more sensitive to the linearity of the deterrence variable than the approaches for the calculation of the accessibility measure (travel-cost or gravity approach).

Figure 6 shows the accessibility map of Europe based on model *c*1 (gravity approach corrected for the agglomeration effect and the linear deterrence variable). Comparison of this figure with previous maps suggests that the correction for the agglomeration effect has changed the relative rankings of accessibility values in Europe significantly. With correction for the agglomeration effect, large agglomerations such as London, Paris, or Moscow get very high rankings compared with the rest of

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[17] The use of simulated data can make the distinctions between the causes more clear.

[18] A TIN (triangular irregular network) is made by constructing a network using municipality centers as nodes with links connecting them to neighboring locations.

[19] The locations are ranked according to their measure of accessibility. The least accessible area is ranked to 0 while the highest ranked location has the value of 100.

[20] Here *Z*-value is the height of each polygon perpendicular to the XY-plane.

FIGURE 3 Accessibility Map of Europe Using Model *a*1

FIGURE 4 Accessibility Map of Europe Using Model *a*2

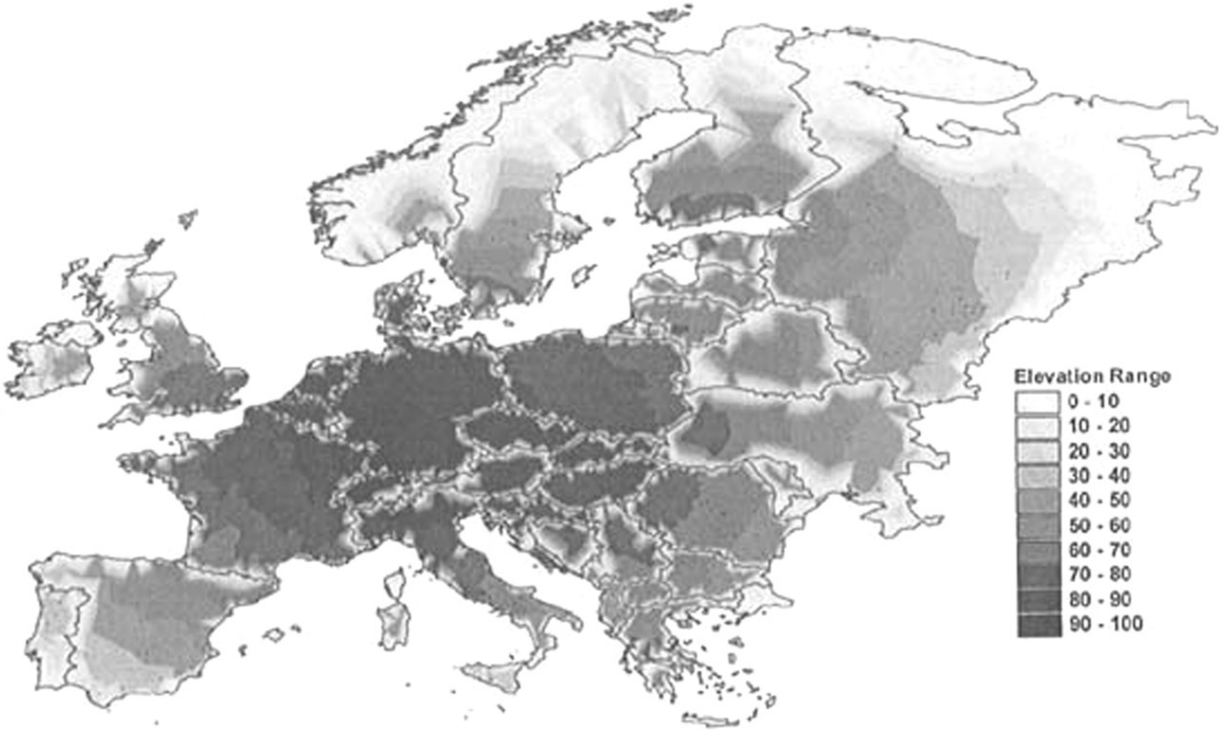


FIGURE 5 Accessibility Map of Europe Using Model *b*2

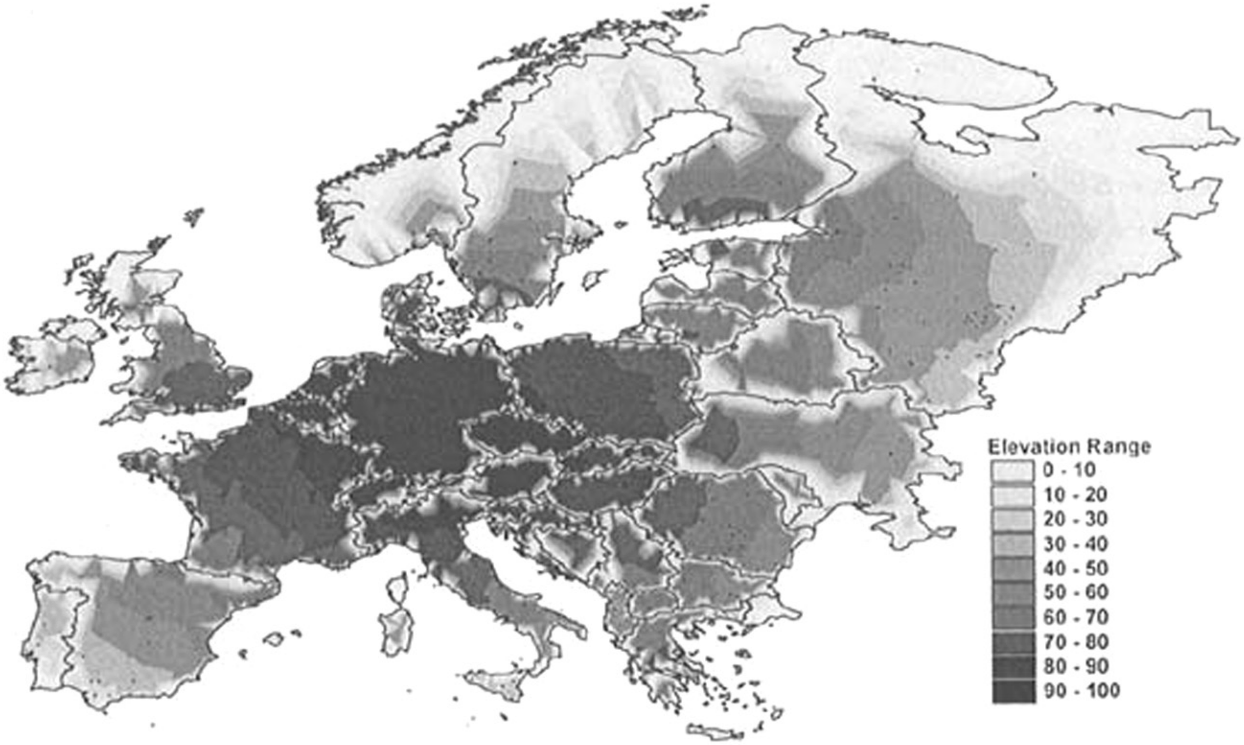
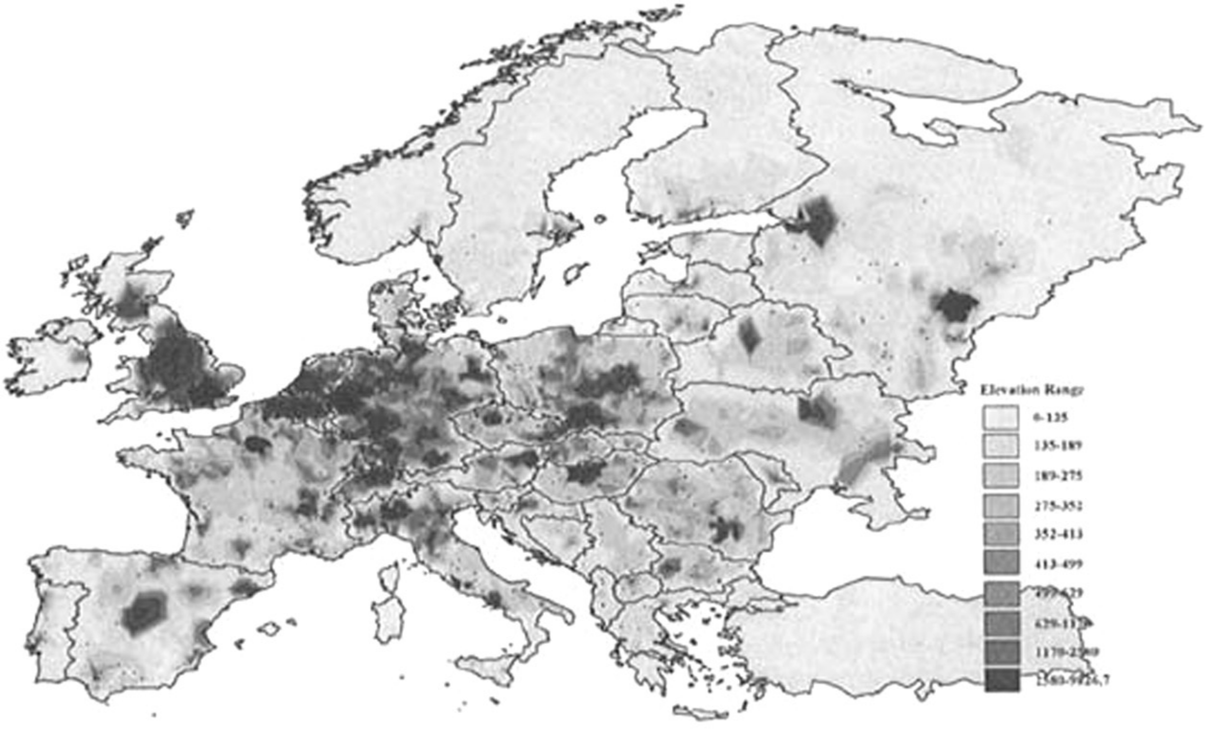


FIGURE 6 Accessibility Map of Europe Using Model *c*1



Europe. In fact Moscow has a significant place on this map compared with maps presented in figures 3, 4, and 5, where the agglomeration effect is not accounted for. These maps show that the most accessible part of Europe is Central Europe (around Germany) and accessibility decreases as one moves away from this area. Note that with a different scale, the relative rankings of accessibility values will change; however, the large agglomerations in Europe will have the highest accessibility values. In general, visual examination of accessibility maps confirm the results from the statistical tests.

Finally, examination of the accessibility maps of Europe suggest important issues with policy implications for the European Economic Community (EEC). One interesting observation is that accessibility measures in border regions of all the European countries seem to be much lower than internal accessibility measures. The lower level of accessibility measures in the border regions can be explained by two factors:

- the density of cities in border regions is usually lower than for the interior of a country, and
- accessibility in border regions is lower due to lower density of transport infrastructure in these locations.

Spiekermann and Wegener (1996) have reported similar observations in an accessibility study. One can expect that by taking congestion into account in calculating travel time, these border problems with respect to accessibility measures should become less severe, but they would not disappear. Indeed, the accessibility at border regions has emerged as an important policy issue for the EEC.

Another important observation is low accessibility in the peripheries of Europe, especially in the regions in the east and southeast. The choices of the demarcation area can at least partly explain this observation.

CONCLUSIONS

In this paper, five approaches for measuring accessibility were classified based on a literature review: travel-cost approach, gravity approach, constraints-based approach, utility-based approach, and composite approach. Certain properties of each class of accessibility models have been discussed as have their pros and cons. Basically, accessibility measures in these classes differ in three respects: theoretical foundation, complexity of construction, and demand on data. In general, the simpler measures are less data dependent, but they fail to adequately address the subject in a theoretically sound manner. Availability of data is usually an important factor in the choice of the appropriate measure in an accessibility study. The purpose of a study is another factor that should influence the choice of the measure. In the empirical part of this study, even with the limited number of measures, we have illustrated that the choice of the measure has an important affect on the accessibility map and hence, the focus on a particular issue.

Furthermore, some important issues relevant in modeling accessibility are summarized:

- measurement of spatial separation,
- measurement of attraction masses,
- choice of demarcation area,
- unimodality versus multimodality,
- agglomeration effects,
- the dimension problem, and
- time of day.

In the empirical part of the study, accessibility measures for more than 4,500 major European cities were constructed based on the travel-cost approach and gravity approach with and without correction for the agglomeration effect. Three different functional forms of the deterrence variable were examined in each approach, one linear and two nonlinear in construction. Differences between the calculated measures were studied using statistical and visual techniques. Correlation coefficients, measures of skewness and dispersion, and different metrics, *mean absolute difference* and *dissimilarity index*, were used. Finally, accessibility maps of Europe were produced for all approaches. We can draw some conclusions by examining different deviation measures:

- the choice of functional form for the deterrence variable explains the differences in accessibility measures more than the model approach,
- a measure with a linear functional form of the deterrence variable is different from measures based on nonlinear functional form,

- a nonlinear specification of the deterrence variable decreases the level of dispersion among the measures, and
- corrections for the agglomeration effect produce significantly different results.

This study is subject to many qualifications. An important qualification relates to the availability of necessary data for the comparison and evaluation of accessibility measures by all identified approaches. The results of this study, however, illustrate the importance of understanding the performance of these measures.

Finally, examinations of the accessibility maps of Europe suggest that the choice of approach influences the relative accessibility of locations, hence, highlighting the importance of issues differently. It is therefore important to use an approach relevant to the problem. Some important issues with policy implications for the EEC can be observed from these accessibility maps. One important observation is the low accessibility measures in border regions of all the European countries compared with internal accessibility values. This can be explained by low density of settlements and transport infrastructure in border regions. Another important observation is low accessibility in the peripheries of the Europe, especially in the regions in the east and southeast.

ACKNOWLEDGMENT

The Swedish National Road Administration supported this research. The authors wish to thank two anonymous referees for their helpful comments and suggestions.

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Appendix

TABLE 3 Descriptive Statistics for Simple and Window Average Transformed Model for Swedish Municipalities (β = 0.00329)

	Min	Max	Mean	Standard deviation
Population	2,859	71,8462	31,020.07	56,370.66
Simple model	0	100	3.926	7.87
Window average model	0	100	17.06	16.03

TABLE 4 Mean Absolute Difference (MAD) Between Accessibility Measures (Normalized)

a_1	0								
a_2	.47	0							
a_3	.38	.09	0						
b_1	.12	.58	.49	0					
b_2	.47	.00	.09	.58	0				
b_3	.36	.11	.01	.48	.11	0			
c_1	.52	.98	.89	.41	.98	.88	0		
c_2	.54	1.0	.91	.43	1.0	.90	.03	0	
c_3	.53	.99	.90	.42	.99	.89	.02	.01	0
	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3

TABLE 5 Dissimilarity Index (DSI) Between Accessibility Measures (Normalized)

a_1	0								
a_2	.35	0							
a_3	.30	.06	0						
b_1	.15	.48	.43	0					
b_2	.35	.00	.06	.48	0				
b_3	.29	.07	.01	.42	.07	0			
c_1	.90	.98	.97	.85	.98	.97	0		
c_2	.92	1.0	.99	.88	1.0	.99	.25	0	
c_3	.91	.99	.98	.86	.99	.98	.11	.15	0
	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3

Accessibility Improvements and Local Employment: An Empirical Analysis

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ABSTRACT

In this paper we hypothesize that the local supply of labor (i.e., labor force participation) is affected, among other things, by the level of accessibility to employment locations. Specifically, we conjecture that improved accessibility in a given area, resulting from transportation infrastructure investment, will enhance labor participation, given intervening factors such as socioeconomic and locational characteristics. We further conjecture that this effect will be more pronounced in low-income areas where costs of labor-market participation, including transportation costs, constitute a real barrier to market entry. Using a simultaneous equation model, this paper empirically explores the impact of accessibility changes on the supply of labor in specific job types in the South Bronx, New York, an economically distressed area. The major sources of data for this study are three U.S. Census Bureau data files from the 1990 Census Transportation Planning Package.

INTRODUCTION

Can accessibility improved through infrastructure development actually affect the level of local employment? If so, what is the nature and extent of this change? In this paper, we hypothesize that if travel time and costs represent a significant barrier to labor-market participation, improved accessibil-

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ity, in terms of reduced travel times and costs, can affect the propensity of potential employees to enter labor markets, given their residential and employment locations and socio-economic attributes. We further hypothesize that this effect is more prominent, and, therefore, more discernible, in economically distressed areas where enhanced accessibility is likely to have a larger impact on labor-market participation. This paper examines these hypotheses with the results from an empirical analysis of accessibility-improvement impacts on employment using data from a low income, high unemployment area in the South Bronx of New York City.

This analysis stems from the fact that many transportation improvement projects are justified by their alleged positive effect on the local economy, primarily an increase in employment beyond that generated by construction of the project. Specifically, transportation investments are suggested for poor areas as a form of economic stimuli under the presumption that increased employment will follow. On the other hand, if improved accessibility does indeed have a tangible effect on employment, it is necessary to understand the nature of this impact relative to the types of employment and socioeconomic groups benefiting from such investments.

It is obvious that accessibility is only one of a number of factors influencing labor-market participation. Factors such as work skills, education, and family size and makeup may have an even greater impact on the employability of potential workers than does accessibility. Therefore, a main objective of this analysis is to discern the degree to which the reduction in the cost of travel to specified work sites can influence an increase in labor supply, given other intervening factors.

It can also be argued that whereas improved accessibility may have a positive effect on labor supply, in affluent areas where income and car ownership levels are high, this effect is likely to be insignificant and quite difficult to detect.[1] If it is at all effective as a means to promote employment, improved accessibility will have a greater impact in poor areas where skill and education levels are lower than in affluent areas.[2] For this reason, we have conducted our empirical analysis in the South Bronx, a distressed urban area in New York City.

On a more general level, improved accessibility has several potential long-term consequences possibly affecting the overall welfare of the area's residents and should be regarded in a general equilibrium framework. First, changes in accessibility can affect property values, possibly rising with increased accessibility, thereby making present nonowner residents worse off by increasing their rent level or even forcing them to relocate to fringe areas where rents are lower. Second, improved accessibility affects location decisions by both firms and households. As a result, the argument that improved accessibility can induce labor-market entry may not hold since spatial rearrangement may, in turn, alter accessibility levels to the disadvantage of low-income residents unable to relocate. A related issue is that improved accessibility can cause migration of residents of adjacent regions with inferior accessibility level into the impacted area.

Still another element to consider when developing a methodology for analyzing the effects of accessibility changes on employment is that transportation improvements are the result of public decisions, possibly not independent of external factors, such as the wealth levels of different areas. Transportation capital improvement projects are neither ubiquitous nor random since local pressure by affluent constituents can result in greater investments made in their locales relative to areas that lack such influence. Hence, a more accurate comparison of areas with and without improved accessibility, relative to their impact on employment, requires a consideration of this and similar factors.

In this paper we do not address these issues, even though we consider them quite important for the overall understanding of the relationship between transportation improvements and employment. Mainly due to data reasons (see the data in

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[1] On the other hand, the value of time tends to increase with income so that the value of accessibility also rises with income. A counter argument is that at higher income, trip-makers can influence their travel time by purchasing the services of high-speed modes, such as a private car, express bus or rail, or travel on toll roads, and that these means are beyond the reach of low-income commuters.

[2] Vickerman et al. (1995) argue that ". . . a lack of labor skills can be compensated for by the provision of a cheap and efficient public transport system. . . ."

Appendix B) and the specific characteristics of the South Bronx, our analysis is a nontemporal and nonspatial equilibrium analysis, which assumes fixed residential and employment locations and a given population level. It focuses on the more immediate response of potential workers to changes in accessibility. We notice that, in general, the changes noted above in property value, location, and population shifts are rather complex phenomena extending over many years and carrying mixed effects on employment. As such, they require complicated modeling and an elaborate database. On the other hand, potential shorter-term adjustments in the level of employment from transportation improvements carry significant implications for policy making, particularly in economically distressed areas with high unemployment rates.

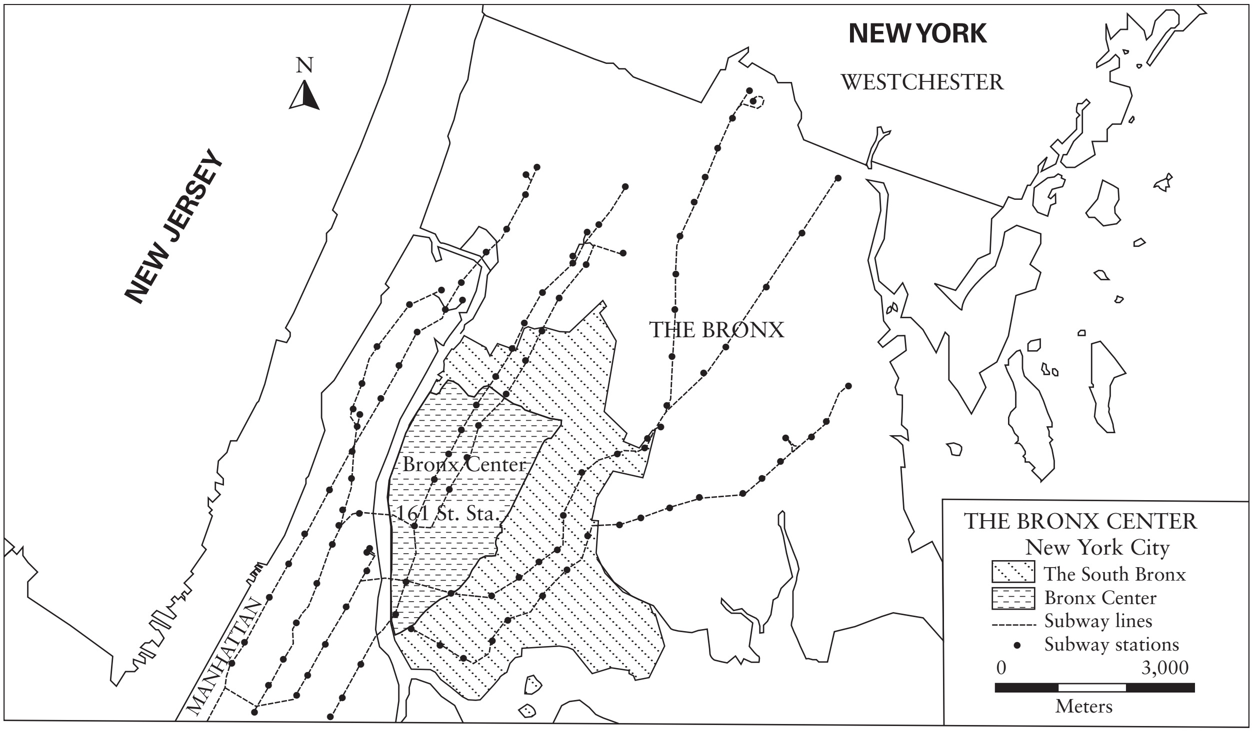
In the following section we describe the socioeconomic and transportation-related characteristics of the South Bronx. The estimated results can best be understood when considered against these factors. In the third section, we briefly present findings from studies that measured the effects of accessibility improvements on the local economy, mainly on employment. Section four presents our theoretical considerations and modeling approach. Empirical results and discussion appear in section five, and major conclusions are in the final section.

THE SOUTH BRONX: SOCIOECONOMIC AND TRANSPORTATION-RELATED CHARACTERISTICS

While Berechman and Paaswell (1996) offers a detailed description, we begin this analysis with a brief description of the studied area. The South Bronx, a 336-square block area in the borough of the Bronx, New York, is a 30-minute subway trip from Midtown Manhattan. Figure 1 displays the boundaries of the South Bronx within the Bronx. A major transportation investment project, labeled the Bronx Center project, was considered for this area. Its location is also marked in figure 1.

Although the area contains a community college, a major hospital, courthouses, and borough offices, it houses a population whose demographics and socioeconomic profile show that the region is economically disadvantaged. The economic decline came about through the closing of manufacturing in the 1960s and through the departure of the middle class to suburban regions. A key factor underlying much of the economic reality of the South Bronx is its high level of unemployment. As shown

FIGURE 1 Location of the Bronx Center



in figure 2, in 1990, while 50% of the residents of the Bronx (excluding the South Bronx) are defined as "employed and at work," the corresponding figure for the South Bronx is only 39%. The participation rate, defined here as the number of employed people out of the total labor force, was 91% in 1990 in New York City, 88% in the Bronx, and 84% in the South Bronx.

As table 1 shows, even in later years the unemployment rate (not seasonally adjusted) in the Bronx, including the South Bronx, is quite high relative to the other boroughs in New York City.

The median income in the South Bronx is only about 69% of that of the Bronx as a whole and about 50% of that of New York City.[3] The poverty rate (the number of persons in poverty out of total persons) is the highest in the New York area, about 40% in 1996.

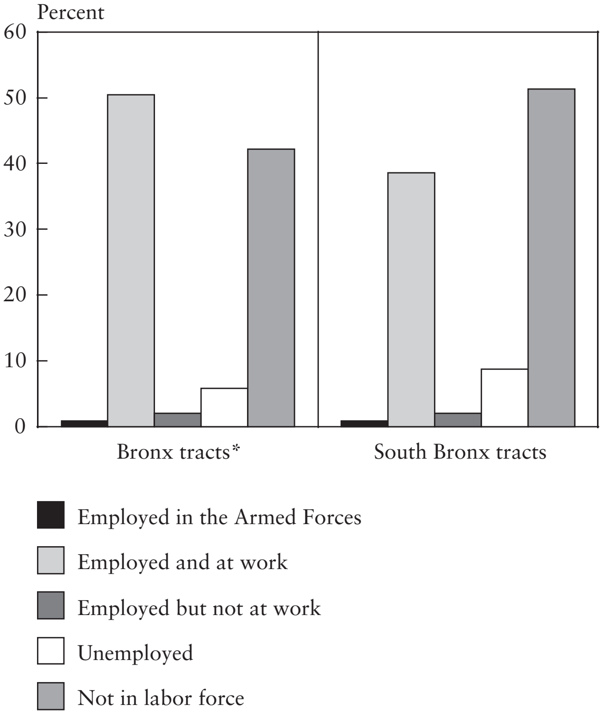
Level of education greatly affects employability. Presently, about 80% of the residents of the South Bronx have only a high school diploma or fewer years of schooling compared with 67% in the rest of the Bronx. This situation is reflected in the occupation profile of the South Bronx residents. The majority of the labor force is employed in administrative support and service occupations. As the estimated results presented later indicate, labor-market participation in these particular occupations is markedly sensitive to changes in accessibility.

TABLE 1 Unemployment Rates in New York's Five Boroughs, 1996–1998 (percent)

	1996	1998
New York City (all boroughs)	8.5	8.1
Bronx (including the South Bronx)	11.0	10.2
Brooklyn	9.5	9.4
Manhattan	7.4	6.9
Queens	7.5	6.9
Staten Island	7.5	7.6

Source: New York State Bureau of Labor Statistics (November 1996, July 1998)

FIGURE 2 Employment Status (1990)



*Excluding South Bronx tracts

Transportation options for the area include commuter rail, rapid rail, and metropolitan bus lines. These, however, are geared to trips ending in mid- to lower-Manhattan. Based on markets existing some decades ago, they do not necessarily represent market demands created by the decline of manufacturing in the Bronx and the growth of services in Manhattan. A close inspection of South Bronx transportation conditions reveals that they are quite deficient in terms of high travel costs, long commute times, and inferior service quality. As shown in figure 1, within the South Bronx many areas are relatively far from a subway station, and bus service is infrequent and expensive. Furthermore, the car-ownership rate in the South Bronx is quite low, about 21% as compared with 49% for the entire Bronx borough and 57% for New York City. It is not surprising, therefore, that residents of the South Bronx rely heavily on public transit for travel to work. About 63% use public modes (subway, elevated train, railroad, or bus), and only 19% use a private car. For the Bronx borough (excluding the South Bronx), the corresponding figures are 54% and 33%, respectively. The remainder is made up by foot travel and other transportation means.[4]

Two other important indicators of travel behavior are time of departure and length of travel time. Thus, whereas the distribution of time of departure

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[3] See Berechman and Paaswell (1996) for a detailed description. Data sources are listed in Appendix B.

[4] See Appendix B for the source of these data.

for the Bronx residents (excluding the South Bronx) displays an almost normal curve, the distribution of time of departure for the South Bronx residents is heavy-tailed with many early and late departures. On the other hand, the majority of trips by South Bronx residents are within the middle range, 30 to 60 minutes, whereas those of Bronx residents are in the shorter, 0 to 30 minute, and longer, 60 to 90 minute, ranges.

In summary, these data demonstrate that the socioeconomic profile of South Bronx residents is quite different from that of Bronx residents as a whole and of the other New York boroughs. They are poorer and less mobile and also have lower levels of formal education and work skills. These qualities effectively reduce their potential employability. This observation has two major ramifications for our analysis. The first is that residents of the South Bronx appear more susceptible to changes in travel time and costs relative to labor force participation than residents of more affluent areas. The second is that estimated results from empirical analysis will be best understood if socioeconomic and transportation characteristics are considered.

EFFECT OF ACCESSIBILITY CHANGES ON EMPLOYMENT

In recent years, interest in the question of whether transportation improvements generate economic growth, mainly employment, has grown (Banister and Berechman 2000). Beeson (1992) argued that in urban areas the degree of labor specialization and division (e.g., diversity of employment), which affects labor productivity and use, depends mainly on the size of the market determined, in turn, by population density and transportation costs. Paaswell and Zupan (1998) showed that increased densities in the core (Manhattan) require the high accessibility provided primarily by rail rapid transit systems. Quite simply, in such extremely high-density areas, an employer can benefit not only from nearby important support services and amenities but also from a diverse labor force within a reasonable commuting distance. The authors showed that few cities in the world, London and Tokyo being exceptions, had that relationship between employment density and accessibility. In contrast, in Chicago, a city with a highly developed rail rapid transit system, opportunities are less than optimal. The more than 50% of the region's population living in the suburbs are served by well-developed highway networks, which also encourage dispersion of employment. In the last decade, this dispersion has taken jobs away from the core, redistributed them throughout the suburbs, and made them accessible only by car, effectively reducing overall accessibility for potential employees (Sen et al. 1998). The costs to enter or participate in the job market for the low-income worker in Chicago, then, are higher than for his New York counterpart.

The empirical literature pertinent to these arguments can be categorized into two broad groups. The first is the Spatial Mismatch Hypothesis (SMH); it focuses on labor force participation of inner city minority residents. The second, labeled here the "production function" approach, focuses on the causality between transportation improvements and growth as well as the degree to which such association actually exists.

Starting with the pioneering work of Kain (1968), the SMH states that inner city minority residents suffer from high rates of unemployment, caused by poor accessibility to employment, which has decentralized to suburbs. These minorities, who have low income and low rates of car ownership, are unable to relocate to these suburbs due to discrimination in the suburban housing markets. Under these conditions, improved accessibility can bring about an increase in market participation rates of inner city minorities.

A recent comprehensive review of empirical results from SMH studies has concluded that the lack of spatial accessibility to employment can explain poor labor-market participation rates of inner city, low-income inhabitants in large metropolitan areas (Ihlanfeldt and Sjoquist 1998). However, this review also suggests that in addition to accessibility, other factors can bring about similar effects. These factors range from the lack of information on job availability at distant employment sites to job discrimination factors. Furthermore, it is also suggested that the lack of important job skills is at least as important as accessibility in affecting employment levels among inner city, low-income groups. A similar argument can be made for the effect of childcare costs, which for low-income groups can be significant. Hence, for policy purposes it is important to discern the relative importance of each factor on spatial mismatch since, in themselves, commuting programs may not appreciably affect deficient market participation among inner city minorities. Still another empirical issue is whether all low-skilled workers, mainly adults, actually are accessibility-deficient. This issue is troublesome since most SMH studies have focused on the analysis of inner city youth.

This study does not intend to examine the SMH. We look at labor-force participation within New York City, a unique urban area atypical of U.S. urban areas, and address impacts of costs of travel in boroughs where accessibility may be high and traditional job markets within reach. Thus, in terms of transportation, the South Bronx is not typical as compared with many inner city areas. Workers in the South Bronx have access to transportation systems that provide high levels of accessibility to the prime locations of employment, the core of Manhattan. In addition, they have access to a highly developed expressway network that can bring them to nearby suburban counties. The problem discussed here is more local. Because the rail network was designed to access the core of Manhattan and the bus network to serve the rail stations, public transport within the South Bronx does not adequately serve local workers. Thus, while a commute to the core of Manhattan or to the suburbs can be achieved in a reasonable time, a commute across the South Bronx becomes quite costly. For this reason, this paper does not attempt to confirm or disprove the SMH.

However, the present analysis accounts for several factors, also necessary for validating the SMH. In particular, it controls for labor skills, for the level of education, and for household variables including age of children. In addition, in this analysis we use an accessibility measure, a function of network-based modal travel times and costs, of time of departure, of car ownership, and of household income. We believe that this measure is comprehensive enough to adequately measure accessibility to employment in the studied area. Moreover, our analysis distinguishes between residents who live *and* work in the Bronx and those who live in the Bronx but work elsewhere.

Within "production function" literature, several empirical studies have found that changes in accessibility (broadly defined) have an insignificant effect on employment growth (Danielson and Wolpert 1991) or on travel-to-work behavior (Ewing 1995). Thus, it was concluded that employment growth took place mainly in outer suburbs and was largely insensitive to highway accessibility (Gilulіano and Small 1999). On the other hand, household characteristics such as size, number of workers, and income have a stronger impact on work trip patterns.

Cervero and Landis (1995), who investigated the employment effects from the San Francisco Bay Area Rapid Transit (BART) system, found that most employment growth took place in corridors not served by BART and that BART's locational advantage was confined primarily to the service sector (mainly finance, insurance, and real estate). Employment densities near BART stations were higher than match-paired freeway interchanges (+12% for suburban and +28% for urban).

Results from these studies do not clearly delineate employment changes from accessibility improvements. Transportation development generates efficiency gains, transfer effects, and activity relocation effects (Banister and Edwards 1995; Berechman 1995; Forkenbrock and Foster 1990). Together these effects influence the demand for employment in conflicting ways. But what about labor supply changes from accessibility improvements? Do people, especially in poor areas, respond to accessibility changes by offering more labor? How do labor skills and labor-market experience affect their willingness to enter the labor market relative to the effect of reduced transportation costs? Are potential employees in some occupations more susceptible to accessibility changes than employees in other occupations? Next we address these questions.

MODELING ACCESSIBILITY AND MARKET ENTRY DECISIONS

When examining the relationships between accessibility improvements and changes in the local supply of labor, it is necessary to distinguish between two types of change. The first is a change in the amount of labor actually provided by existing employees and measured by, for example, the number of daily hours worked. The second is a change in the actual number of people in the labor force, resulting from new market entry.

A common approach to assessing changes in actual labor supplied by existing employees is to consider work/nonwork activity substitution. Individuals divide their total daily hours between work and nonwork activities, and the latter can further be divided between travel and other nonwork (leisure time) activities. Travel time, in turn, which confers negative utility, is a function of accessibility (by mode). Hence, reduced travel time resulting from improved accessibility will leave more time available for work and leisure time activities. Given some reasonable assumptions on work/leisure time substitution as well as on the effect on income of reduced travel times and costs, improved accessibility is likely to have a positive effect on the actual amount of labor individuals can supply (Berechman 1994). At equilibrium, the allocation of time between work and nonwork activities will depend on the reservation wage rate, the lowest wage an unemployed worker will accept; individual preferences with respect to work/leisure substitution; and travel time to work, a measure of accessibility.[5] Since the focus here is on market entry due to accessibility improvements, we do not examine the possibilities of part-time work or working more or fewer hours. Also the database used here (see Appendix B) does not report such information.

A plausible explanation for new labor-market entry due to improved accessibility is the net-pay entry threshold argument. Net pay is defined as the after-tax total earnings minus the costs associated with labor-market participation. Accordingly, individuals regard their expected net pay as a key determinant in their labor-market entry decisions. The costs of participation include the costs of child-care arrangements as well as the time and out-of-pocket expenses associated with travel to work. With other key factors, such as skills and family size, kept constant, the net-pay argument implies that when given after-tax expected earned income, lowering the time and money costs of travel will also lower entry thresholds, thereby positively affecting the propensity of individuals to enter the labor market. It also follows that the larger the entry cost share is of total after-tax expected income, certainly the case for low-income individuals,[6] the larger the elasticity of the labor supply with respect to travel cost reduction will be. Again, we emphasize the short-term and partial equilibrium nature of this analysis since, in the longer run, changes in the labor supply function will affect equilibrium wage rates which, in turn, will affect the actual level of employment.

Empirically, changes in the labor-participation rate can be observed only if individuals willing to enter the labor market, following accessibility improvements, actually become employed. For this to happen, it is necessary for some firms to employ these individuals. In this short-term analysis, we assume a quite elastic labor-demand function so that an increase in labor supply following accessibility improvements will indeed result in employment of workers at present wage rates for firms' location and production technology.

In his well-known study, Cogan (1980) developed a methodology for assessing the effect of the costs of labor-market participation on entry decisions by women. Using 1976 household-panel data from the Michigan Panel Income Dynamics survey and applying a probit model to estimate a reduced-form index of women's labor force participation, Cogan found that the effect of time and monetary costs (unrelated to travel) associated with labor-market entry was rather substantial. Specifically, he

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[5] One caveat to this conclusion: many employees are constrained by employment rules, making it unfeasible for them to be paid for more than a fixed number of hours per day, week, or month. These work rules vary between firms and occupations as well as by seniority and labor union contracts. In the Bronx, a large number of employees are part-time workers, who, for various reasons, such as lack of skills, cannot increase the number of hours they work; if they could, they would have done so, considering their income level.

[6] It might be argued that low wages also imply low value of time and, hence, low travel costs. In the New York area, however, direct monetary costs of travel are quite high, so their effect on low wage earners probably outweighs the effect of low value of time.

found that estimated at the sample mean, these costs were equivalent to 1,151 annual hours to the worker. Overall, his results indicate that the annual cost of participation in the labor market amounts to 16% of women's average earned income. These results, however, were not categorized by employment type and did not account for transportation costs associated with market entry.

In this study, we have followed Cogan's approach to examine the effect of lowering travel times and money costs on the supply of labor. Here we test two main hypotheses: 1) improved accessibility, all else unchanged, will positively affect individuals' propensity to enter the labor market and 2) this effect will vary across employment types and industries. Appendix A provides a discussion of the analytical underpinnings of our modeling approach, primarily on the nature of the supply function, which represents participation decisions in the wage-travel costs space.

We measure accessibility as a combination of travel time and monetary costs, known as generalized travel costs, adjusted for the type of mode used. It is important to point out that, to a certain extent, accessibility costs are endogenous variables in the decision process of potential employees. That is, given their location, factors such as mode choice, time of departure, car ownership, and car utilization are used by individuals to effectuate their travel times and costs. On the other hand, mode availability, bus and train headways, fares, and road tolls are largely exogenous. In the analytical model, we regarded accessibility as an endogenous variable but have also introduced into the accessibility function some exogenous travel variables.

The level of accessibility between residential and employment locations i and j, respectively, measured in units of weighted travel time and costs, denoted by T_{ij}, is specified as a function of the following five components:[7] c_{ij}^{m} is the monetary costs of travel by mode, weighted by the proportion of people using that mode between these locations, w_{ij}^{m}; t_{ij}^{m} is travel times by mode, also weighted; d_{ij} is time of departure; C_i^H is car ownership by households (at residential location i); and Y_i^H is households' income level.

$$T_{ij} = f\left(w_{ij}^{m} c_{ij}^{m}, w_{ij}^{m} t_{ij}^{m}, d_{ij}, C_i^H, Y_i^H\right) \qquad (1)$$

The specific accessibility function used in this study is given by

$$T_{ij} = \eta_0 + \sum_m \eta_1^m \left(w_{ij}^m c_{ij}^m\right) + \sum_m \eta_2^m \left(w_{ij}^m t_{ij}^m\right) + \eta_3 d_{ij} + \eta_4 C_i^H + \eta_5 \ln Y_i^H + \varepsilon_1 \qquad (2)$$

The weights $w_{ij}^m = \dfrac{L_{ij}^m}{L_{ij}}$, where L_{ij}^m is the number of people using mode m (m = car, transit, walk) for home-to-work travel between i and j; L_{ij} is the total number of people traveling between i and j.

Equation (2) does not represent a transportation choice model. That is, often after the implementation of a transportation improvement, for example, a new express bus, travelers may shift route or mode, thereby affecting accessibility. While equation (2) does not account for route or mode choices, it explicitly asserts that whatever transportation improvements are made, their accessibility impact is captured through changes in travel time and costs and time of departure, given car availability and income.[8]

Next, we specify the labor-supply function, where $Q_{ij}^{k,s}$ denotes the number of employees in job type k, employed in industry type s, residing in location i, and working in location j, respectively. See Appendix A for definitions.

$$Q_{ij}^{k,s} = \lambda_0 + \lambda_1^k \exp(-\upsilon T_{ij}) + \lambda_2 \ln Y_i^H + \lambda_{3,k} \ln W_j^{k,s} + \lambda_4 E_i + \sum_{I=1}^{3} \lambda_{5,I} F_{I,i} + \lambda_6 SB + \varepsilon_2 \qquad (3)$$

where ε_1 (equation (2)) and ε_2 are the error terms. For the empirical analysis, the accessibility function's decay factor, υ, is set to 1.0. Experi-

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[7] We have also used a travel time and cost matrix calculated from actual bus and subway information relative to headways, in-vehicle time, and average walk time to/from nearest stations. These two matrices are highly correlated though on some specific routes there were some significant variations. We did not find significant differences when we tested the empirical model for each of these matrices.

[8] In any case, conducting route and mode choice analysis requires an individual choice database, largely unavailable.

ments with other values for υ did not yield significantly different results.

Equations (2) and (3) were estimated simultaneously using a two-stage least squares (2SLS) procedure. In the first stage, equation (2), the level of accessibility, T_{ij}, between residential location i and employment location j is estimated.[9] In the second stage $Q_{ij}^{k,s}$, the number of employees living in i, working in j, and working in job type k in industry type s is assumed to be a function of several factors: 1) inverse of the accessibility level, T_{ij}, estimated from the first stage; 2) income Y_i^H ; 3) the actual wage rate paid in job type k in industry type s $\left(W_j^{k,s}\right)$; 4) the level of education, measured in units of school years, E_i; and 5) the number of children in 3 age groups ($F_{l,i}$;$l = 1,2,3$): 0-5, 6-13, 14-18. We have also used a dummy variable, *SB*, to indicate whether a person who lives in the South Bronx also works there (*SB* = 1) or not (*SB* = 0).

The database used for this analysis is composed of 1990 U.S. Census Bureau data. The major data files used contain data at the census block group level and not at the individual household level. The observations pertain to employment, travel behavior, and socioeconomic attributes of residents of the South Bronx, New York. Employment is categorized into 13 job types in 17 employment sectors. In the study area, there are approximately 56,000 census-block-based origin-destination pairs, including persons living and working in the Bronx and people living in the Bronx but working anywhere. As already mentioned, this database does not account for part-time employees or for changes in the number of weekly work-hours actually worked by already employed workers. A detailed description of the database and its organization, including variables definition, appears in Appendix B.

RESULTS AND DISCUSSION

Our principal hypothesis is that with all else constant, reductions in accessibility costs between places of residence and places of employment will enhance the propensity of individuals in the South Bronx to participate in the labor force. Thus, the main thrust of the empirical analysis is the estimation of point elasticities of labor-force supply in specific job categories with respect to travel costs, given a set of other intervening variables. The main results from the estimation are presented in table 2.

As already mentioned, there are 13 job types. Table 2, however, shows results for four types only. One reason is that some employment types (e.g., farming) are not well represented in the South Bronx and thus can be omitted. Another reason is that not all job types proved sensitive to accessibility changes, that is, the relevant estimated parameters were insignificant at 0.05.[10] For brevity, table 2 lists all variables for each equation but shows only those parameters that are significant at the 0.05 level or better. For the accessibility and employment equations, the reported parameters are scale-adjusted coefficients as the units of measurement of variables in these equations are noncomparable.[11]

As can be expected, the results of the accessibility function, equation (2), indicate that overall accessibility is positively and significantly affected by public transit, car, and walk travel times. Reductions in transit travel times have the greatest impact ($\eta_2^{Transit} = 0.807$), while reductions in car travel times have the least effect ($\eta_2^{Car} = 0.212$). The importance of these results is that in the South Bronx, considering the low levels of car ownership, improvements in transit service will have the greatest impact on accessibility.

Interesting results pertain to time of departure. As the number of people leaving home for work at the early and late time periods increases, accessibility improves (the negative sign of the 6:30–7:30 and 8:30–12:00 departure time variables). Apparently, a rush hour departure time is associated with poorer accessibility as factors such as crowding, unreliability, and general inconvenience

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[9] In the South Bronx, 68.3% of trip-makers travel by public transit for which monetary cost (fare) is constant relative to trip length and time of day. Therefore, in some runs of the model, the travel cost variable, C_{ij}^m, was omitted from the accessibility equation due to lack of variability.

[10] It remains to be examined why these sectors are not affected by travel costs reduction. This is the subject of a follow-up analysis.

[11] See Montgomery and Peck (1992, chapter 4) for a statistical explanation.

TABLE 2 A Two-Stage Least Squares Estimation of the Accessibility and Employment Functions

Accessibility (equation 2)		Employment (equation 3)				
			Type of job			
Variable	Parameter	Variable	Executive parameter	Technician parameter	Administrative parameter	Transport parameter
Mode		**Accessibility**	–.237740	–.187414	–.096016	–.079812
car	.212161	**Wage rate**				
transit	.806815	(3) Construction	NS	.283052	NS	NS
walk	.413026	(4) Manufacture 1	.129783	.136822	.048485	NS
others	NS	(5) Manufacture 2	NS	.090696	NS	.235875
Departure						
12:00–5:59	NS	(6) Transport	.338492	NS	.235395	.575081
6:00–6:29	NS	(7) Communication	NS	NS	NS	NS
6:30–6:59	–.140844	(8) Wholesale	NS	–.145514	.163956	.256606
7:00–7:29	–.198046	(9) Retail	.285929	NS	NS	NS
7:30–7:59	.286117	(10) FIRE	.485281	.447685	.422971	NS
8:00–8:29	.103212	(11) Business and repair	NS	.347708	NS	–.353465
8:30–8:59	–.126580	(12) Personal Services	NS	–.142507	.068464	NS
9:00–9:59	–.137373	(13) Entertainment	.210809	NS	.052301	NS
10:00–11:59	–.149063	(14) Health	NS	.858439	.172036	.384054
Car ownership						
0 cars	–.042637	(15) Education	NS	.122671	.074335	.179501
1 car	–.004050	(16) Other	.140571	–.143720	NS	.454775
2+ cars	.017643	(17) Public administration	–.141837	.00407	.161577	NS
Income, in $ thousands		**Education:**				
0–9.9	.571909	Less than 9th grade	NS	–.275950	NS	NS
10–19.9	.521587	Less than 12th grade	–.235460	.408651	NS	–.684124
20–29.9	NS	High school diploma	NS	–.326228	.168903	NS
30–34.9	.340198	No college degree	NS	NS	.179568	.212217
35–49.9	.367278	Associate degree	.146286	NS	.166667	–.268634
50–74.9	.189123	Bachelor degree	NS	–.224551	NS	–.288028
75.0+	–.012188	Graduate degree	NS	.187507	NS	–.538609
Constant	44.3827	**Childrens' age:**				
R-Squared	.362	Under 3	NS	NS	NS	–.258383
		3–5	NS	–.235078	NS	–.275407
		6–11	NS	–.159645	–.132387	.455364
		12–17	NS	–.425830	.130015	NS
		Income, in $ thousands				
		0–9.9	NS	.089148	–.055030	NS
		10–19.9	NS	.155627	NS	NS
		20–29.9	.058064	NS	–.043658	NS
		30–34.9	.093460	NS	NS	NS
		35–49.9	NS	NS	NS	NS
		50–74.9	0.082358	NS	–.158341	NS
		75.0+	NS	NS	NS	.121987
		Constant	–4.286843	6.516566	–25.94905	–.841860
		R-Squared	.866	.869	.953	.765

Note: Parameters shown are adjusted coefficients (see text) and significant at 0.05 level or better.
NS = not significant.

affect accessibility.[12] Since New York City public transit is priced uniformly over time and space, improved transit in vehicle travel times, headway, and capacity is likely to have a profound impact on overall accessibility.

The relatively low value of the car ownership parameter ($\eta_4 = -0.04050$) reflects the basic reality of the South Bronx of a very low level of car ownership. Another analysis (Berechman and Paaswell 1997) showed that the car occupancy variable has an indirect effect on accessibility, as higher levels of occupancy are associated with

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[12] Early departure may also suggest a multi-purpose trip pattern. Dropping a child at a day-care center is an obvious example.

reduced travel times. Car ownership by itself, however, does not seem to have such an effect.

Income has an interesting effect on measured accessibility. In 1990, in the South Bronx over 65% of the population earned less than $20,000 per year, and over 45% earned less than $10,000. There is no doubt that at these income levels public transit is the mode of choice which, compared with car use, is a slow mode offering lesser accessibility. This explains why we find a significant and positive (i.e., higher travel times) relationship between accessibility and low-income variables (parameter value is $\eta_5 = 0.571$ for $10,000 or less, and $\eta_5 = 0.521$ for $10,000–$20,000 income level). As income increases, there is a gradual shift to private modes, associated with greater accessibility, hence the smaller value of the relevant parameters. When income is at its highest level ($75,000+), its effect on accessibility actually peaks ($\eta_5 = -0.012188$).

Turning now to the employment function, equation (3), a key result is that only for some job types are the accessibility parameters (λ_1^k) statistically significant and with the correct sign. For example, in table 2, the accessibility parameters of Executive, Technician, Administrative, and Transport types of jobs are significant and have a negative sign (i.e., improved accessibility, in terms of *reduced* costs of access, will *increase* employment in these job categories). Why is this result important? Actual accessibility improvements in the South Bronx seem to affect labor supply in some job types only but not in others. In assessing the policy impacts of accessibility improvements on employment in this area, not all job types should be treated similarly. We return to this issue when we discuss the policy implications of this analysis.

As expected, the estimated parameters indicate that a higher wage rate is associated with a greater propensity for workers to enter the labor market. This is particularly true for Executive and Administrative support type jobs in the 17 industries. For Technician and Transport occupations, however, the wage rate effect is positive for only some employment sectors and is negative for others (e.g., for Technicians employed in Personal Services, $\lambda_3 = -0.142507$). It is not quite clear how to explain this result. We surmise that wage differentials in various industries can suppress the willingness of one member of a two-employee household to enter the job market when the other member earns a much higher wage. Another possible explanation is that the increase in accessibility expands the search area. People who were unemployable at present wage rates in their previous search area can now find jobs at a lower wage in the expanded area.

The parameters pertaining to the variable "level of education" have a positive effect on labor-market participation though their magnitude is less than the impact of other variables. For some job types, Executive and Administrative, the estimated parameters indicate that having some formal college education positively contributes to employability, whereas for Technician and Transport, the opposite is true ($\lambda_4 < 0$).[13]

Underlying our analysis is the hypothesis that the costs of travel and other nontravel expenses an individual incurs when entering the labor force represent an actual barrier to labor-force participation. Thus, the costs associated with childcare represent a major market-entry barrier. A negative sign for the pertinent (and significant) parameter (i.e., $\lambda_5 < 0$) indicates that for a given job type having more children of a given age group poses higher market-entry costs. And these, in turn, negatively affect the propensity of individuals to be employed in this occupation. A positive (and significant) parameter indicates the opposite. By and large, the significant parameters of the children-age variable in the employment equation have the expected negative sign (e.g., for job type "Technician" having children in the age group 3–5, $\lambda_5 = -0.235078$). One probable explanation for the few parameters with a positive sign is that, for these particular job types, having children of a certain age does not represent actual costs while, concurrently, it does induce a greater labor-market participation due to income needs.

Except for Executive type jobs and the very low income levels of Technician and highest level of Transport, the income parameter of all other job types (λ_2) was either insignificant or had a nega-

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[13] We are unable to explain $\lambda_4 = 0.187507$ for Technician with a graduate degree. Perhaps in this job type overqualification has an offsetting impact on employment.

tive effect on participation decisions. The main reason seems to be the general low level of income in the South Bronx that, save for a small percentage of jobs (Executive being 5.9% of all jobs), is a result of low wages paid in all other job categories. Above, we saw that the wage rate parameters, by and large, have a positive and a sizable impact on participation. Since in the South Bronx wages and income are highly correlated, participation rates are largely captured by changes in the wage level.

How can these parameter estimates be used to assess the impact of improved accessibility on labor supply in the South Bronx? When assessing the size of the employment effect from a given improvement in accessibility, it is necessary to recall that our employment model assumes locations as given. Therefore, a specific reduction in travel costs (equation 2) will affect the propensity of potential employees at their present residential location *i*, to enter job type *k* in industry type *s* at location *j*, by the magnitude of the estimated parameters (λ_1^k in equation 3) *and* the actual change in accessibility. Thus, if we assume a certain percentage increase in accessibility between locations, *i* and *j*, ΔT_{ij}, the total change in labor supply at location *j*, ΔQ_{ij} is

$$\Delta Q_{ij} = \Delta T_{ij} \sum_{k,s} \lambda_1^k \cdot P_{ij}^{k,s} \tag{4}$$

where $P_{ij}^{k,s}$ is the number of potential employees (the number of employable adults) residing in the zones affected by the accessibility change (*i* and *j*) who work in job type *k* in industry type *s*.

To illustrate, consider a particular transportation development, such as the introduction of an express bus to a major employment area *j*, which improves accessibility (i.e., lowers the composite travel costs measure, T_{ij}) by 10% relative to present accessibility level (thus, $\Delta T_{ij} = 0.1$) for all potential employees who reside in *i* and would travel to work at *j*. From table 2, there are four job types whose accessibility parameters are statistically significant. Within the South Bronx, the observed distribution of these four job types is as follows: Executive (executive, administrative, and managerial) makes up 5.9% of the labor force; Technician (technicians and related support occupations), 2.1%; Administrative (administrative support occupations), 22.4%; and Transport (transportation and material moving occupations), 5.2%. Jointly, they make up 35.6% of the total labor force in the South Bronx.[14] Hence, for every 1,000 potential employees in the relevant *i* and *j* area, 356 are employed in job types that are positively and significantly affected by accessibility changes. For these calculations we assume that this observed distribution of job types applies also to every *i* and *j*.

Given these figures, from equation (4) we get that for each 1,000 potential employees, this accessibility improvement will induce 4.4 new market entries in these job categories. That is:

$$\Delta Q_{ij} = \Delta T_{ij} \sum_{k,s} \lambda_1^k \cdot (1{,}000 \cdot w^{k,s}) = 4.4 \qquad (5)^{15}$$

where $w^{k,s}$ is the above proportion of employees in each job type *k* in industry *s*. Thus, under these conditions a 10% improvement in accessibility, which affects 1,000 potential employees, will stimulate 1.23% new market entry in these 4 job types.[16] The accuracy of these calculations depends, of course, on the degree to which the working assumptions above are valid. It is safe to conclude, however, that overall the net effect of accessibility improvements on employment in the South Bronx is rather small. In this regard, the results obtained in this study agree with those reported in the Spatial Mismatch Hypothesis literature.

CONCLUSIONS

The main objective of this paper was to examine the effect of improved accessibility from transport investment on the local supply of labor in an economically distressed area. The South Bronx, which, according to key socioeconomic indicators, is such an area, has been considering a major transportation improvement investment, known as the Bronx

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[14] The proportions of job types cited here represent observed figures and not supply figures, which are unavailable. Therefore, in this example we use the observed percentages as approximations for the supply figures.

[15] $\Delta Q_{ij} = 0.1\times(0.059\times0.23774+0.021\times0.187414+0.224\times0.096016+0.052\times0.079812)\times1{,}000 = 4.4$

[16] $(\frac{4.4}{356}\times100)$.

Center project. The increases in employment that derive from transportation investments designed to improve accessibility also result in a more positive economic future for the area. The question then is, if implemented, will this project indeed bring about an increase in employment?

Fundamentally, increased employment from transportation investments results from the interaction of two main factors. The first is the impact on the willingness of a potential worker to enter the job market and travel to a specific employment site once generalized travel costs have been lessened. The second relates to employers' demand for labor, which, among other things, is predicated on the level of access to a properly skilled labor force. In this paper we have examined the first factor, which essentially amounts to an investigation of the effect of a transportation-cost reduction on labor-market participation, assuming that additional employment will be made available by present employers at present wage rates. We have also explicitly assumed a short- to medium-run framework in which households and firms do not relocate in response to the improved accessibility.

Using an analytical framework similar to that of Cogan (1980) to model market-entry decisions by potential employees facing significant entry costs, we have estimated a two simultaneous equations regression model of accessibility and employment. Accessibility is modeled as a function of modal travel time and costs, of time of departure, of car ownership and use, and of income. The employment equation is specified as a function of accessibility costs, wage rate by industry, work skills, level of education, and household demographic characteristics. Our database included 1990 census travel and employment data from the South Bronx, New York. The empirical estimation has yielded point estimates that indicate the effects of accessibility improvements on labor-force participation by job type and employment categories, given residential and employment locations.

The central conclusion from the empirical results is that changes in accessibility costs have a discernible effect on labor-market participation in the studied area. However, with respect to job type, the effect of accessibility is not ubiquitous, both in terms of magnitude and (statistical) significance. Depending on skill requirements, offered wage rates, household income, and children of specific age groups, participation in employment sectors such as Executive, Technician, Administrative, and Transport are more responsive to travel cost reduction than are other employment types. In fact, the empirical estimation shows that labor supply in some employment types such as Retail and Wholesale and Personal Services (statistically) is largely not amenable to changes in accessibility costs.

Another important result is that the magnitude of the estimated net employment effect is rather modest. However, in an economically distressed area like the South Bronx, even a relatively small employment increase can provide an important boost to the welfare of area residents. In particular, this is the case for improving women's labor-market participation following travel costs reductions. In places like the South Bronx, where the proportion of all households headed by a woman is rather large, a reduction in female unemployment is, undoubtedly, of major interest.

Although it was not the intent of the authors to carry out SMH analysis, the results shown in the paper do not negate the principal results of the spatial mismatch literature. For example, for occupations in which there are a large number of low-skill workers (and low wages) such as service occupations or sales occupations, for the most part accessibility coefficients are insignificant. For administrative and transport type jobs, they are significant but quite small. Thus, as the SMH literature confirms, accessibility is not a major factor explaining labor-force participation in areas like the South Bronx.

Within the framework of this analysis it is important to observe that, even in the short run, location can matter when assessing labor-supply changes from accessibility improvements. That is, a large-scale transportation investment, like the Bronx Center Project, is likely to strongly affect some locations but not others, as only a subset of all origin-destination pairs will experience a consequential travel-cost reduction. As a result, only those households located within the impacted area of the planned new rail and bus routes will potentially change their labor-market participation, given all other intervening factors.

A second caveat is that in the empirical analysis we have used "number of employees" as the labor supply variable rather than "number of hours worked." This practice may have affected the estimated results since, in a low-income area like the South-Bronx, many people may be employed in part-time jobs. Therefore, the increase in the supply of labor can be in the form of more hours worked rather than new entry into the labor market. It also does not tell us whether new workers are part-time or full-time employees. If data on the number of hours worked were available, an alternative approach would be to investigate the trade off between work and nonwork activities from a reduction in travel time and cost. It would also permit the investigation of the full change in employment resulting from overall equilibrium adjustment of hours of work.

ACKNOWLEDGMENT

Financial support was provided by the University Transportation Research Center. We wish to thank two anonymous referees and the Editor-in-Chief of the *Journal* for their very helpful comments and suggestions.

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APPENDIX A: A MODEL OF LABOR-MARKET ENTRY DECISIONS

In assessing the effect of reduced travel costs on labor supply, a key analytical issue is that existing costs of labor-market entry introduce discontinuity in the labor-supply function. The reason is that an increase in entry costs will raise reservation wages, thereby reducing the probability that a person will work. To test these ideas within the context of women's labor-market participation, Cogan (1980) introduced the concepts of *reservation hours* and *notional hours* of work. The former is defined as the minimum number of hours a person is willing to work. The latter is the number of hours a person would choose to work if required to spend at least a (positive) number of hours in the labor market. We follow a similar approach by formulating the reservation and notional work-hours functions and the reservation and notional wage-rate functions. To each of these functions we also add an accessibility component, our central explanatory factor, estimated from a separate accessibility function.

Within this analytical framework, the labor-market participation decision is defined as the case when the amount of a person's notional hours exceeds his reservation hours. Let the notional work hours be denoted by $h_{k,j}^{N}$ and the reservation work hours by $h_{k,j}^{R}$. Labor-force participation requires that $h_{k,j}^{N} > h_{k,j}^{R}$.

We conjecture that labor-market participation decisions by potential employees are based on three major variables: 1) her/his notional work hours relative to her/his reservation work hours, 2) her/his reservation wage rate relative to the offered wage rate, and 3) the costs of travel to work she/he faces if deciding to participate. To simplify the analysis, we assume that each of these variables can be expressed as a linear function of its determinant variables but that the supply function must be upward rising throughout, with respect to the relevant variables.[17] These variables (indexed for locations) are the wage rate offered by job type k, at location j, W_j^k; household income at location i, Y_i^H; level of employee education in units of number of school years E_i; employee age, A_i; number of children, by age category l, at residential location i, $F_{l,i}$; labor-market experience (years employed) X_i; and travel costs, T_{ij}, between residential and employment locations ($i,j = 1,\dots,M$). Next we define the notional and reservation work hours functions, the reservation wage function, and the travel cost function. We assume that the random disturbance term, associated with each of these functions (u), distributes with mean vector zero and an unknown but constant variance-covariance matrix.

For each household in a residential zone i, employed in employment zone j, the notional work-hours equation, given the employment sector k, $h_{i\neq j}^{k,N}$, is expressed as a function of the market wage rate, W_j^k, the accessibility costs T_{ij}, and a vector of socioeconomic variables:

$$h_{ij}^{k,N} = \gamma_0 + \gamma_1 \ln W_j^k + \gamma_2 \ln Y_i^H + \gamma_3 E_i + \gamma_4 A_i + \sum_i \gamma_{5,l} F_{l,i} + \gamma_6 T_{ij} + u_1 \qquad (A1)$$

Since accessibility costs are regarded here as endogenous choice variables, the parameter γ_6 measures only the *partial effect* of a small change in travel cost on work hours.[18] A further caveat is that since participation is a discrete choice variable, the parameter γ_i actually measures the partial changes in the propensity of potential employees to change work hours.

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[17] The labor-supply function represents participation decisions in the wage-travel costs space. Hence, the above variables (a) and (b), in fact, are a one-choice variable.

[18] If accessibility costs were completely exogenous and fixed for each *ij* pair, the effect of a change in these costs could be interpreted as a *full* change in hours of work as employees adjust to their new equilibrium levels.

The reservation work-hours equation is described as a function of the above variables. That is,

$$h^R_{k,ij} = \delta_0 + \delta_1 \ln Y^H_i + \delta_2 E_i + \delta_3 A_i + \sum_l \delta_{4,l} F_{l,i} + \delta_5 T_{ij} + u_2 \qquad (A2)$$

From equations (A1) and (A2), the following reservation wage function is derived.[19]

$$\ln W^R_{ji} = \beta_0 + \beta_1 \ln Y^H_i + \beta_2 E_i + \beta_3 A_i + \sum_l \beta_{4,l} F_{l,i} + \beta_5 T_{ij} + u_3 \qquad (A3)$$

where: $\beta_\rho = \frac{1}{\gamma_l}(\delta_\rho - \gamma_\rho)$; $\rho = 0.5$; and $u_3 \sim N(0, \sigma^2)$

For a potential employee residing in origin zone *i*, the wage offer equation at location *j* is specified as a function of level of education, E_i; age, A_i; and labor-market experience, X_i (not included in the empirical analysis since the relevant information was unavailable). Thus,

$$\ln W^O_{ji} = \alpha_0 + \alpha_1 X_i + \alpha_2 E_i + \alpha_3 A_i + u_4 \qquad (A4)$$

To empirically assess the impact of reduced transportation costs on the propensity of potential employees to participate in the labor force, we can follow two alternative approaches. Following Cogan, we have defined the participation condition as $h^N_{k,j} > h^R_{k,j}$. In terms of the wage functions (A3) and (A4), this condition is expressed as $\ln W^O{}_j > \ln W^R{}_j$ (given *i*). Using these functions, we can derive an explicit form for this condition by properly grouping all variables in the left-hand side and the disturbance terms in the right-hand side. The result would be an index describing the probability of labor-force participation. Given the above assumption of the distribution of the disturbance factors, it is possible to estimate the parameters of this participation index using a probit analysis. Such an analysis is quite useful since the participation index, in fact, provides a reduced-form measure for the participation function, the combination of equations (A3) and (A4).

An alternative approach is to use the condition $h = \max(h^N, h^R)$ and the wage-offer equation (A4) to obtain the following expression for the actual hours worked:

$$h_{ij} = \rho_0 + \rho_1 \ln W^{k,O}_j + \rho_2 \ln Y^H_i + \rho_3 E_i + \rho_4 A_i + \sum_i \rho_{5,l} F_{l,i} + \rho_6 X_i + \rho_7 T_{ij} + u_5 \qquad (A5)$$

where $W^{k,O}_j$ is the wage rate offered in sector *k* in location *j*.

To carry out empirical analysis following the first approach, it is necessary to have a database composed of survey information on specific households relative to their labor-market participation decisions, their labor-market experience, and their socioeconomic attributes.[20] Such a database was unavailable for this study. Therefore, in what follows we use the second approach and simultaneously estimate equation (A5) with the accessibility function (equation 2 above), using a two-stage least squares procedure. In this estimation we assumed that each new market entry is a full-time employee because part-time employment is not considered. Given the database (see Appendix B), such an approach is quite useful as it directly elicits the impact of accessibility and its components on labor-market participation.

APPENDIX B: SOURCE AND STRUCTURE OF THE DATABASE

The major sources of data for this study are three U.S. Census Bureau data files: 1) the 1990 Census Transportation Planning Package—Urban Element (CTPP), 2) the Summary Tape File 1 (STF 1a), and 3) Summary Tape File 3 (STF 3a) (USDOC 1990). The prime source of data used for the analysis in this paper comes from the CTPP, which contains data at the census block group level. There are approximately 56,000 census block group origin-destination pairs used in the analysis: persons living in the Bronx and working anywhere.

The CTPP data is actually a data set broken into three different files (see figure A-1). The first file is demographic data for place of residence (*i* loca-

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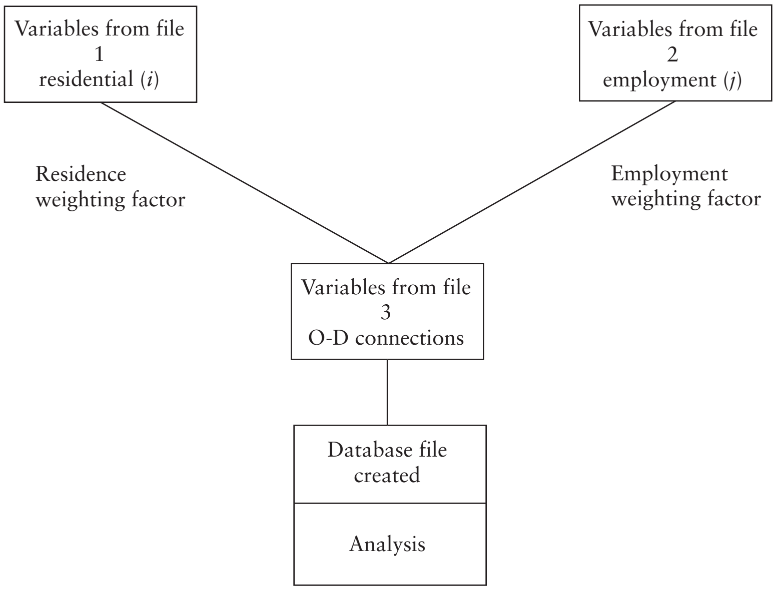
[19] For this derivation, $h = \max(h^N, h^R)$, where h is actual hours worked.

[20] Using data on residential and employment locations and their origin-destination (O-D) interactions introduces statistical complexities into the estimation of a probit model.

FIGURE A.1 Structure of Database



tion). The second file is demographic data for place of employment (*j* location). The third file is the origin-destination matrix for every block group in the New York metropolitan area (a 14-county region of New York, 14 counties of New Jersey, and 3 counties of Connecticut). The matrix contains all modes of travel, peak and off-peak travel, as well as the number of persons traveling between locations *i* and *j*.

The principal variables used in the analysis and their ranges are as follows:

I. **Mean travel time by mode:** mean travel time between *i* and *j* in minutes by mode

II. **Household range of income:** number of households within an income range:

1) $0–$9,999
2) $10,000–$19,999
3) $20,000–$29,999
4) $30,000–$34,999
5) $35,000–$49,999
6) $50,000–$74,999
7) $75,000 and above

III. **Mode use:** number of employed people, 16 years of age or older, who use a mode to travel to work:

1) car
2) public transit (bus, street car, trolley, subway, rail, ferry)
3) other (bike, taxi, motorbike)
4) walk

IV. **Car ownership:** number of households that own *x* cars:

1) 0 cars
2) 1 car
3) 2 or more cars

V. **Time of departure:** number of employed people, 16 years of age or older, during 1 week prior to the census, who leave to work at

1) 12 AM–5:59 AM
2) 6:00 AM–6:29 AM
3) 6:30 AM–6:59 AM
4) 7 AM–7:29 AM
5) 7:30 AM–7:59 AM
6) 8 AM–8:29 AM
7) 8:30 AM–8:59 AM
8) 9 AM–9:59 AM
9) 10 AM–11:59 AM

VI. **Type of industry:** number of people, 16 years of age or older, during 1 week prior to the census, who work in

1) agriculture, forestry, and fisheries
2) mining
3) construction
4) manufacturing, non-durable goods
5) manufacturing, durable goods
6) transportation

7) communications and other public utilities
8) wholesale trade
9) retail trade
10) finance, insurance, and real estate (FIRE)
11) business and repair services
12) personal services
13) entertainment and recreation services
14) health services
15) educational services
16) other professional and related services
17) public administration

VII. **Wage rate by industry:** wage rate for each of the above industries, based on NYC ES202 1994 data.

VIII. **Type of job:** number of people, 16 years of age or older, during 1 week prior to the census, who work at the following job types

1) executive, administrative, and managerial
2) professional specialty occupations
3) technicians and related support occupations
4) sales
5) administrative support occupations, including clerical
6) private household occupations
7) protective service occupations
8) service occupations, except protective and household
9) farming, forestry, and fishing occupations
10) precision production, craft, and repair occupations
11) machine operators, assemblers, and inspectors
12) transportation and material moving occupations
13) handlers, equipment cleaners, helpers, and laborers

IX. **Educational level:** number of persons who have attained a given educational level

1) less than a 9th grade high school level
2) less than a 12th grade level
3) high school diploma
4) attended college but no degree
5) Associates degree
6) Bachelors degree
7) graduate degree

X. **Presence and age of children:** number of children present of different age groups

1) number of children less than 3 years old
2) number of children 3 to 5 years old
3) number of children 6 to 11 years old
4) number of children 12 to 17 years old

The above database contains two interzonal accessibility matrices, one based on travel time and costs reported by travelers making home-to-work trips and the second based on travel time and costs calculated from actual bus and subway information relative to headway, in-vehicle time, and average walk time to or from the nearest stations. Comparisons of these two accessibility matrices showed some variations. Therefore, we carried out the empirical analysis separately for each of these two accessibility matrices though no major differences were found for the estimated parameters.

Evaluating Neighborhood Accessibility: Possibilities and Practicalities

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ABSTRACT

Efforts to improve transportation choices and enhance accessibility at the neighborhood level have been hampered by a lack of practical planning tools. This paper identifies the factors that contribute to accessibility at the neighborhood level and explores different ways that planners can evaluate neighborhood accessibility. A gap between the data needed to describe important accessibility factors and the data readily available to local planning departments points to two complementary strategies: a city-wide approach using available data and geographic information systems to evaluate accessibility for neighborhoods across the city, and a neighborhood-specific approach to building a detailed accessibility database. Examples of both are presented.

INTRODUCTION

Several trends in the 1990s brought new attention to the importance of alternatives to driving. Federal transportation policy, as shaped by the Intermodal Surface Transportation Efficiency Act of 1991 and the Transportation Equity Act for the 21st Century of 1998, emphasizes transit, as well as walking and biking, out of concern for both the environment and equity of service. The New Urbanism move-

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ment has focused attention on how the design of neighborhoods encourages or discourages walking, among other things, and has given weight to the idea that land-use regulations are also an important element of a transportation program. In addition, the relative lack of services in many lower income neighborhoods, where auto ownership is often low as well, has been the target of renewed attention in recent years. In response, planning agencies are taking a new look at both transportation policies and neighborhood planning in an effort to enhance transportation choices. Their efforts are hampered, however, by a dearth of applicable planning tools, particularly measures or indicators that can be used to identify problems and needs, determine the adequacy of current policies, or evaluate the impacts of proposed policies at the neighborhood level.

Planners are beginning to turn to accessibility measures as a way of evaluating the availability and quality of basic services and alternative modes at the neighborhood level. As generally defined, accessibility reflects the ease of reaching needed or desired activities and thus reflects characteristics of both the land-use system (where activities are located) and the transportation system (how the locations of activities are linked). Extensive academic literature on accessibility measures suggests many ways to define and measure accessibility, although examples of the actual use of accessibility measures in planning are relatively scarce. In addition, the literature offers few approaches that adequately assess accessibility to different modes of travel at the neighborhood level. While traditional measures of accessibility focus on the distance to and size of potential destinations, for example, other characteristics of the local environment may have an important impact on modes like walking and biking. Unfortunately, incorporating such qualities into an assessment of accessibility requires data that are not readily available or easy to collect, a real obstacle to developing practical accessibility measures. In addition, traditional measures of accessibility combine a variety of factors to produce a single measure of accessibility. This approach is useful for comparisons but masks important qualities of the neighborhood that contribute to accessibility. As an alternative, planners might build and analyze an accessibility database rather than calculate an accessibility measure.

The goals of this paper are twofold: to identify the factors that contribute to accessibility at the neighborhood level and to explore the options available to planners for measuring this accessibility. A gap between the data needed to describe important accessibility factors and the data readily available to planning departments points to two complementary strategies for measuring accessibility: a city-wide assessment of neighborhood accessibility using existing data sources and the capabilities of geographic information systems (GIS), and a neighborhood-specific approach to building a detailed accessibility database. This paper begins with a brief overview of the literature on accessibility measures and a summary of factors identified in travel behavior research and planning practice that may contribute to neighborhood accessibility. After establishing a framework for evaluating neighborhood accessibility, the paper turns to an assessment of available data sources and a discussion of the two proposed approaches to measuring neighborhood accessibility.

MEASURING ACCESSIBILITY

Accessibility is an important concept for urban planners because it reflects the possibilities for activities, such as working or shopping, available to residents of a neighborhood, a city, or a metropolitan area. Accessibility is determined by attributes of both the activity patterns and the transportation system in the area. The spatial distribution of activities as determined by land development patterns and their qualities and attributes are important components of accessibility, as are the qualities and attributes of the transportation system that links these activities, such as travel time and monetary costs by mode. Although most researchers agree on this general definition of accessibility, they have developed a wide variety of ways to measure it.

The literature on accessibility measures has a long history. Most measures can be classified as one of three basic types (Handy and Niemeier 1997). *Cumulative opportunities measures* are the simplest type. These measures count the number of opportunities reached within a given distance or travel time and give an indication of the range of choices available to residents. *Gravity-based measures* are derived from the denominator of the gravity model used to predict trip distribution; these measures weight the amount of activity at different destinations by the cost, time, or distance to get there. The third type of measure is based on *random utility theory,* in which the probability of an individual making a particular choice depends on the utility of that choice relative to the utility of all choices; the accessibility measure comes from the denominator of the model and reflects the total utility of all choices. In general, the three approaches offer different tradeoffs between the simplicity and thus ease of comprehension of the measure and the sophistication with which the activities and transportation system are characterized. The more sophisticated measures also require more sophisticated data.

In developing a practical technique for assessing neighborhood accessibility, a number of questions must be addressed. First, what factors tend to matter most to residents? Clearly it is impossible to measure, let alone know, every factor that matters to every resident. Fortunately, a number of studies help to identify the factors that seem to be most important to a majority of residents, and a list of these factors is compiled below.

Second, what kind of data are available or can be collected about these factors? The data commonly used by planning departments miss many of the factors important to neighborhood accessibility and may not be available in a useful format if they are available at all. These issues are explored in the section on data availability.

Third, how can planners make sense of the available data on neighborhood accessibility factors? Traditional accessibility measures can, depending on their structure, specification, and calibration, combine a number of important factors into a single, all-encompassing measure of accessibility. This approach, however, may be neither practical nor desirable for planning purposes. The more complex the measure the more data and analysis skill required, limiting the ability of most planning departments to develop such measures. The development of utility-based measures, for example, is probably beyond the capability of most departments. In addition, much important information is lost when the data are collapsed into a single or even a few measures. Traditional measures of accessibility may help planners identify neighborhoods with relatively high or low accessibility, but they do not, on their own, point to the specific factors contributing to accessibility. As an alternative, the possibilities and practicalities of developing a database of neighborhood accessibility factors using either a city-wide or neighborhood-specific approach is explored in this paper and this effort is described in the section on strategies.

Finally, the use of the neighborhood as the spatial unit of analysis presents both opportunities and challenges. Analysis at the neighborhood level allows for a more detailed examination of the qualitative characteristics of the local environment than would an analysis at a larger geographic level. However, if neighborhoods are defined by their natural boundaries, usually major arterials or open space, their areas and populations may vary considerably. Some normalization by area or population may be necessary if the goal is to compare accessibility between neighborhoods. In addition, accessibility may vary considerably within a neighborhood depending on the distribution of retail and services relative to the population within and beyond the neighborhood. Therefore, it is important also to evaluate accessibility from different points or for different areas within the neighborhood. Residents also make use of activities outside of the neighborhood, not just those found within their boundaries. Thus, an assessment of accessibility within the neighborhood would provide only part of the picture. On the other hand, an assessment of accessibility within and beyond the neighborhood must consider what distance beyond the neighborhood is appropriate. These issues arise in many of the examples presented in the strategies section of this paper.

The first step in designing a neighborhood accessibility database is to identify the factors that contribute to accessibility for residents. Although few studies address this need directly, we found a number of studies that provide insights into the factors that matter to residents and a smaller number that provide ways of measuring these factors. These studies can generally be classified in two ways: empirical studies of travel behavior and level-of-service measures designed for use in planning practice. Although both types prove useful in identifying potentially important accessibility factors, both also have notable limitations. In the case of the former, observed behavior, which is constrained by the available options, provides a convenient but imperfect way of assessing true preferences and priorities. In the case of the latter, the relative importance of different factors is often assumed rather than tested. Nevertheless, these studies provide an important starting point.

Activity Factors

The most basic characterization of activity is that a particular type of activity can be found at a particular location. Cumulative opportunities measures, for example, typically reflect a simple tally of locations of a particular type of activity. Another common approach is to account for the relative amount of activity at each location, usually measured by the number of employees or the square footage of buildings. This approach is commonly used in both gravity measures and utility measures of accessibility. But beyond the existence of an activity and the amount of an activity at a particular location, what factors influence the attractiveness of a particular destination to residents?

Our previous research identified several specific characteristics that residents consider in evaluating the activities in and around their neighborhood; these characteristics range from mostly objective to highly subjective (Handy et al. 1998; Handy and Clifton 2001). The more objective factors of an activity such as grocery shopping include size of store, prices, ease of parking, and range of product selection. More subjective factors include quality of products, crowds, and length of check-out lines. Highly subjective factors like atmosphere also matter. The relative importance of such factors is difficult to assess, however. Not only does the importance of these factors vary by individual, but it may vary at different times for each individual: residents may use different criteria in evaluating stores for major food shopping than for a trip to buy a gallon of milk, for example.

Recker and Kostyniuk (1978) studied factors that influence destination choice for grocery shopping trips in urban areas. Their study included a survey of respondents' perceptions of grocery stores they frequented on a variety of different attributes. Using factor analysis, they reduced these attributes to four factors: quality (determined by reasonable prices, variety of items, meat and produce quality, and selection of goods), accessibility (determined by ease of getting from home to stores and back and to stores from work), convenience (determined by parking facilities, proximity to other shops, hours of operation, ease of finding items in stores, and crowding in stores), and service (acceptance of credit cards, check cashing, and ease of returning goods). In the destination choice models estimated, only the service factor proved insignificant.

Research in the field of retailing provides additional insights into factors that influence a customer's choice of a particular establishment. A 1980 study by Nevin and Houston, for example, looked at the role of image in the attractiveness of urban shopping areas. Besides factors such as the quality of stores, the variety of stores, product quality and selection, and general price level, they found that the availability of lunch or refreshments, the adequacy of restrooms, the friendliness of the atmosphere, the helpfulness of store personnel, and whether the center was an easy place to take children also contributed to the attractiveness of a shopping area.

These studies suggest a list of factors that contribute to the attractiveness of a particular activity site. These factors can be grouped as relating to the activity itself or relating to the design of the site (table 1). This list is by no means exhaustive, but it gives a sense of the wide range of factors that contribute to attractiveness. It is also important to remember that the relative importance of these factors will vary depending on the type of activity.

What activities to include in an assessment of neighborhood accessibility is also an important question. Most examples of accessibility measures in the literature use total retail and service employment without further differentiation of activity types. Some studies focus on specific kinds of activities, such as grocery shopping (Handy and Niemeier 1997) or health care services (Wachs and Kumagai 1973). One study (Handy et al. 1998) gives some indication of the local businesses most frequently used by residents of six Austin, Texas,

TABLE 1 Activity Factors

Factors related to activity	Size and scale Quality of products/services Variety of products/services Price of products/services Hours of operation Crowds/lines Interior design Atmosphere Ownership (local vs. chain) Customer recognition
Factors related to site design	Mix of activities at site Density of activities at site Parking facilities Atmosphere Landscape design

neighborhoods. Supermarkets and grocery stores topped the list, followed by drug stores, restaurants, discount stores, convenience stores, video stores, laundromats or dry cleaners, and bakeries. This list can serve as a guide to activities to include in an assessment of neighborhood accessibility. What it leaves out, however, are possible high-priority activities not located in or near those particular neighborhoods.

Transportation Factors

Just as important as the activities found in and around the neighborhood are the options residents have for getting to them. Distance and time are used most often as measures of impedance in accessibility functions and represent the burden required to travel to a particular destination. While distance and time can be important considerations in the decision to drive, walk, bike, or ride transit, additional factors contribute to the varying degrees of accessibility offered by different modes of travel in different neighborhoods. Mode choice models and level-of-service measures as well as exploratory studies suggest a long list of transportation factors that contribute to neighborhood accessibility for different modes (table 2). These factors can be categorized as impedance, level-of-service, terminal, and comfort.

Accessibility factors for drivers are, perhaps, the most straightforward. Mode choice models consistently show that travel time, or sometimes a generalized travel cost including travel time and monetary costs, is the most significant factor to drivers. Factors that influence the travel time or cost, including traffic volume, signalization, directness of route, and continuity of route, may also be important as well as the availability and cost of parking at the destination. Some drivers may consider comfort factors in their perception of accessibility. Poor lighting, bad weather, excessively high or low traffic speeds, high volumes of traffic, unappealing scenery, inadequate signage, or poor pavement condition may contribute to a negative perception of accessibility. The importance of these perceptual factors is mostly undocumented. Work by Ulrich et al. (1991), however, shows that the kind of chaotic visual environments found along many arterials in metropolitan areas significantly increases driver stress.

Mode choice models further show that travel time is the most significant factor in the decision to use transit. However, most models also show that transit users differentiate between in-vehicle and out-of-vehicle time, assigning significantly greater cost to the latter. This finding reflects the exposure of the transit user to the elements as well as to the uncertainty of transit service. As a result, amenities such as benches and shelters are important to transit users as are factors that influence the feeling of safety while waiting, including lighting, the speed and volume of passing traffic, and crime levels in the area. A study of customer satisfaction among riders of the San Francisco, California, Bay Area Rapid Transit (BART) system (Weinstein 2000), for example, used factor analysis to group over 40 attributes of the system into 8 factors influencing satisfaction, listed in order of relative importance: service and information timeliness, station entry and exit, train cleanliness and comfort, station cleanliness, police presence, policy enforcement, and parking.

Although pedestrians also are sensitive to travel time and are limited in how far they can travel by walking, they are also highly sensitive to the character and quality of the environment through which they walk. One study showed that perceptions of safety, shade, and the presence of other people were important determinants of the fre-

TABLE 2 Transportation Factors by Mode

	Automobile	Transit	Walking	Bicycling
Impedance factors				
Distance	X	X	X	X
In-vehicle time	X	X		
Out-of-vehicle time	X	X	X	X
Cost	X	X		
Topography			X	X
Level-of-service factors				
Volume/crowding	X	X	X	X
Signalization	X	X	X	X
Service frequency		X		
Hours of operation		X		
Directness of route	X	X	X	X
Continuity of route	X	X	X	X
Information availability		X		
Signage	X	X	X	X
Facility widths	X		X	X
Vehicle design	X	X		X
Shelter		X	X	X
Benches		X	X	
Terminal factors				
Parking availability	X	X		X
Parking cost	X	X		
Terminal locations		X		
Intermodal connections		X	X	X
Terminal design	X	X	X	X
Comfort factors				
Traffic speed	X	X	X	X
Traffic volume	X	X	X	X
Pavement condition	X	X	X	X
Lighting	X	X	X	X
Weather	X	X	X	X
Shade		X	X	X
Scenery	X	X	X	X
Crime/police presence		X	X	X
Cleanliness		X	X	X
Conflicts with other modes	X	X	X	X
Other users	X	X	X	X

quency with which residents walked in the neighborhood (Handy et al. 1998).

Several recent efforts to evaluate the pedestrian environment also point to important accessibility factors. In the LUTRAQ ("Making the Land-Use, Transportation, Air Quality Connection") studies, a Pedestrian Environmental Factor was calculated from four factors: ease of street crossing, sidewalk continuity, local street connectivity, and topography (1000 Friends of Oregon 1993). In Fort Collins, Colorado, a pedestrian level-of-service measure was used to evaluate the traffic impacts of new development. This measure incorporated the directness of street layout, the continuity of sidewalks, the width of street crossings, visual interest and amenities, and security and safety evaluations (Moe and Reavis 1997). Gainesville, Florida, developed a pedestrian level-of-service measure that included the provision of a pedestrian facility, conflict points with vehicles, amenities, motor vehicle level-of-service, maintenance, and transportation demand management or multimodal policies (Dixon 1995). Pedestrian level-of-service is also influenced by the degree to which sidewalks and curb ramps meet the requirements of the Americans with Disabilities Act of 1990. Sidewalk characteristics such as driveway crossings, cross slopes, level irregularities, clearance widths, and protruding objects determine the accessibility of sidewalks to persons with disabilities (Axelson et al. 1999); parents with strollers; children on skateboards, scooters, or bicycles; and pedestrians in general.

Bicycle riders are influenced by a mostly parallel set of factors. The Federal Highway Administration's (FHWA) National Bicycling and Walking Study included an assessment of the reasons why bicycling is not used more extensively (USDOT 1992). In reviewing a number of surveys on bicycle use, this study found that primary deterrents to cycling included traffic safety concerns, adverse weather, inadequate parking, and road conditions, and that secondary deterrents included fear of crime, lack of bicycle routes, inconsiderate drivers, and inability to bring bicycles on buses. FHWA has, more recently, developed a "bicycle compatibility index" to evaluate the appropriateness of a roadway for bicycle use. This index includes the presence and width of a bicycle lane, curb lane width, traffic volume in the curb lane and other lanes, traffic speed, parking lane presence and occupancy, truck volume, parking turnover, and right-turn volume (USDOT 1999). Gainesville also developed a bicycle level-of-service measure similar to its pedestrian measure but with slightly different definitions of each factor (Dixon 1995).

DATA AVAILABILITY

Unfortunately, data for only a few of the accessibility factors identified earlier are readily available. Data can usually be found for basic characteristics of land use and transportation systems, but data on qualitative and subjective factors are scarce; these factors are hard to assess and the accuracy and stability of the observations are often questionable. The result is a significant gap between the data needed to describe important accessibility factors and the data readily available to planning departments.

Land-Use Data

At a minimum, an accessibility analysis requires information about what kinds of activities exist and where they are located. The availability and level of detail of land-use data often vary by local planning department. Data about employment are more difficult to find than data about residents, which are available through the decennial census. Most metropolitan planning organizations (MPOs) and some cities have developed databases of employment by type and by area, census tract or traffic analysis zone, but the quality of such data is notoriously poor and the categories of employment are usually quite broad. Data on floor space by type of commercial or industrial use can sometimes be extracted from the databases of local tax assessors, and zoning classifications are also sometimes used as an indication of land use. However, it is often difficult to find accurate and specific information about current land use in electronic format, and collecting detailed information through field work can be laborious and time consuming. In most cases, data on the quantity of several general categories of activities at the zone or tract level are available, if nothing more.

Business and residence telephone directory listings provide more specific data on land use and are readily available in electronic format. For a study of accessibility in Austin, Texas, neighborhoods, the Select Deluxe CD-ROM was used for the year 1996[1] (Handy and Clifton 2000). These data include business or residential name, address, phone number, and geographic coordinates in latitude and longitude. Business listings also include approximations of the appropriate Standard Industrial Classification (SIC) codes to the four-digit level.

The use of telephone listings as a source for land-use data offers several advantages. First, the data are readily available and relatively inexpensive. The CD-ROM can be purchased at many computer

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[1] Select Deluxe CD-ROM is available from ProCD, Inc., 222 Rosewood Drive, Danvers, MA 01923, http://www.procd.com.

software retail stores, and data for the entire United States cost less than $150 as of this writing. Second, the SIC approximation allows for easy classification of business types and thus permits disaggregate analysis on specific industries or services. Third, the addresses for business and residential listings are already geocoded and can be easily imported into GIS software. Last, the availability of disaggregate data for an entire urban area permits a detailed analysis at both the local and regional levels. However, using these data for accessibility analysis also has its drawbacks. Establishments with multiple telephones are overrepresented in the database, and businesses without a phone at the time of publication are missing from the data set. Also, the SIC codes are only approximations based on the category under which the business is listed in the directory.[2] In addition, frequent business turnover reduces the accuracy of the available data, and those listings that do not include an address in the telephone directory are omitted. Although these data provide detailed information about the location and type of establishment, other land-use characteristics such as size, quality, or site design cannot be obtained from this data set.

Transportation Data

The availability and detail of transportation information also varies widely by planning department. In most areas, zone-to-zone characteristics such as travel time or travel cost are available, but data are not usually available for travel within neighborhoods and for modes other than automobile and transit. The task of compiling the necessary transportation data is complicated by the lack of coordination between the various government agencies responsible for data on different transportation factors.

Transportation network files can be obtained from the U.S. Census Bureau in the TIGER/Line files. Enhanced and updated network files can be obtained from private vendors, MPOs, or other local agencies. These files allow for distance calculations between points on the network, although travel times are usually more important to residents. Estimating the travel times between two points requires estimations of the average travel speeds for each link in the network, which for drivers is dependent on traffic volume. Data on automobile travel times are available from regional transportation planning models usually maintained by MPOs. These data can be problematic, however; they are not always accurate, are not available for most local roads in the network, rarely include temporal variations, and give zone-to-zone rather than point-to-point times. As an alternative, speed limits can be used to estimate travel time, but speed limit data are often not available in GIS format. A few studies have estimated point-to-point travel times and distances using the capabilities of a transportation modeling package (Handy 1996; Handy et al. 1998) or GIS (Crane and Crepeau 1998). These estimates provide a reasonably accurate indication of driving distances at the neighborhood scale and also walking and biking distances.

Data for modes other than driving are often more difficult to locate. For transit, data about the location of transit stops, routes, capacity, and schedules are usually available but not always in electronic format. Accurate information about the spatial distribution of benches, shelters, and lighting, and crime and safety statistics is less often available. For example, as of this writing, Capital Metro, the transit authority in Austin, Texas, has data on the locations of transit stops in electronic format but no additional information about the stops, such as presence of bus shelters, that might be valuable in an accessibility analysis. Ridership information has been available in electronic format by route and stop for some time, but bus routes have been added only recently.

Data on infrastructure for pedestrians and bicycling are not generally available, although this situation seems to be changing. Some cities may have an inventory of sidewalks, but such data seem rarely to be in electronic form. In the mid-1990s, the city of Portland, Oregon, completed a city-wide sidewalk inventory that required considerable time and labor. Data on other factors that influence the quality of the walking and biking experience, such as tree canopy, can sometimes be extracted from aerial photos. Data on more qualitative factors, such as the scenery and the presence of interesting

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[2] In an ironic, and we hope inadvertent twist, we found driving schools (of the sort for ticketed drivers) classified as “drinking places.”

houses or gardens to look at, can only be evaluated through field work and the development of criteria by which to judge such factors. The LUTRAQ study used such a system to evaluate less qualitative factors, such as topography and the interconnectedness of the street network (1000 Friends of Oregon 1993).

The changing attitudes about alternate modes and the availability of federal funding for transit, bicycling, and pedestrian projects have influenced some planning agencies to focus more attention on the deficits in modal data. In Austin, Texas, an extensive effort was initiated to collect data about the street conditions and physical characteristics along existing and proposed bike routes and their adjacent streets. Data about traffic volume and speed, pavement condition, street and lane width, presence and continuity of bike lanes, number of stop signs and traffic signals along the route, and other objective criteria were compiled. Based on this information, the street segments were then ranked for bicycle friendliness and published on the bicycle route maps for public distribution. Such efforts can contribute to the development of a database of accessibility factors for use in both neighborhood-specific and city-wide analyses.

STRATEGIES

What can a planning department do, given the gap between the data needed to describe important accessibility factors and the readily available data? Two complementary strategies might prove useful: one is a city-wide approach using existing data and GIS to evaluate accessibility for neighborhoods across the city and the other involves a neighborhood-specific approach to building a detailed accessibility database. If the goal is to compare accessibility across neighborhoods to identify neighborhoods with deficiencies in accessibility or to evaluate the equity impacts of proposed policies, then a city-wide approach makes sense, even though the available data are limited to the most basic accessibility factors. If the goal is to develop a neighborhood plan, then the neighborhood-specific strategy might prove useful, even though extensive data collection is involved. Planning departments might employ both strategies at different stages of a planning effort.

City-Wide

Several recent research projects demonstrate some of the ways that existing data can be combined with the capabilities of GIS to evaluate accessibility at a relatively coarse level on a city-wide basis. In all these examples, researchers point to the power of visualization as an important benefit of the use of GIS for accessibility analysis.

Talen (1998) used GIS to evaluate the distribution of public facilities, such as parks, in terms of the match between the facilities provided and the needs of residents and in terms of the equity of the distribution across socioeconomic groups. Four different measures of access from census blocks to parks were calculated: the *gravity model,* with parks weighted by size and separation distance between origin and each park destination; *minimizing travel cost,* determined by the straight-line distance between each origin and each park destination; *covering objectives,* measuring the number of parks located within a critical distance (essentially a cumulative opportunities measure); and *minimum distance* between each origin and the nearest park. This study demonstrates the power of GIS as a tool for evaluating accessibility across an urban area and the impact of public facilities plans on the equity of accessibility patterns. As Talen points out, the analysis can be refined through more precise measurement of accessibility, including an assessment of the quality of the facility or service, the use of origin zones smaller than census blocks, and more sophisticated measures of transportation. However, the increased costs of data collection and analysis may outweigh any benefits from increased precision. “The real benefit of the approach outlined in this paper is that it is a technique that is readily available to local planners” (Talen 1998).

A study by Grengs (2000) underway at Cornell University uses GIS to evaluate accessibility of inner-city neighborhoods to supermarkets. The initial approach was to use a buffer of a given distance around a bus line that serves a supermarket and then analyze the portion of each traffic analysis zone within the buffer area. Assuming that population and households are uniformly distributed throughout the zone, the area within the buffer can then be translated into the share of population within the buffer and, in particular, the share of carless households within the buffer. Grengs points to several limitations of this analysis. First, the analysis would ideally account for the affordability and quality of products offered by each supermarket. Second, the buffers were drawn around bus lines rather than bus stops given limitations of the data. Third, only transit trips possible without transfers were considered. Fourth, the approach estimates equal accessibility for households with and without cars. Nevertheless, an application of the analysis approach to Syracuse, New York, points to the probability of underestimated disparities in accessibility to supermarkets for low-income and African-American households.

The British Government's Planning Policy Guidance 13, which encourages plans that promote development at locations accessible by modes other than automobile and that improve access by non-car modes, has led to the creation of at least two models that evaluate accessibility using GIS. One project evaluated both the accessibility of a particular residential location to public transit, *local accessibility,* and the accessibility of locations to specific destinations using public transit, *network accessibility* (Hillman and Pool 1997). Local accessibility was calculated as a combination of the walk time to a transit stop and the average wait time for service at that stop. For each residential location, access to all possible stops was evaluated and combined into one measure. Network accessibility was calculated by defining a set of destinations (e.g., schools or shopping centers), identifying the transit routes that link the residential zone to the selected destinations, and estimating the total travel time to those destinations. An integrated system consisting of a GIS and public transit planning software was used to compile an extensive database and calculate accessibility measures, but the lack of required data on public transit systems has been an obstacle to the more widespread use of this tool.

A second U.K. project focused on selected destinations and determined the number of residents within various travel times of a destination by each transportation mode (Hardcastle and Cleeve 1995). Although data on land uses and road networks were readily available for this model, estimates of travel times by mode were relatively crude, depending on assumptions about the match between the pedestrian network and the road network, for example, and about average travel speeds by mode.

In an exploration of the potential for using GIS with available data to assess neighborhood accessibility on a city-wide basis, a variety of measures was calculated for seven neighborhoods in Austin, Texas (Handy and Clifton 2001). Simple counts of the numbers of selected types of retail establishments located within buffers of various distance around the neighborhood were used to measure activity *intensity* (total number of establishments); *diversity* (number of types of activities); and *choice* (number of establishments of each type). These measures were also normalized for neighborhood population and for neighborhood area in order to facilitate comparisons. A more direct assessment of the number of retail establishments found in one neighborhood compared with others was made using a location quotient, defined as the share of establishments of a certain type within a neighborhood relative to the share of establishments of this type for the city overall. A value greater than one indicates that the neighborhood has a greater share of establishments of that type than the city as a whole and may thus be overserved; a value less than one indicates that the neighborhood may be underserved. A high location quotient is not always positive, however. The location quotients for seven neighborhoods in Austin showed that the low-income neighborhood had over nine times the share of drinking establishments as the city overall. These analyses demonstrate both the usefulness and the limitations of relying on existing data and the capabilities of GIS to assess neighborhood accessibility.

Neighborhood-Specific

The available data and the capabilities of GIS clearly fall short of providing planners with a full assessment of the factors that influence neighborhood accessibility as listed earlier. Developing a comprehensive neighborhood accessibility database, consisting of detailed data about a wide range of accessibility factors for all neighborhoods in a city, requires a significant commitment of resources on the part of a planning department. An intriguing alternative is to make data collection itself an important part of the planning process and to use neighborhood residents to design and build the neighborhood accessibility database. Not only is this approach cost-effective for the city, it uses data collection as way to facilitate public involvement and build technical capacity within neighborhoods, important benefits in their own right.

In Austin's neighborhood planning program, for example, residents and other local stakeholders are responsible for developing their own plan for the neighborhood, with guidance and some assistance from city staff. An early task is to compile data about existing conditions in the neighborhood, such as inventories of existing land uses and infrastructure and an assessment of the condition of infrastructure. In addition, the planning team is required to conduct surveys of residents' concerns and priorities. This approach has many benefits. Such data-collection efforts are labor-intensive and thus need many volunteers from the neighborhood involved. Those who participate learn the kinds of information useful for planning purposes and the techniques effective in collecting that information. Participants are likely to understand and appreciate the results more than if city staff simply presented the results to them. In addition, participants can decide for themselves which accessibility factors are of greatest importance. The data produced by this effort can also be incorporated into a detailed city-wide database, constructed over time as more neighborhoods participate.

Providing the neighborhood planning team with direct access to GIS software and sufficient training to use it effectively could be even better and may not be as costly or impractical as one might think, as demonstrated by a growing number of examples. In 1993, a group of graduate students at the University of Wisconsin-Milwaukee developed a process for training neighborhood residents to use GIS to analyze a publicly accessible database of property characteristics, including ownership, zoning, land use, assessed value, and other useful information (Myers 1994). One step in the process included a walk through the neighborhood to collect information about the condition of properties. The project succeeded in providing residents with the capability to use GIS to analyze and address a variety of problems in the neighborhood. In Philadelphia, the city has allocated funds to Community Development Corporations (CDCs) for GIS hardware, software, and training so that the CDCs can better illustrate the quality and character of the environment of the neighborhood (Casey and Pederson 2000). Such examples hint at the power of GIS not only as a planning tool but also as a public involvement technique.

CONCLUSIONS

As efforts to promote the use of modes other than driving grow and as neighborhood planning programs proliferate, planners need new and better tools to identify problems, highlight inequities, and evaluate potential solutions at the neighborhood level. The concept of neighborhood accessibility provides a useful framework for the development of such a tool. As defined here, neighborhood accessibility includes a wide range of factors that describe both the quantity and quality of activities in and around the neighborhood and the characteristics of the transportation systems that link one activity to another. The key to identifying the factors that contribute to accessibility is to examine their relative importance to residents. Although no systematic effort has been undertaken to catalog these factors, a review of the literature points to a long list of factors likely to be important.

Unfortunately, data are readily available for only a small subset of these factors. The gap between the data needed to measure these factors and the data that are readily available demands a creative approach to measuring accessibility. Two strategies are proposed here: a city-wide strategy using available data and the capabilities of GIS and a neighborhood-specific strategy that asks residents themselves to build a detailed accessibility database as a part of a neighborhood planning process. Several documented planning efforts provide examples of how these strategies might be implemented and the kinds of benefits they can produce. Other strategies may also prove effective. This paper provides a starting point and, it is hoped, will lead to new efforts and greater creativity on the part of others to define and measure neighborhood accessibility.

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Path-Based Accessibility

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ABSTRACT

This paper explores the development of an accessibility measure based on daily travel patterns. In contrast to traditional zone-based measures, distance is calculated using a predefined travel matrix. The travel pattern for each zone is used as a weight in the accessibility measure. This path-based accessibility measure is implemented in a computer program that is closely coupled to a transport-oriented geographic information system. The measure is demonstrated in an application for two Swedish counties. The properties of the measure are evaluated and compared with standard accessibility measures used in the planning process. This paper shows that there are differences between traditional measures and the suggested path-based measure and differences in accessibility between socioeconomic groups with different travel patterns. It is concluded that path-based accessibility measures could be very useful to analyze accessibility for high-mobility groups.

INTRODUCTION

Accessibility implies the ability to physically travel to a resource at a fixed location. The introduction of new technologies, such as electronic commerce, has complicated the definition of presence, but in

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this article we are concerned with physical presence as a result of travel to a supply source. Because accessibility is a crucial positive outcome of the transportation system,[1] how it is measured is important.

Accessibility measures (AMs) can be categorized in many different ways, but in the recent literature there is a tendency to discriminate between zone-based and individual AMs (see, e.g., Hanson 1995, Kwan 1998, and Miller 1999). As the labels indicate, zone measures try to capture the overall accessibility for a zone, while individual measures try to capture the accessibility of individuals based on detailed characteristics of space, available time, and means to overcome space. One of the main advantages of individual measures is that they can take into account the fact that most individuals face a mandatory daily travel pattern, such as to and from work. Zone-based measures neglect the importance of mandatory travel patterns on accessibility.

In the simplest form, zone-based measures result in one figure of accessibility for each zone, which may become a target of criticism. In practice, however, different accessibility scores are calculated based on gender, socioeconomic status, etc., but these scores are still averages across a number of individuals. Disaggregating population data is one way of obtaining more realistic accessibility figures using zone-based measures.

Individual measures, on the other hand, may lead to as many values of accessibility as there are individuals in the study area. Individual measures are conceptually attractive, but face difficulties from an operational standpoint (Hanson 1995). One of the most notable difficulties with obtaining individual measures is collecting data because revealed preference data cannot be used. Information on time constraints and mandatory activities cannot be obtained from a single travel survey question, but result from a series of questions. Although conceptually the two measures are very different, their mathematical formulation can be identical (Hanson 1995). The conflict is between conceptual elegance and implementation. One way of increasing the realism of aggregated zonal measures is to use detailed population data. Another option is to add mandatory travel pattern information on a zonal level, thus maintaining the operational advantages of zonal measures while bringing in components from individual AMs. This latter approach will be developed in subsequent sections.

The paper is organized as follows. In the next section we take a look at different approaches to measuring accessibility. In the third section, an alternative AM is defined where a mandatory travel pattern is taken into account. In the forth section, data for an empirical example are presented and implementation of the AM in a GIS software is described. Then an analysis of the properties of the suggested AM and comparisons with more established AMs are presented. Finally, the last section provides concluding remarks.

ACCESSIBILITY MEASURES

Regardless of the type of AM, two components are always present—representation of travel cost (in a wide sense) and representation of opportunities at the destination. Travel cost could be represented as a simple 0/1 variable or defined in detail using a parameterized function. Similarly, description of the opportunities can range from a simple description of the resource location to detailed address-coded registers of a multitude of opportunities. Population or number of work places are frequently used as measures of opportunitites.

Individual space-time accessibility measures (STAMs) (Miller and Wu 2000) have gained increasing popularity recently (see, e.g., Kwan 1998 and Miller 1999). This is partly due to GIS developments that include programming facilities and techniques for visualizing individual behavior. Examples of implementation of individual AMs in GIS can be found in Miller (1999), Miller and Wu (2000), and Kwan (1998). Despite the fact that most implementation of individual AMs are recent, the theories behind those AMs are mature and originate from Hägerstrand's space-time framework[2] (Hägerstrand 1970; see also Lenntorp 1976). In the space-time framework, the

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[1] Many other effects, such as pollution, accidents, and consumption of land, are negative.

[2] This is frequently illustrated using the space-time prism (see, e.g., Lenntorp 1976).

mobility of the individual is constrained by transportation resources available, which affect access to opportunities and encourage combining activities with other people.

Mandatory travel patterns, such as going to and from work and picking up children, play an important role in space-time theory. The implications for accessibility of mandatory travel patterns are twofold. On the one hand, a mandatory travel pattern restricts mobility and prevents the individual from reaching certain opportunities, on the other hand, a mandatory travel pattern brings the individual to places that may provide opportunities and reduce the need for special purpose trips.

Possibilities for overcoming distance and other obstacles to mobility differ among individuals depending on where they live and work as well as on their mobility resources. All these restrictions define an area, called the potential path area (PPA), that a specific individual can cover given the set of constraints. Despite its conceptual simplicity, the functional form of the travel impedance for individual space-time measures may be a complex sequence of conditions, depending on how many restrictions in space and time are taken into account. The PPA simply defines a subset of the total study area that should be taken into account when measuring accessibility for an individual. This is in contrast to standard measures where even distant opportunities can contribute to accessibility, although to a limited extent.

A next step is to determine the utility of opportunities that can be reached. Here, a weighting scheme is necessary. A similar accounting of distance to opportunities can be applied in both individual and aggregate zonal AMs. The simplest alternative is to put equal weight on all opportunities within a cutoff value of distance in aggregate AMs and let the PPA define the cutoff value for individual measures of distance (cumulative AMs). Another alternative is to use a gravity-based weight function. Accessibility measures based on gravity principles adopt a weighting scheme according to some aggregate travel behavior. Formally, gravity-based measures can be written as follows:

$$a_i = \sum_j x_j f\left(t_{ij}\right) \qquad (1)$$

where a_i is the accessibility of zone i with regard to the supply of x across all zones j, and t_{ij} is the distance or some other measure of the travel impedance between i and j. The shorter the distance the better. Common alternatives for $f(t_{ij})$ is the exponential function and the power function. Cumulative opportunity measures can be written in the same form as gravity measures by using

$$f\left(t_{ij}\right) = \begin{cases} 1 \text{ for } t_{ij} < T \\ 0 \text{ otherwise} \end{cases} \qquad (2)$$

where T is the cutoff value. Cumulative opportunity measures are simpler to use compared with gravity measures, because they do not require estimation of parameters.

A third alternative is to use an AM based on random utility theory. The most widely used model of this type is the logit model from which the logsum is derived:

$$a_i = \log \sum_j x_j \exp\left(-\beta t_{ij}\right) \qquad (3)$$

In equation (3), the utility is simply a function of distance as in previous measures and of the opportunities of zone j. Logit models can handle time constraints in the choice set and constrained models have been successfully used by Thill and Horowitz (1997). An application to accessibility where the logsum is used in a time-space framework can be found in Miller (1999). In an article by Richardson and Young (1982), the properties of the logsum as an accessibility measure are explored for linked trips.

The formulation of the functional form of the distance function has no doubt attracted the most interest in the literature. In some respects, perceptions of opportunities at the destinations are critical. At one extreme you may find opportunities characterized by "the more the better" and at the other extreme "one is enough." In the first alternative an additive indicator is appropriate, and in the second case a maxitive indicator is required (see Weibull (1980) for a discussion on additive and maxitive indicators).

There are several problems with zone-based AMs. We must remember that accessibility analysis does not differ from any other zone-based analysis of spatial data. The resulting accessibility will depend on how and to what scale we have aggregated our data and zones (i.e., the modifiable areal unit problem). By using zones we cannot explicitly take individual time constraints into account. Zone-based measures also fail to analyze interactions between individuals, which is one of the strong arguments for individual measures.

AGGREGATE PATH-BASED ACCESSIBILITY

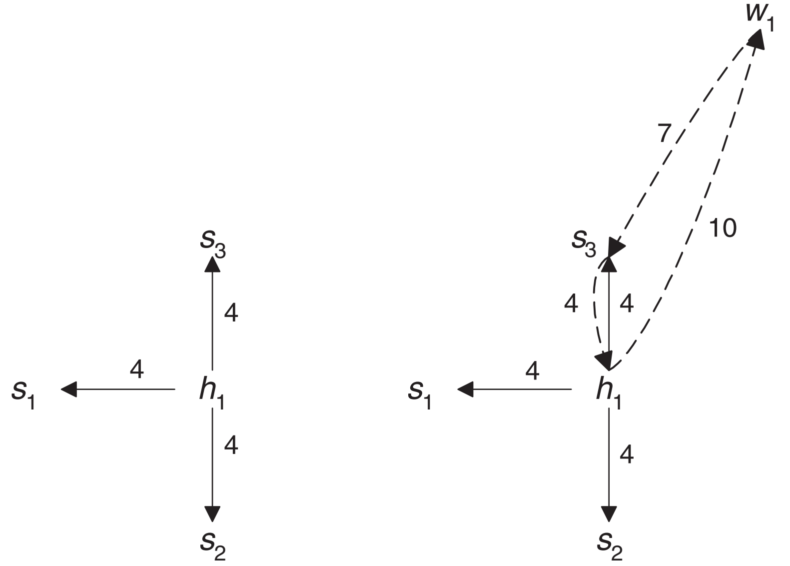
In order to take advantage of the information present in a predefined travel (to work) matrix, an AM will be developed wherein the accessibility of each zone is weighted by a travel matrix. This is illustrated in figure 1 (left) where the housing area is denoted *h*, alternative destinations (e.g., for shopping trips) are denoted *s*, and the travel distance is equal across all alternatives. The AM used in association with figure 1 (left) will be a standard aggregate AM as in equation (1)

If the alternatives (which we assume) are equal, all alternatives can be chosen with equal probability. If we add information about a mandatory trip (e.g., a trip to and from work), we have a new activity pattern to consider, figure 1 (right). In this setting the available shops will not be indifferent to the traveler in the example. With path-based measures, it is possible to calculate the extra travel time the activity requires given the two initial activities at *i* and *j*. This is an important aspect not taken into account by other types of accessibility measures. The extra travel time caused by going to *k* (s_3) is given as

$$t_{k|ij} = \left(t_{ik} + t_{kj}\right) - t_{ij} \tag{4}$$

where *i* is allowed to be equal to *j*, which means a trip was not made or that job and home are in the same zone. In this case there will be no difference between a traditional zone-based AM and a (non-) path-based AM. A modified distance measure like this can be found in Richardson and Young (1982). If $i \neq j$ and *k* is along the road from *i* to *j*, the extra time equals the time consumed by activity *l*, and will be denoted by t^l. The total extra time consumed by activity *l* at an arbitrary *k* will equal $t_{k|ij} + t^l_k$. If it is impossible (or difficult) to obtain some reasonable estimate of t^l_k, we could use some other stop penalty. The probability of making an additional trip or stop is not modeled in the application below. Changes in that respect, however, will not alter the fundamental properties of the path-based AM. Just changing the distance meas-

FIGURE 1 Illustration of the Difference Between Traditional Accessibility Measures (left) and Path-Based Measures (right)



ure by taking one possible trip pattern into account will not add much realism to our AM. To gain something more, we must weight the AM by incorporating information on probabilities for mandatory destinations using a trip pattern that is not evenly spread across all destinations. The next component is, thus, a travel matrix F_{ij}, where i represents the residential zone and j represents the work zone. This matrix could be observed from a travel survey or estimated by some model.

$$\omega_{ij} = F_{ij} / F_i \tag{5}$$

where $F_i = \sum_j F_{ij}, \left(\sum_j \omega_{ij} = 1\right)$, we can then write a path-based AM weighted by the trip pattern ω_{ij}:

$$a_i = \sum_j \omega_{ij} \sum_k x_k f\left(t_{k|ij}\right) \tag{6}$$

We noted above that ω_{ij} is a predefined travel matrix that could be obtained from a survey (as available in Sweden) or be the results of an earlier estimation. But, if the matrix is estimated, it may originate from a process like $F_{ij} = F_i \times P_{j|i}$. If we substitute the right side of (5) into (6) and use the assumed model for F_{ij} we will obtain:

$$a_i = \sum_j \frac{\left(F_i P_{j|i}\right)}{F_i} \sum_k x_k f\left(t_{k|ij}\right) \tag{7}$$

which will simplify to

$$a_i = \sum_j P_{j|i} \sum_k x_k f\left(t_{k|ij}\right) \tag{8}$$

One important determinant of our AM will be the number of trips outside the residential zone. If the travel pattern only consists of within-zone trips, ω_{ij} will be zero except for the diagonal. Then our AM will equal traditional zone-based AMs. If the travel pattern consists of trips between any pair of zones, the path-based accessibility score will be equal to or higher than scores of traditional AMs. The usefulness of the suggested AM will, thus, depend on zone size because the share of within-zone trips can be expected to be proportional to the zone size. If we disaggregate ω_{ij} into groups that can be expected to have different mobility characteristics, the analytical power will increase. Segmentation can be made with regard to socioeconomic status or education. Yet another alternative is to transpose the weight matrix and obtain an accessibility score for the work zones.[3]

Our suggested AM is still a zone-based measure and suffers from the same problems as other aggregate AMs (mentioned in the previous section). For example, using a path-based measure of this type will not capture interactions between individuals. What could be done is to impose a complex weighting scheme and argue that the realism of our AM has increased. This, however, would not alter the fundamental properties of zone-based AMs (e.g., we still do not capture interactions between individuals). Instead, the argument for our measure is that we maintain the operational properties of aggregate AMs while adding information on one important daily activity—trips to work.

EMPIRICAL EXAMPLE, DATA, AND PROGRAM

In order to illustrate our measure we provide one application with an observed travel pattern and one application with an estimated travel pattern. For the empirical example we used two sets of data—one from the Stockholm region and one from the county of Jämtland about 600 kilometers (km) northwest of Stockholm (see maps in figures 2 to 4). For characteristics of the two regions, see table 1. The regional division is based on small area marketing statistics zones of varying size. In the city centers, the zones consist of just a few blocks, while in the periphery the largest zones are over 100 km^2. The two application areas are different in two important aspects: 1) for the Stockholm region we used an estimated matrix as the travel pattern weight $\left(\omega_{ij}\right)$, while we used a matrix from a total survey for Jämtland; and 2) Stockholm is an urban region with more than 1.7 million inhabitants with a dense population, while Jämtland is rural and sparsely populated.

One of the contributions of the AM put forward in this article is the weighting of the travel paths. As

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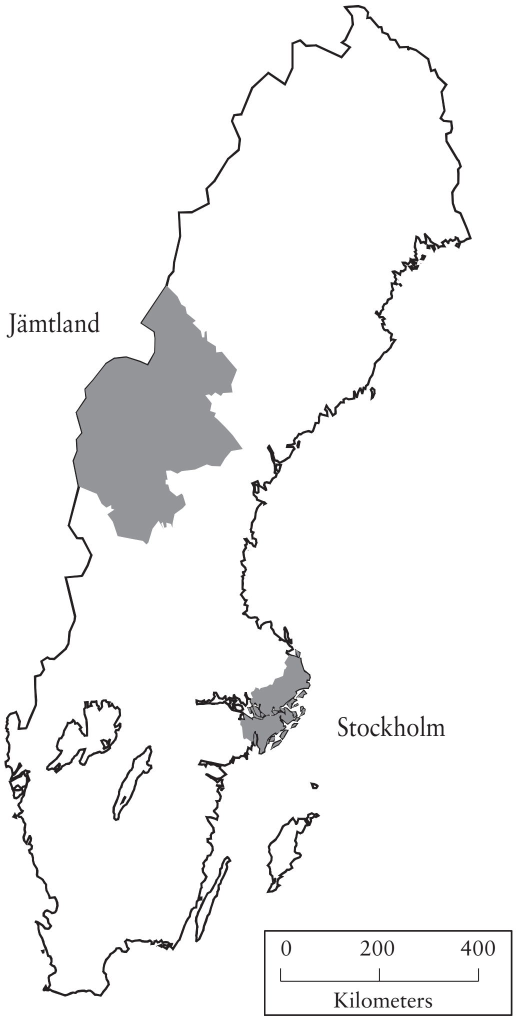
[3] This option is available in the software developed for this paper but is not used in the application below.

FIGURE 2 Application Areas



shown in the section on aggregate path-based accessibility, this can be done using observed or estimated travel flows of a compulsory trip pattern. In the application for Jämtland, we used a matrix obtained from a total survey, the 1990 census—the last year in which data with mode choice are available on a geographically detailed level. Our data set contains variables for gender, education, and mode. To restrict the empirical example, only the car mode was considered. For the Stockholm region, we used estimated matrices for men and women as weights for trips by car.

Two different types of opportunities were selected: one where "more is better" (additive) and another where "one is enough" (maxitive). For the additive opportunity, the number of jobs in retail trade was used. As the maxitive opportunity, pharmacies were used. Pharmacies were selected because this type of opportunity is independent of the size or number of opportunities.[4] In this study, alternative ways of distributing prescription drugs were not taken into account.[5] Access to retail trade and access to pharmacies were measured to the centroid of the STAMs that contains the relevant opportunity.

Network data were obtained from the Swedish road administration and the Swedish Institute for Transport and Communications Analysis (SIKA). In the sparsely populated region we used free flow travel times, while in the Stockholm region we used travel times from the afternoon peak hour. In our example, we have used a precalculated travel time matrix. Another alternative is to include the shortest path algorithm in the calculation of the AM and avoid storage of the travel time matrix. This might be an alternative for GISs that cannot handle matrices, but is not a restriction in our case.

We defined the general form of our AM in terms of one opportunity (x_j) and one impedance function $f(t_{k|ij})$ or $f(t_{ij})$. In the applications presented below, we used the simple formulation from equation 2 (cumulative opportunity) and the logsum from equation 3. For the cumulative opportunity measure, we used a cutoff time of 25 minutes. The reason behind choosing cumulative opportunity is that, despite its shortcomings, this is a frequently used measure in applied work. An alternative measure is the logsum, which is a natural alternative in association with transport models. The logsum is a parameterized AM and needs estimation of the parameters of a logit model. This model was estimated using data from the national travel survey[6] (RVU 94) where information on secondary trips was available. In order to concentrate on the AM, a simple model with travel time as impedance and number of workplaces (w_k) in retail trade at k as attraction was estimated, $u_{k|ij} = 0.3603 \log w_k - 0.2265 t_{k|ij}$, where $u_{k|ij}$ is the utility of going to k

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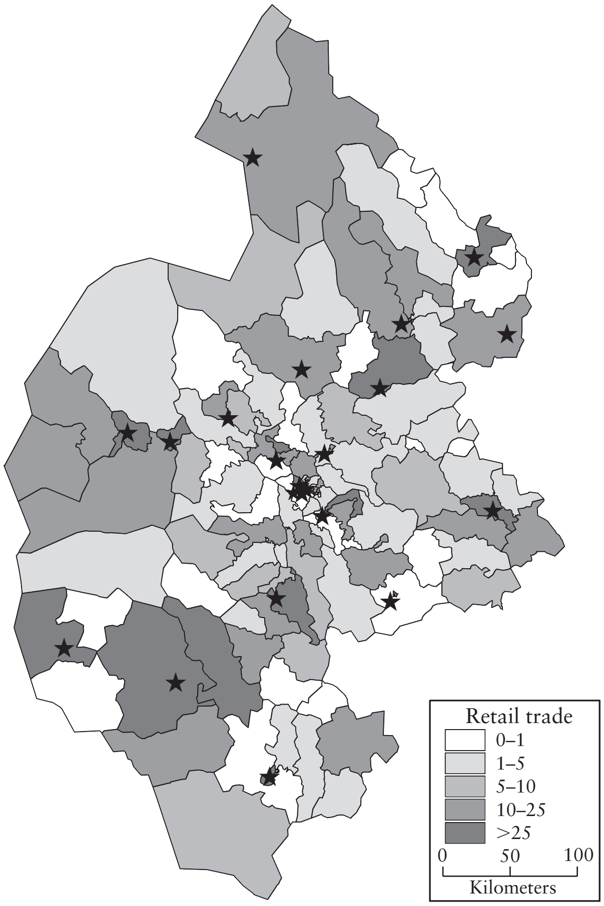
[4] It is not reasonable to regard a destination with two pharmacies as twice as good as a destination with one pharmacy. For retail trade in general, it could be a reasonable assumption that a large destination (e.g., a shopping mall) constitutes a more attractive alternative than a small one (e.g., a single store).

[5] In some sparsely populated areas, drugs are distributed by a local shop or post office the day after an order has been placed.

[6] This travel survey is sample based.

FIGURE 3 Location of Pharmacies and Employment Within Retail Trade in Jämtland County



conditioned on a trip from *i* to *j*. Most secondary trips are short, and the destination is either close to home or close to work, consequently our parameter is rather high (–0.2265). We used these estimates for both applications.

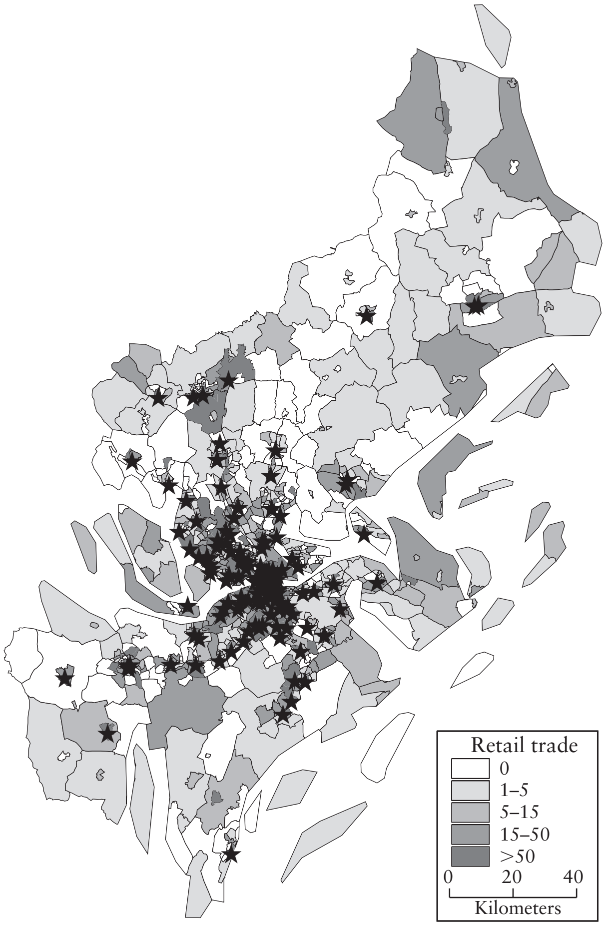
In a nested logit model, the secondary trips will most likely be in a nest below the destination choice. In such a model structure, different levels should be coupled by the inclusion of a logsum term. It is, however, not likely that someone would choose their place of work with regard to the service supply along the road between home and work. We have, thus, not included any logsum term from the secondary trips into the utility function of the destination choice model.

TABLE 1 Characteristics of the Application Areas

	Jämtland	Stockholm
Inhabitants	135,584	1,725,756
Km^2	49,347.5	5,812.3
Inhabitants/km^2	2.75	296.91
Nodes	1,000	4,400
Links	2,000	9,000
Zones	150	900
Time	Free flow	Afternoon peak hour
Mode	Car	Car

The application platform is a transport-oriented GIS, TransCAD[7] (TC). Beside the standard GIS tool box, TC contains routines for transportation analysis, such as different modeling tools. TC also provides an internal matrix database format (lacking in most GISs), which simplifies our application. The program[8] that computes the accessibility is written in TC's internal programming language (Caliper script) and integrated in a "tool box" where different AMs are available (see Berglund 1999). The usage of a native GIS programming language makes it possible for us to offer a close

FIGURE 4 Location of Pharmacies and Employment Within Retail Trade in the Stockholm Region



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[7] Available at http://www.caliper.com.

[8] The program is available from the author on request.

integration between GIS and the computational routines. The program can only run within TC.[9]

COMPARATIVE ANALYSIS OF AMS

Using aggregate path-based accessibility measures, accessibility with regard to spatial location (which is traditional) and impacts of socioeconomic status (education) and mobility pattern (based on groups) will be analyzed.

In order to explore some of the properties of the path-based AM, it is compared with existing and well known AMs. Such AMs are the nonpath-based equivalent of the AMs selected for this study. In previous studies, comparisons between different AMs were made using correlation coefficients (see, for example, Kwan 1998). The fact that two AMs are correlated does not indicate quality but may provide an intuitive sense of their properties. Remember that the case with no compulsory trips will yield the same value of path-based accessibility as the corresponding traditional AMs. Thus, low mobility groups are expected to have a path-based accessibility similar to standard zone-based accessibility.

In standard AMs, the only factor that determines accessibility is the location of the zone in relation to the opportunities. This might imply a continuous pattern of accessibility. Given equal access to mobility resources, the differences between socioeconomic groups will be negligible. For path-based measures, the resulting accessibility will also depend on the travel pattern associated with the population in each zone and its socioeconomic composition. It is well known that different socioeconomic groups have different mobility patterns and that different travel time sensitivities are obtained when estimating models.

When we weight the AM with the travel pattern, we expect to discover inequalities in accessibility that are difficult to uncover using other types of AMs. This will also result in less continuous patterns of accessibility, and adjacent zones will show different accessibility depending on socioeconomic composition. We can check this by using a test for the degree of similarity between adjacent zones (spatial autocorrelation). The most widely used test for global spatial autocorrelation is Moran's I (Moran 1948; Cliff and Ord 1972). The value of Moran's I will be in the range +1 to –1. Moran's I will be positive when neighboring areas have similar attributes and negative when the attributes are dissimilar. The hypothesis is that the path-based measures score lower than the conventional AMs.

Results

Let us first look at the correlation coefficients in tables 2 through 5. The first two letters of the code in the "variable" column of tables 2 through 5 refer to the type of AM, where CU = cumulative opportunity and LS = logsum. Letters 3 and 4 refer to the opportunity: RT = retail trade and PH = pharmacy. Letter 5 refers to gender: M = men, W = women. In tables 2 and 3, the last letter in the code indicates educational level: L = low, I = intermediate, and H = high. Finally, AA is the traditional zonal measure that is unweighted. Three questions are now considered.

- *Is there a difference between the weighted measures and the traditional ones, i.e., to what extent are the traditional AMs (in bold face in tables 2 and 3) correlated with the weighted AMs?*

The coefficients with regard to retail trade range from 0.788 to 0.922 (cumulative opportunity) and 0.511 to 0.833 (logsum). The differences are more obvious for accessibility with regard to pharmacies, with overall lower coefficients indicating less similarity between the path-based measures and the zone-based measures. The same pattern holds for the AMs weighted by estimated matrices. The maps in figures 5 and 6 illustrate the difference between traditional AMs and weighted AMs. For the weighted AM, a larger area in the central region obtains high accessibility scores while the scores for the unweighted AM declines toward the periphery. A notable difference between the two types of measures can be found in the northeastern part of the region where the weighted AM scores high while the unweighted is quite low. This pattern can be attributed to the fact that the most important commuting flows (or commuting probabilities as estimated by the model) move toward areas where pharmacies can be reached.

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[9] Since this AM goes over a loop that is $n \times n \times n$ (see equation 6), where n is the number of zones and GIS programming languages are not very computationally efficient, we also wrote an alternative program in FORTRAN.

TABLE 2 Correlation of Accessibility Scores for Retail Trade in Jämtland (see page 86 for explanation of row codes)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
(1) CURTML													
(2) CURTMI	.954												
(3) CURTMH	.866	.879											
(4) CURTWL	.950	.932	.870										
(5) CURTWI	.941	.948	.887	.966									
(6) CURTWH	.940	.942	.871	.963	.976								
(7) CURTAA	.904	.852	.788	.918	.922	.917							
(8) LSRTML	.889	.840	.757	.780	.772	.786	.699						
(9) LSRTMI	.785	.855	.719	.722	.749	.745	.626	.859					
(10) LSRTMH	.422	.394	.556	.411	.378	.416	.346	.490	.377				
(11) LSRTWL	.833	.833	.805	.884	.846	.852	.740	.787	.735	.560			
(12) LSRTWI	.822	.878	.824	.847	.896	.865	.745	.767	.828	.371	.864		
(13) LSRTWH	.655	.692	.686	.671	.694	.721	.586	.646	.666	.458	.708	.772	
(14) LSRTAA	.852	.847	.836	.871	.899	.891	.851	.741	.686	.511	.833	.831	.759

TABLE 3 Correlation of Accessibility Scores for Pharmacies in Jämtland (see page 86 for explanation of row codes)

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13
(1) CUPHML													
(2) CUPHMI	.840												
(3) CUPHMH	.652	.659											
(4) CUPHWL	.782	.800	.697										
(5) CUPHWI	.743	.798	.614	.887									
(6) CUPHWH	.744	.794	.688	.844	.776								
(7) CUPHAA	.676	.644	.571	.670	.707	.705							
(8) LSPHML	.777	.715	.528	.609	.575	.604	.535						
(9) LSPHMI	.683	.786	.533	.575	.616	.589	.508	.908					
(10) LSPHMH	.526	.598	.790	.574	.505	.599	.499	.702	.720				
(11) LSPHWL	.728	.743	.649	.839	.750	.759	.625	.824	.809	.726			
(12) LSPHWI	.690	.727	.597	.748	.811	.717	.660	.799	.850	.700	.917		
(13) LSPHWH	.697	.735	.628	.719	.697	.817	.631	.808	.828	.739	.900	.905	
(14) LSPHAA	.726	.662	.625	.741	.760	.735	.868	.593	.528	.563	.672	.706	.682

- *Does accessibility differ between groups depending on travel pattern, i.e., to what extent is the path-based AM for different groups correlated?*

Looking at the correlation between cumulative opportunity measures of retail trade (table 2, upper left) with different weights, the answer would probably be, "they are not very different." Taking weights 1 to 6 into account, the coefficients range from 0.866 to 0.976. Looking at the parameterized measure (the logsum, table 2, lower right), the answer is different. The same 6 groups (8 to 13) yield correlation coefficients ranging from 0.371 to 0.864. Turning to the example with accessibility to pharmacies, the differences are more pronounced for the cumulative opportunity measures and less obvious for the logsum. In the example with estimated matrices as weights (tables 4 and 5), we find that the differences between men and women are very small, and it appears that our model that generated the weight matrix has not been able to capture differences between genders. One reason is that our AM does not take mode choice into account, which would seriously affect the accessibility for women.

- *Will the map of accessibility be more heterogeneous with path-based AMs?*

TABLE 4 Correlation of Accessibility Scores for Retail Trade in Stockholm (see page 86 for explanation of row codes)

Variable	1	2	3	4	5	6
(1) CURTM	1.000					
(2) CURTW	.999	1.000				
(3) CURTAA	.592	.599	1.000			
(4) LSRTM	.822	.818	.381	1.000		
(5) LSRTW	.827	.823	.388	1.000	1.000	
(6) LSRTAA	.749	.751	.615	.836	.840	1.000

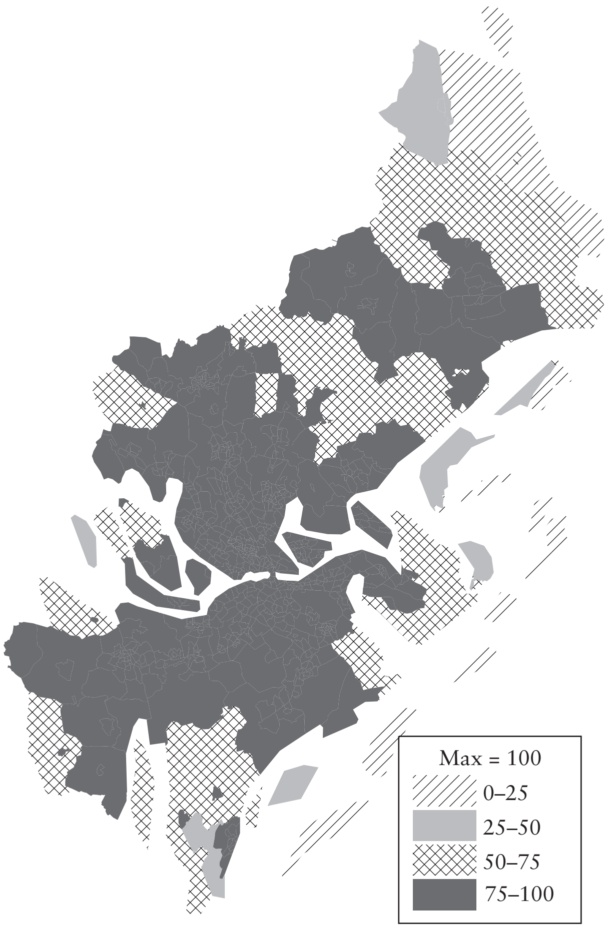
TABLE 5 Correlation of Accessibility Scores for Pharmacies in Stockholm (see page 86 for explanation of row codes)

Variable	1	2	3	4	5	6
(1) CUPHM	1.000					
(2) CUPHW	1.000	1.000				
(3) CUPHAA	.465	.467	1.000			
(4) LSPHM	.892	.891	.436	1.000		
(5) LSPHW	.891	.890	.435	1.000	1.000	
(6) LSPHAA	.538	.539	.817	.488	.486	1.000

In table 6, Moran's I for the AMs are presented. Table 6 shows a mixed pattern. For accessibility to retail trade, except for women in the Jämtland application, the traditional AMs are spatially more homogeneous and show a more continuous accessibility surface. Access to pharmacies shows the opposite pattern. This is not surprising since location of pharmacies is a 0/1 variable (a zone either has one or not and no zone has more than one) for the cumulative opportunity measure. Hence, there will be zones with an accessibility score of 1 or of 0 (remember, pharmacies are assigned a maxitive AM). The very low value for Moran's I is not a surprise in this case. Taking the opportunities along a path into account will even out the accessibility between the zones. Again we can see a similar pattern between the two applications.

Low and High Accessibility Mobility Patterns

FIGURE 5 Access to Pharmacies in the Stockholm Region (unweighted logsum)



Note: Accessibility is presented as an index where 100 is the highest accessibility score.

Using path-based AMs, it is possible to detect differences in accessibility related to differences in mobility patterns. From an initial calculation, one zone was selected (see figures 7 and 8) with quite different accessibility for two groups—men with low and high education.[10] The zone under consideration has no pharmacies, is quite distant from everything else (this is a sparsely populated area), and is separated from the regional center by a lake. To reach more qualified service from this zone, a trip is necessary.

The two groups under consideration have quite different mobility patterns. The most significant difference is that for the group with high education the rate of commuting out of the residential zone is 85 percent, while it is 56 percent for the group with low education. The commuting patterns (see figures 7 and 8) indicate a stronger concentration

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[10] For this zone, the accessibility score was about twice as high for the highly educated group compared with the group with low education.

FIGURE 6 Access to Pharmacies in the Stockholm Region (logsum weighted by travel pattern for women)

Note: Accessibility is presented as an index where 100 is the highest accessibility score.

of the commuting flows to the service centers for the highly educated group than for the less educated group. In this case, with a low local level of service, commuting to service centers will yield high accessibility.

CONCLUSIONS

In this paper an accessibility measure has been presented where accessibility is calculated with regard to a mandatory travel pattern for each zone. It is shown that there are quite large differences in accessibility between groups with different travel patterns if an observed matrix is used as a weight. In our example with estimated matrices the differences between groups were negligible. It is of course difficult to capture details in travel patterns by a model. The differences between traditional AMs and the path-based AMs are not as evident for the cumulative opportunity measure as for the logsum. The same pattern holds for the AMs weighted by estimated matrices.

TABLE 6 Moran's I for AMs Used by Gender and Education (L = low, I = intermediate, H = high)

	Retail trade		Pharmacy	
Group	Cum. opp.	Logsum	Cum. opp.	Logsum
	Jämtland county			
Men L	0.86	0.60	0.46	0.65
Men I	0.83	0.50	0.41	0.61
Men H	0.78	0.44	0.48	0.48
Women L	0.90	0.65	0.68	0.68
Women I	0.91	0.67	0.73	0.73
Women H	0.90	0.42	0.66	0.65
Unweighted	0.90	0.80	0.38	0.48
	Stockholm region			
Men	0.90	0.80	0.70	0.70
Women	0.90	0.80	0.70	0.71
Unweighted	0.95	0.83	0.57	0.69

The pattern of similarities between adjacent zones shows a mixed result. For access to retail trade, neighboring zones can have very different accessibility scores depending on the mandatory travel pattern. For the case of pharmacies (using a maxitive AM), the path-based AMs show a more smooth pattern.

- ■ *When could a path-based AM be useful?*

For low-mobility groups who work close to home, the path-based component will not change the accessibility score much and will not be very useful (but not less useful; see the aggregate path-based accessibility discussion). For high-mobility groups, a path-based AM can capture accessibility obtained along the daily travel path and, thus, is useful. A situation where a path-based AM could be useful is in transition regions outside urban areas where part of the population is active in sectors where jobs are found locally (mainly traditional sectors of the labor market) and others find their employment within sectors located in the urban center. If an estimated matrix is used as a weight, the model must be able to capture differences depending on socioeconomic status.

FIGURE 7 Mobility Pattern: Low Accessibility to Pharmacies (Men With Low Education) (56% commuters)

FIGURE 8 Mobility Pattern: High Accessibility to Pharmacies (Men With High Education) (85% commuters)

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JOURNAL OF TRANSPORTATION AND STATISTICS

Volume 4 Numbers 2/3
September/December 2001
ISSN 1094-8848

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