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16. Abstract

This report comprises a review of the literature regarding the measurement of accessibility for transportation planning purposes. A comparison matrix presents summarized information about the papers reviewed. Different types of accessibility measures are discussed in separate chapters. Special attention is given to the elements of previous measures developed as they compare with the goals of the research project. The goal of this research is to develop a measure that is responsive to both the transportation system and land use. In addition, the measure developed is intended to disaggregate along four dimensions (mode, time of day, activity type, and spatial detail) and then aggregate along any one or combination of these dimensions for use in transportation planning at the local, regional, and state levels.

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DEVELOPMENT OF AN URBAN ACCESSIBILITY INDEX:

LITERATURE REVIEW

by

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Development of an Urban Accessibility Index

Conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

by the

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THE UNIVERSITY OF TEXAS AT AUSTIN

May 2000

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CHAPTER 1. INTRODUCTION

In the face of rising traffic volume, decreasing open space, increasing air pollution and reduced funding, transportation planners are looking for responsive and accurate ways to evaluate the effectiveness of alternative transportation projects. They are looking for additional information when prioritizing transportation projects that address these issues, as well as growing concerns about the equitable distribution of limited resources.

The overall goal of this project is to develop a measure of urban accessibility that reflects the extent of interaction between an area's land development patterns and transportation supply modes that can be used to identify areas with low accessibility and to prioritize alternative projects. In addition, the measure is intended to provide accessibility information specific to multiple levels of spatial interest, modes, activity purposes, and times of day.

For several decades now, accessibility has been the focus of much literature in various fields of study. This indoubtably reflects the different study purposes for which any particular measure may have been proposed. However, there does not appear to be a common definition of "accessibility." Some researchers discuss accessibility "to" some place (or places) as opposed to accessibility "from" some place (or places). Some researchers characterize accessibility as a measure of the transportation system from the perspective of users of that system (Ref 1). In this project, we use the following, qualitative definition of accessibility: accessibility is a measure of the ease of an individual to pursue an activity of a desired type, at a desired location, by a desired mode, and at a desired time.

Once accessibility can be quantified, there are many potential uses for this measure. First, it succinctly captures the quality of the existing state of the transportation system at many spatial levels, and it reflects the effect of improvements (potential or real) to existing travel modes and the introduction of new modes (such as light rail). Second, it tracks and monitors changes in accessibility caused by shifts in the distribution of land uses and can aid evaluation of the impact of alternative land use policies. Third, it can support multimodal priority programming decisions. Fourth, it can be used in travel demand modeling to determine changes in trips generated and trip-making patterns due to changes in level-of-service of one or more travel modes or changes in land use patterns. Fifth, purpose-specific accessibility indices provide information for policy makers to more effectively target investments for specific purposes, such as improving accessibility to recreation or shopping.

In addition, an accessibility measure can be used by individual households and businesses as a quality-of-life index when making relocation decisions. It may function as a land use/transportation version of a cost-of-living index.

This first report of a three-year TxDOT-funded project to develop an accessibility index focuses on a comprehensive literature review. Chapter 2 discusses theoretical issues and methodological considerations in the development and application of an accessibility measure, as described in the literature. Chapter 3 of this report presents a matrix for comparing different accessibility measures defined in the literature and includes a brief overview of the measures reviewed. Chapters 4 through 8 review different kinds of accessibility formulations. Within each of these chapters, the first section describes the generic formulation, the second presents alternative forms of the generic formulation, and the third discusses case-study applications. Chapter 9 reviews studies that have compared different accessibility measures based on the same data to highlight differences and similarities. Chapter 10 reviews applications of accessibility measures for planning purposes, instead of research. And the last chapter, Chapter 11, draws important insights gained from this literature review. The Appendix of this report contains abstracts of articles included in this review.

CHAPTER 2. ACCESSIBILITY THEORY

Accessibility is often discussed in contrast to mobility (Refs 2, 3). Mobility emphasizes the transportation system, while accessibility also accounts for land use patterns. Accessibility has been a part of transportation policy discussions, but is not a part of traditional transportation models; consequently, it lacks a formal definition. Responsiveness to changes in land use patterns and the transportation system is at the heart of the mobility-versus-accessibility discussion. A measure that includes only parameters related to the transportation system would be more of an indicator of mobility than accessibility. The addition of attractions accounts for the land use aspect of the accessibility measure.

Bach (Ref 4) posits that there are several issues to resolve related to not having a universal definition of accessibility. One is the notion of accessibility "from" versus accessibility "to." These two concepts are defined as relative accessibility (accessibility between two points) and integral accessibility (accessibility between one point and all the other points in an area) (Ref 5). These typically are calculated at the zone level. Knox (Ref 6) argues that it is not the accessibility of places that needs to be measured, but the accessibility per person in a zone. Several authors maintain that the purpose of the accessibility measure should dictate the form (Refs 7, 8).

Pirie (Ref 9) argues that one purpose for developing such measures is to maintain a certain level of accessibility for citizens. These measures would reflect people interacting with the built environment. They also would identify social inequities (Ref 10). Similarly, several researchers propose using an accessibility measure to highlight the need for changes in the transportation system or land use patterns. For this purpose, Davidson (Ref 11) develops an inverse accessibility measure that he calls 'isolation.' Other researchers develop a normalized measure for an area. One researcher uses a desired minimum standard to identify areas below standard (Ref 12). Another researcher proposes scaling all accessibility measures in an area to the highest value (Ref 6).

Breheny (Ref 13) disaggregates accessibility into three components: benefits at the end of a trip, the cost in reaching that benefit, and the individual gaining that benefit. By holding any of these variables constant, information can be aggregated for different conditions (see Table 5.1).

Breheny stresses that this is a measure indicating need for accessibility, not market demand for travel.

Many European nations are looking at accessibility as an indicator for sustainability in the transportation system. Efforts are being pursued in the Netherlands (Ref 14), the United Kingdom (Refs 15, 16), and Spain (Ref 17) to develop an accessibility measure to use in planning. Work in the Netherlands concentrates on three areas: reducing automobile use, access to needed activities (education, medical facilities, etc.), and the promotion of economic development (Ref 14).

2.1 CHARACTERISTRICS OF AN ACCESSIBILITY MEASURE FOR GENERAL USE

After studying the gamut of accessibility measures, several researchers have proposed basic criteria that need to be addressed by any accessibility measure (Refs 9, 4, 18, 19, 20). Because accessibility is a combination of the transportation system and land use patterns, many agree that any measure should respond to changes in either, or both, of these elements (Refs 20, 21, 22, 23, 24).

Weibull developed several axioms for the form of an accessibility measure (Ref 18). Many researchers adhere to these basic criteria (Refs 25, 26, 27). These are the order of opportunities should not affect the value of the measure; the measure should not increase with increasing distances or decrease with increasing attractions; and opportunities with zero value should not contribute to the measure.

The first criterion describes a measure that is independent of the order of the data. The second describes a behavioral assumption of an accessibility measure–attractions have utility and travel has disutility. The third criterion addresses the area of relevance, and the proper coding of attractions when developing a measure.

Morris et al. (Ref 20) propose several other criteria. They are related to the parameters and performance of an accessibility measure. Their criteria are:

- a measure should have a behavioral basis;
- it should be technically feasible; and
- it should be easy to interpret.

The first criterion suggests the need to incorporate sociodemographic factors that may influence activity participation. However, researchers don't necessarily agree as to what the behavioral basis should be. For example, several researchers (Refs 9, 13, 22, 23) argue that observed behavior is not necessarily an indicator of preferred behavior. The second criterion presages today's performance measures. It highlights the real-world application of accessibility measures developed in the academic literature. In addition, researchers call for the use of data already gathered to increase feasibility. Lastly, having a measure that is easy to interpret facilitates policy-making and public involvement.

Others have proposed additional criteria. Davidson (Ref 28) indicates that accessibility should increase as another mode is added to an area, and conversely not decrease the accessibility of the original modes. A measure should explicitly acknowledge the addition of a new mode to the choice set. Voges and Naudé (Ref 21) argue that disaggregation is an important quality of accessibility measures that allows evaluation along several different dimensions.

Before an accessibility measure is planned, Wilson (Ref 30) proposes several questions that need to be answered. These are:

- what is the degree and type of disaggregation desired;
- how are origins and destinations defined;
- how is attraction measured; and
- how is impedance measured.

This last point is an important characterization of a measure. A distance measure does not account for level of service and a time measure is time-of-day dependent. Savigear (Ref 29) suggests that parking availability should be a consideration when trying to determine accessibility to places—particularly central business districts (CBDs). There is no straightforward answer to this question, and the following chapters include researchers' resolutions to this issue.

Besides the specific criteria outlined above, researchers investigated other parameters potentially affecting an accessibility measure. Bach (Ref 4) assessed to what extent different ways of measuring separation and different levels of aggregation influence a measure's value. In terms of trading off exactness and efficiency, Bach concludes that cities today generally have information available at a zonal level that is appropriate for determining the placement of public facilities (libraries, post offices, swimming pools, etc.). He still cautions that level of aggregation should be considered when trying to measure the accessibility of a location, because the level of aggregation can change but the location of the point in question is constant.

Also affecting the parameters of an accessibility measure is the difference between perceived and objective accessibility (Refs 9, 20). Wilson (Ref 30) argues that impedance factors need to be weighted to reflect individuals' perceptions. Davidson (Ref 11) also argues in favor of the use of perceived distances as the most accurate way to measure accessibility. However, construction of perceived accessibility measures requires subjective data, and applications of such measures are more difficult from a data standpoint than using objective parameters in the accessibility measure.

2.2 CHARACTERISTICS OF AN ACCESSIBILITY MEASURE FOR USE IN TRANSPORTATION PLANNING MODELS

Several researchers have investigated the requirements for an accessibility measure that could be included in trip generation models. Several studies have shown that accessibility is an important factor in trip-making (Refs 22, 31, 32). Lee and Goulias (Ref 33) argue that, because accessibility is such a significant indicator of travel behavior, it should be included in trip generation models. Leake and Huzayyin (Ref 34) suggest that any accessibility measure included in trip generation modeling should meet the criteria outlined above, as well as meeting the needs of transportation modeling, such as disaggregation across mode and trip purpose.

Hazel (Ref 35) classifies accessibility into personal and spatial components which would then be used in different parts of transportation modeling. He suggests that personal accessibility (characterized by availability of a car, availability of the individual, and availability of the destination) should be a factor in trip generation models, and spatial accessibility (based on an attraction factor and spatial separation) should be used in trip distribution.

Wilson (Ref 30) suggests using origins and destination (O/D) data to calibrate accessibility measures. He also advocates the use of a gravity-type accessibility model for statistical averaging to improve trip model development. He proposes using a series of linked equations to aggregate and then disaggregate data in order to determine modal split.

CHAPTER 3. COMPARISON MATRIX OVERVIEW

In order to compare the papers reviewed for this report, a comparison matrix was developed. The measures included in this literature review are divided into five main categories: spatial separation, cumulative opportunity, gravity, logsum/utility, and time and space models. We distinguish between these broad classes of measures in our review. Within each of these classes, the studies are listed alphabetically by name of the author (Table 3.1).

For each measure considered, three types of information were extracted from the literature. The first is data- and model-specific information. Second is a description of the theoretical basis of the accessibility measure. Third is information about the application of such measures.

The columns of the comparison matrix (Table 3.1) indicate to what extent the measure accommodates dimensions of mode, trip purpose, time of day, level of service, and spatial detail. The last column presents additional relevant information.

Many measures have focused on accessibility to one activity—primarily to employment activities, but also to shopping, medical services, and other destinations. This research attempts to develop a more robust measure. The preliminary framework for an appropriate, useful, and robust accessibility measure indicates that it should reflect the characteristics of two types of attributes: basic components such as travel impedance (i.e., level of service) and activity attraction. Additional types of attributes to be considered are related to disaggregation choices, such as time of day, mode, activity type, and spatial detail. These attributes represent the columns of the comparison matrix.

In the next five chapters, we discuss each of the five broad categories of accessibility measures in detail, referencing the overall comparison matrix (Table 3.1) as appropriate.

Table 3.1 — Comparison Table of Accessibility Research

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
Graph Theory and Spatial Separation Measures	Allen, Liu and Singer (1993) (Ref 38)	Auto	----	---	Average road travel speed	Zone	---
	Baxter & Lenzi (1975) (Ref 36)	---	---	---	---	Eight-directional pattern is superimposed over the area, taking into account geographical constraints	---
	Guy (1983) (Ref 39)	---	Shopping	---	Euclidean distance	---	---
	Ingram (1971) (Ref 5)	---	---	---	Distance	Zone	---
	Kirby (1976) (Ref 37)	---	---	---	Distance	---	---
	Leake & Huzayyin (1979) (Ref 34)	Transit	Home-based work, home-based other, and non-home-based	Average weekday	Measure A1: bus frequency and length of route	Zone	---
		Auto	Home-based work, home-based other, and non-home-based	Average weekday	A3: inverse of the minimum travel times; A4: ratio between route distance and Euclidean distance	Zone	
		All modes	Home-based work, home-based other, and non-home-based	Average weekday	Three measures were evaluated: A3*A1, A4*A1 and A4*A1/zone area (see Table 4.1)	Zone	---

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
	Muraco (1972) (Ref 42)	Auto	---	---	Travel time as derived from the posted speed limit	Node	Artificial flow on major arterials is modeled
	Savigear (1967) (Ref 31)	Auto	---	---	Inverse of the weighted mean travel time	Zone	---
Cumulative-Opportunities Models	Allen Jr., & Perincherry (1996) (Ref 49)	Transit and walk	Employment	Peak period	Travel time	Zone	---
	Black & Conroy (1977) (Ref 47)	Auto and transit	Employment	Peak period	Travel time	Zone	Called macro-accessibility in the paper below
	Black, Kuranami and Rimmer (1982) (Ref 50)	---	Public and private facilities	---	---	---	Meso-accessibility 1) number of facilities per capita, 2) distance to the nearest facility 3) distribution of popu-lation around a facility
	Breheny (1978) (Ref 13)	---	---	---	Travel cost	Zone	---
	Handy (1992) (Ref 45)	Auto	Regional Malls	---	Travel times	Households	---
	Hanson & Schwab (1987) (Ref 43)	Auto and non-motorized	Non-work	---	Euclidean distance	Individual	---
	Hardcastle & Cleeve (1995) (Ref 15)	---	---	---	---	---	Details of their measure, developed on ARC/INFO, were not described

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
	Ikhrata & Michell (1997) (Ref 1)	---	Employment	---	Travel time	---	---
	McKenzie (c.1984) (Ref 23)	---	Employment	---	Travel time	Zone	---
	Mowforth (1989) (Ref 46)	Transit	Employment	AM Peak	Travel time	Zone	Uses two thresholds – 75% and 90% of the mean travel time in the study area
	Sherman, Barber and Kondo (1974) (Ref 48)	Auto and transit	Employment, Health care, airport, recreational facilities, CBD, educational facilities	---	Travel time	Zone	Auto time reflect congestion effects and transit times reflect frequency
	Wachs and Kumagi (1973) (Ref 10)	Auto and transit	Employment (via auto) Health care (via auto and transit)	---	Travel time	Zone	Calculations are made for target income groups
	Weibull (1976) (Ref 18)	Auto and transit	Employment	---	Travel time	Zone	---
	Wickstrom (1971) (Ref 12)	Auto and transit	Employment	Peak	Travel time		Target – 75% of employment opportunities within 45 minutes travel
	Zakaria (1974) (Ref 24)	Auto and transit	Employment	Weekday	Travel time weighted by trip interchanges to zone	Zone	---
Gravity-Type Models	Agyemang-Duah and Hall (1997) (Ref 55)	Auto	Shopping	Weekday	Network travel time	Zone	---

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
	Bhat, Carini and Misra (1999) (Ref 31)	Auto, transit, and walk	Shopping	---	IVTT, OVTT, travel cost	Zone	---
	Black, Kuranami and Rimmer (1982) (Ref 50)	---	Employment	Weekday	Euclidean distance	Zone	---
	Carrothers (1956) (Ref 51)	---	---	---	---	---	Overview
	Cervero, Rood and Appleyard (1999) (Ref 54)	Auto	Employment and Housing	---	Highway network distances	Zone	---
	Davidson (c. 1980) (Ref 11)	---	Activity	---	Perceived cost	Zone	---
	Echeverria Jadraque, et al. (1996) (Ref 17)	Public transit	Employment	---	Travel time	Metro area	---
	Giannopoulos & Boulougaris (1989) (Ref 57)	Auto and bus	Railway stations	---	Travel time and cost	1.1 hours by auto or 1.8 hours by bus from the railway station	---
	Guy (1983) (Ref 39)	---	Shopping	---	Euclidean distance	---	---
	Handy (1992) (Ref 45)	Auto	Shopping	---	Travel time	Zone	Considered accessibility within a neighborhood
	Hansen WG (1959) (Ref 52)	Auto	Employment	Peak weekday	Travel time	Zone	---
	Knox (1978) (Ref 6)	Auto and transit	Doctors' offices	---	Travel time	Zone	---
	Kockelman (1997) (Ref 32)	Auto and walk-bike	All trips	Weekday	Euclidean distance	Zone	---
	Koenig (1980) (Ref 25)	Auto	Employment	Peak weekday	Travel time	Zone	---

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
	Lee and Goulias (1997) (Ref 33)	Auto	Shopping	---	Shortest Travel Distance	Households and shops	Use GIS to display and aggregate
	Levinson and Kumar (1994) (Ref 44)	Auto and transit	Work/Non-work	PM peak	Multimodal trip impedance function	Zone – weighted by number of households	---
	Linneker and Spence (1992) (Ref 56)	Auto and commercial trucks	---	Daytime off-peak	Network travel time and vehicle operating cost	Zone	---
	Tagore and Sikdar (1996) (Ref 27)	Auto and transit	Employment	---	Network travel time	Zone	---
	Weibull (1976) (Ref 18)	Auto and transit	Employment	Peak weekday	Regional median travel times to work	Zone	---
	Wilson (1971) (Ref 30)	---	Employment	---	Distance	Zone	---
	Zhang, Shen and Sussman (1998) (Ref 53)	Auto and transit	Employment	---	Travel time	Zone	---
Logsum/ Utility Models	Algers, Daly and Widlert (1997) (Ref 80)	Auto, transit, bike, and walk	Employment, school, and shopping tours	---	---	Zone	
	Ben-Akiva & Lerman (1979) (Ref 59)	---	---	---	---	---	Model is based on hierarchy of travel choices
	Koenig (1980) (Ref 25)	Auto and transit	Employment	Peak weekday	Travel time	Zone	---
	Niemeier (1997) (Ref 58)	Auto and transit	Employment	AM weekday	Travel cost	Zone	---
	Sweet (1997) (Ref 62)	Auto and transit	White collar Employment	AM peak weekday	Travel time	Zone	---
Time-Space Models	Burns (1979) (Ref 68)						

	Author	Travel Mode	Trip Purpose	Time of Day	Level of Service (LOS)	Spatial Detail	Other
	Hall (1983) (Ref 67)	Auto and transit	---	---	Expected travel time plus safety margin	---	---
	Miller (1999) (Ref 26)	---	---	---	Travel time	Individual	---
	Wang and Timmermans (1996) (Ref 64)	Auto and transit	Activity programs	All day	Travel time	Individual places	---
Empirical Comparisons of Accessibility Measures	Guy (1983) (Ref 39)	---	Shopping	---	Cum. Opp. – Euclidean distance	---	---
	Kwan (1998) (Ref 66)	Auto	Tours	---	Network travel time	Individuals	Gravity, cum. opp., and space-time measures compared
	Song (1996) (Ref 70)	---	Employment	---	Euclidean distances	Zone	Distance to CBD, gravity, cum. opp., and weighted-average-distance measures compared

CHAPTER 4. GRAPH THEORY AND SPATIAL SEPARATION

4.1 THEORY AND GENERAL STRUCTURE OF GRAPH THEORY AND SPATIAL SEPARATION AS AN ACCESSIBILITY MEASURE

The simplest accessibility measure is the distance or separation measure. The only dimension used is distance. Because these measures do not consider attraction level (e.g., land use), strictly speaking they do not fit the general definition of an accessibility measure discussed above. But, they are more than a mobility measure because they discount distances. The most general network accessibility measure computes the weighted average of the travel times to all the other zones under consideration. Equation (4.1) is a general version of this type of measure.

$$A_i = \frac{\sum_j d_{ij}}{b} \qquad \text{(Eq. 4.1)}$$

In this general formulation of this version of an accessibility measure, d_{ij} is the distance between zones i and j, and b is a general parameter. Early work in the graph theory area used a completely abstract version of the road network (Refs 36, 37). There were two reasons for this: one was the cost of analysis at that time, and the other was the argument that the measure should be compared to the ideal of the Euclidean distance between two areas.

The early interpretations of the graph theory version of the measure reduce a transportation system to an abstract representation composed of nodes and links represented in matrix form. Besides the general form above, accessibility can be evaluated in a number of different ways:

- degree of node—the number of links coming from a node (higher values are better);
- associated number—the number of links from a particular node to the one farthest away (lower values are better); and
- Shimbel's accessibility measure—a summation of the links between a particular node and all the other nodes in the network (lower values are better) (Ref 34).

Allen, Liu, and Singer (Ref 38) use a spatial separation measure to compare the accessibility of large metropolitan areas in the United States, arguing for its superiority based on its reflection of transportation quality. They also argue that owing to its normalization with respect to the number of locations (zones) in an area, it can be used to compare different areas (Table 4.1).

Table 4.1 — Graph Theory and Spatial Separation Formulations

Allen, Liu, and Singer (1993) (Ref 38)	$A_{total} = \frac{1}{N(N-1)} \sum_{i \neq j}^{N} \sum_{j=1}^{N} a_{ij}$	A_{total} = overall accessibility for an area a_{ij} = travel time between locations *i* and *j*
Guy (1983) (Ref 39)	$A_i = \sum_k d_{ij(k)} E_k \Big/ \sum_k E_k$	$d_{ij(k)}$ = Euclidean distance to a shop *j* in which good *k* is available E_k = mean expenditure per household on good *k*
Ingram (1971) (Ref 5)	$A_{ij} = 100 \cdot e(-(d_{ij}^2 \cdot v^{-1}))$	*v* = average squared distance between all points
Leake and Huzayyin (1979) (Ref 34)	$A_1 = \sum_r f_r^i l_r^i$ $A_2 = \sum_j d_{ij}$ $A_3 = 1 \Big/ \sum_j t_{ij}$ $A_4 = \frac{1}{n-1} \sum_j \frac{a_{ij}}{d_{ij}}$	*h* = number of public transit routes serving zone *i* *f* = frequency of public transit (veh/hr), operating over route *r* in zone $i = (N_r/T_r)\lambda_r$ *l* = length of route *r* (km) passing through zone *i* *N* = number of buses operating daily on a weekday route *r* *T* = headway of the bus on route *r* $\lambda = (T/T_{max})100$, where T_{max} is the longest operation time among all buses serving the area d_{ij} = shortest travel distance between centroids of zones *i* and *j* *n* = number of zones in area t_{ij} = minimum total travel time between the centroids of zones *i* and *j* a_{ij} = Euclidean distance between the centroids of zones *i* and *j* Three measures were evaluated for all modes: A_3A_1, A_4A_1 and A_4A_1/area of zone
Savigear (1967) (Ref 29)	$A_i = \frac{\sum_j g_{ij}}{\sum_j g_{ij} t_{ij}}$	g_{ij} = measure of demand on trips between zones *i* and *j* t_{ij} = travel time between zones *i* and *j*

4.2 ALTERNATIVE FORMS OF GRAPH THEORY AND SPATIAL SEPARATION AS AN ACCESSIBILITY MEASURE

Alternative formulations of this measure include the addition of weighting factors to the distance. These weighting factors may be the number of zones in an area (Ref 38) (Allen, Liu, and Singer in Table 4.1), or an attractive factor determined by importance in the household budget (Ref 39) (Guy in Table 4.1). These factors are not based on land use in the area. Table 4.1 illustrates the variety of ways this measure has been reformulated. While these measures begin to more closely resemble the types of measures discussed in the following chapters, they are included here due to the nature of the weighting measure.

4.3 APPLICATIONS OF GRAPH THEORY AND SPATIAL SEPARATION AS AN ACCESSIBILITY MEASURE

Dupuy and Stransky (Ref 40) use the graph theory and spatial separation approach to characterize 190 cities in Europe. Links are described by their length, capacity and mean speed. This allows them to be grouped into strong and weak categories. For this macro-scale analysis with a limited number of sites and many natural boundaries, their approach is satisfactory. But it does not lend itself to the finer scale of an urban area that may be made up of thousands of zones. Pooler (Ref 41) specifically points out the limitations of this research based on its neglect of any information concerning population or facilities.

An application of the abstract version of a spatial measure was undertaken by Muraco (Ref 42) (Table 3.1), who evaluated proposed changes to the interstate highway system in two large metropolitan areas. He used a distance-based measure and artificial flows to compare before- and after-accessibility measures for the entire metro areas.

Because many researchers have found the effect of accessibility on trip generation to be significant (Refs 34, 43, 44), Leake and Huzayyin developed a measure for that specific purpose (Ref 34). Table 4.1 presents the measures they found particularly effective in their trip generation model.

If accessibility is an indication of the combination of land use and the transportation system, then criticism of the spatial separation measure's lack of land use information is wellfounded (Ref 21). Another criticism of such measures is their reflexive nature (Ref 9). Accessibility from point A to point B is the same as from point B to point A, which indicates independence from land use information and behavioral data.

CHAPTER 5. CUMULATIVE OPPORTUNITIES

5.1 THEORY AND GENERAL STRUCTURE OF THE CUMULATIVE-OPPORTUNITIES ACCESSIBILITY MEASURE

The simplest accessibility measure that takes account of both distance and the objective of a trip is the cumulative-opportunities measure. This measure defines a travel time or distance threshold and uses the number of potential activities within that threshold as the accessibility for that spatial unit.

$$A_t = \sum_t O_t \quad \text{(Eq. 5.1)}$$

Here t is the threshold, and O_t is an opportunity that can be reached within that threshold. Often, several time or distance increments are used to create an isochronic map (Ref 2, 15). The only information needed for this measure is the location of all the destinations within the desired threshold (e.g., jobs or hospitals). An argument for this method is that it bypasses the zonal aggregation problem of other methods (Refs 10, 43).

5.2 ALTERNATIVE FORMS OF THE CUMULATIVE-OPPORTUNITIES ACCESSIBILITY MEASURE

Researchers have investigated different ways of characterizing the parameters for this type of measure. Zakaria (Ref 24) uses a weighted impedance measure balanced by trip interchanges (Table 5.1). Wachs and Kumagi (Ref 10) use a factor related to job class to determine residents' accessibility to jobs within their classification (Table 5.1). In contrast, Wickstrom (Ref 12) uses the converse of this measure (the length of time it takes to reach a target percentage of jobs). This version of the measure can account for the job market in an area and allow different areas to be compared.

The more sophisticated versions of this measure begin to resemble gravity-type measures where the attractions are weighted by a value related to transportation. Weibull (Ref 18) weights attractions by the number of jobs in a zone and a term related to travel time and car ownership (Table 5.1). Handy (Ref 45) uses a distance-decay function to weight the opportunities (Table 5.1).

Table 5.1 – Cumulative-Opportunities Formulations

Black and Conroy (1977) (Ref 47)	$A_i(T) = O_i(T)(T - t_i)$	$O_i(T)$ = proportion of opportunities that have been passed in time T from zone i t_T = mean travel time to the opportunities from zone i
Black, Kuranami, and Rimmer (1982) (Ref 50)		1. Number of facilities per capita in each zone 2. Distance from household to nearest facility 3. Population distribution around facility
Breheny (1978) (Ref 13)	Basic data for each zone: $A_s = \sum_{j\varepsilon B} O_{jm}$, $B = \langle j\varepsilon N \mid D_{ij} \le C_k \rangle$ 1) Origin activities constant $A_q = \sum_{i\varepsilon N_l} A_s P_{it} \Big/ \sum_{i\varepsilon N_l} P_{it}$ 2) Opportunities constant $A_v = \sum_{i\varepsilon B} P_{it}$, $B = \langle i\varepsilon N_l \mid A_s \ge U_m \rangle$ 3) Cost constant $T_c = \sum_{i\varepsilon B} P_{it}$, $B = \langle i\varepsilon N_l \mid W_n \le S_{imk} \rangle$	A_s= cumulative opportunities of type m available to zone i up to cost limit k O_{jmk} = opportunities of type m available in zone j D_{ij} = cost of travel between zones i and j C_i = cost at cost limit k N = complete set of zones A_q = average number of opportunities of type m available to origins of type j in area l P_{it} = origins in zone i of type t N_t = full set of zones in area t A_v = origins in area l of type t reaching opportunities of type m up to cost limit k U_m = set level of opportunity type m T_c = origin activities in area l of type t allocated to opportunity band n of type m W_n = opportunity level at opportunity band n S_{imk} = cumulative opportunities of type m available to zone i at the set cost level k
Guy (1983) (Ref 39)	$A_i = O_i(D)\left[D - \left(\sum_{j=1}^{O_i(D)} d_{ij} \Big/ O_i(D)\right)\right]$	$O_i(D)$ = total number of opportunities available to home i within distance D from the home d_{ij} = straight-line distance between home i and opportunity j
Handy (1992) (Ref 45)	Accessibility is defined as in Eq. 5.1 and: $O_i = N_i = \sum_j \exp(-bt_{ij})$	N_i = time-discounted number of supermarkets i = origin household j = destination supermarket b = distance-decay parameter taken to equal 0.52 (calculated from local travel diaries) t_{ij} = travel time from household i to supermarket j
Hanson and Schwab (1987) (Ref 43)	$A = \sum_{n=1}^{10} \frac{R_n}{0.5n}$	R_n = number of establishments between 0.5n km and 0.5(n - 1) km from an individual's home or work
Ikhrata and Michell (1997) (Ref 1)		Measure is percent of work trips within average travel time.
McKenzie (1984) (Ref 23)	$A_{abs} = \int_0^T E(t)\,dt$ $A_{(p)} = A_{abs} \Big/ \sum_j E_j$	A_{abs} = Absolute accessibility index for zone i E = number of relevant employment opportunities that can be reached t = travel time by mode of interest T = critical travel time threshold $A_{(p)}$ = relative accessibility index for zone i E_j = number of relevant employment opportunities in zone j

Mowforth (1989) (Ref 46)	$A_{ik} = \left(\frac{E_{ik}}{\sum E_i}\right) \Big/ \left(\frac{E_{gk}}{\sum E_g}\right)$	E_{ik} = number of appropriate jobs available to individuals of employment group *k* in zone *i* $\sum E_i$ = sum of jobs of all types in zone *i* E_{gk} = number of jobs appropriate to group *k* in the whole study area $\sum E_g$ = sum of jobs of all types in the study area
Sherman, Barber, and Kondo (1974) (Ref 48)		Graph percent of population versus travel time via current and proposed transportation systems
Wachs and Kumagi (1973) (Ref 10)	$A(T)_i = \frac{1}{100} \sum_j \sum_k P_{ijk} E(T)_{ijk}$	*T* = travel time radius *j* = income category *k* = occupation category or job class P_{ijk} = proportion of workforce of zone *i* in income category *j* and occupation category *k* $E(T)_{ijk}$ = employment opportunities (in hundreds) in income category *j* and occupation category *k* within *T* minutes of zone *i*.
Weibull (1976) (Ref 18)	$A_i = \sum_{j=1}^{n} q_t(d_{ij}) \cdot E_j / e_j$ where: $e_j = \sum_{k=1}^{n} \left[p_1(d_{kj}^1) \cdot h_k^1 + p_2(d_{kj}^2) \cdot h_k^2\right]$	q_t = 1 for $d \le t$ and 0 for $d > t$ d_{ij} = travel time E_j = number of jobs in zone *j* *p* is a non-increasing function calculated from empirical data such that $p(0) = 1$ and $p(x) \to 0$ as $x \to +\infty$ *d* = travel time via auto (1) and transit (2) *h* = population in the zone of car owners (1) and non-car-owners (2)
Wickstrom (1971) (Ref 12)	$B = \sum_{i=1} P_i O_{ri}$ where: $O_{ri} = \sum_{pi} Q_{pi} \left(\sum_{m1} M_m O_{pim} \right)$	*B* = measure of balance with an optimum value of 100 P_i = proportion of regional population in zones 1 to *n* O_{ri} = ratio of actual to desired opportunities reached within a given travel time for zone *i* Q_p = relative magnitude of different trips for purpose *k* M_m = relative use of mode *m* O_{pm} = actual to desired opportunities reached in a given travel time for a purpose
Zakaria (1974) (Ref 24)	Accessibility is defined as in Eq. 5.1 and: $t = TI_a = \frac{\sum_j \sum_{i \ne j} C_{ij} x_{ij}}{\sum_{j1} \sum_{i \ne j} x_{ij}}$	TI_a = weighted travel impedance from all zones in a region C_{ij} = minimum travel impedance between zones *i* and *j* x_{ij} = trip interchanges between zones *i* and *j*

5.3 APPLICATIONS OF THE CUMULATIVE-OPPORTUNITIES ACCESSIBILITY MEASURE

Cumulative-opportunities has often been used to measure accessibility to employment (Refs 1, 44, 46) (Table 3.1). In this instance, the number of employment opportunities is used as the attraction. To evaluate impacts on different subpopulations, researchers have disaggregated the data by income (Ref 10), employment type (Ref 46), gender (Refs 46, 47), and sociodemographic parameters (Ref 43).

This measure has been used to monitor changes in accessibility due to changes in land use, the transportation system, or growth in general (Refs 47, 48). For example, Mowforth (Ref 46), using the equations in Table 5.1, shows how accessibility to employment declined in London over a decade, especially for unskilled males.

Accessibility measures have also been used as a data source for other transportation models. Allen and Perincherry (Ref 49) use a cumulative-opportunities accessibility measure in their model to derive utility equations demonstrating the effect of accessibility on vehicle availability.

The main criticism of the cumulative-opportunities measure is that there is no behavioral dimension, and near and far opportunities are treated equally (Ref 21). Weibull addresses the former issue by including a parameter related to car ownership and Handy addresses both issues with her distance-decay weighted count, as described above, and calibrated to observed travel choices (Refs 18, 45) (Table 5.1).

CHAPTER 6. GRAVITY MEASURE

6.1 THEORY AND GENERAL STRUCTURE OF THE GRAVITY MEASURE OF ACCESSIBILITY

In 1956 Carrothers discussed the use of physical mathematical relationships that could be applied to relationships between cities—specifically the gravity model of interaction (Ref 51). This well-researched paper (it references eighty-three works) includes a phrase often found in accessibility literature—the "possibility of interaction." His paper discusses an attracting force and the friction of intervening space. There are earlier applications of gravity equations to sociological situations dating from the 1930s. But Hansen (Ref 52) is the author generally credited with the earliest application of the gravity model to accessibility.

The gravity measure includes an attraction factor as well as a separation factor. While the cumulative-opportunities measure uses a discrete measure of time or distance and then counts up attractions, gravity-based measures use a continuous measure that is then used to discount opportunities with increasing time or distance from the origin. The general form of the model has an attraction factor weighted by the travel time or distance raised to some exponent.

$$A_i = \sum_j \frac{O_j}{t_{ij}^{\alpha}} \qquad \text{(Eq. 6.1)}$$

Data requirements for this measure are the size and placement of the attractions under investigation and the travel time or distance between zones in the study area.

The cumulative-opportunities model is criticized for treating opportunities equally, whether they are right at the origin of study or just inside the isochronic line determined by the time or distance parameter (although Weibull and Handy mitigate for this effect [Refs 18, 45]). Including the time or distance in the denominator of the equation, gravity-type measures provide a dampening effect that devalues attractions far from the origin.

Many researchers have explored the appropriate nature of the impedance factor of the gravity equation. As discussed in the next section, some argue for a Gaussian form that values nearby attractions highly and then falls off more quickly with distance or time. Searching for an appropriate form and value of the impedance function, many researchers find it appropriate to have different parameter values for different kinds of attractions. An example often cited is that many individuals are willing to travel farther for work than for other activities. Handy (Ref 45) empirically found a parameter for convenience shopping higher than that for comparison shopping.

6.2 ALTERNATIVE FORMS OF THE GRAVITY MEASURE OF ACCESSIBILITY

There are three main components of the gravity model that researchers model differently. These are the characterization of a zone's attractiveness, impedance measure between zones (e.g., time or distance), and the form of the impedance function.

The attractiveness of a zone can be modeled in several different ways. When assessing accessibility to employment, many researchers use the number of jobs in a zone (Refs 27, 53). For accessibility to shopping, the number of retail positions might be used (Refs 31, 32, 45) or the square footage devoted to retail sales (Ref 30).

Researchers use several methods to characterize spatial separation:

- Euclidean distances (Refs 32, 39);
- Actual network distances (Refs 33, 45, 54);
- Travel time (Refs 6, 17, 55);
- Combined measure (Refs 31, 44); and
- Perceived distance or cost (Refs 11, 30).

Lee and Goulias (Ref 33) find shortest network distances preferable to Euclidean distances in model formulation. Bhat et al. (Ref 31) argue that the travel impedance factors used should be policy sensitive in order for the model results to be useful in policy analysis and, consequently, to construct a multimodal impedance factor for their analysis (Ref 31). Levinson and Kumar (Ref 44) create a multimodal measure because they are particularly interested in mode split as a result of the addition of high occupancy vehicle lanes (in eight potential configurations).

Ingram (Ref 5) argues that the form of distance impedance should be Gaussian-centered on the origin. He claims the flatness near the origin is intuitive in that nearby activities are more attractive than those farther away. The function gradually drops off, approaching zero at infinite distance. An important parameter in the Gaussian model is the distance (from the origin) at which the function has the steepest slope. Behaviorally, this is where distance-normalized attraction decreases fastest. Lee and Goulias (Ref 33) use travel survey data to determine this value behaviorally for their research.

Researchers use various methods to determine the value of the parameter in the impedance function (Eq. 6.1). The most common form used is the exponential form. The cumulative-opportunities measure can be thought of as the case where this factor, α, equals zero. Many researchers set α equal to one (Refs 55, 56). Others use empirical data to determine a value that best describes the area under consideration (Refs 31, 45, 54).

Table 6.1 — Formulations of the Gravity Measure of Accessibility

Agyemang-Duah and Hall (1997) (Ref 55)	$A_i = \sum_{j=1}^{n} d_j \exp(-t_{ij})$	d_j = destination attractiveness t_{ij} = network travel time
Bhat, Carini, and Misra (1999) (Ref 31) and **Bhat, Pulugurta, and Govindarajan (1997)** (Ref 77)	$A_i = \left[\frac{1}{J}\sum_{j=1}^{J}\left(\frac{\log R_j}{\log H_{ij}}\right)\right]$ where: $H = (1-\theta_t)(1-\theta_w)C + \theta_t(1-\theta_w)\left(\frac{C}{1+\frac{C}{T^{\lambda}}}\right) + \theta_w(1-\theta_t)\left(\frac{C}{1+\frac{C}{W^{\mu}}}\right) + \theta_t\theta_w\left(\frac{C}{1+\frac{C}{T^{\lambda}}+\frac{C}{W^{\mu}}}\right)$	R_j = retail plus service employment in zone j (proxy for shopping opportunities) H_{ij} = composite travel impedance between zones i and j J = total number of zones in the area C = Equivalent auto in-vehicle time units = Auto IVTT + β*Auto OVTT + η*Auto Cost T (Equivalent transit in-vehicle time units) = Transit IVTT + β*Transit OVTT + η*Transit Cost W (Walk impedance) = Δ* Walk time Parameter values are obtained from mode choice modeling among motorized modes. β = 1.75 η = 0.15 Δ = 1.00 The estimated parameter values are: λ = 1.6155 μ = 0.9988
Cervero, Rood, and Appleyard (1999) (Ref 54)	Job accessibility for neighborhoods $A_i = \sum_{j,k}(p_{ik} E_{jk}) d_{ij}^{-\gamma}$ Accessibility to housing opportunities from employment centers $A_j = \sum_{j,k}(p_{jk} R_{ik}) d_{ij}^{-\gamma}$	p_{ik} = proportion of employed residents in zone i working in occupational class k, where k = 1 (executive, professional, managerial), 2 (sales, administration, clerical), 3 (services), 4 (technical), and 5 (all others, excluding noncivilian positions) E_{jk} = number of workers in zone j working in occupational class k d_{ij} = distance (in miles)-highway network distances between zonal centroids, for all i-j interzonal pairs γ = empirically derived impedance coefficient, set at –0.35 for commute trips in the San Francisco Bay Area

		P_{jk} = proportion of workers in employment center j working in occupational class k R_k = number of employed residents in residential zone i working in occupational class k
Echeverría Jadraque, Monzón de Cáceres, Pinto, and Martín Duque (1996) (Ref 17)	Absolute accessibility via transit $A_i = \sum_j \frac{D_j}{\exp(T_{ijt})}$ Relative accessibility via transit $A_i = \sum \frac{D_j}{\exp(T_t - T_g)}$	D_j = number of trips attracted by zone j on all modes T_{ijt} = overall journey time via public transit between zones i and j = $2.0{*}t_a + 1.2{*}t_e + 1.5{*}t_s + t_v$ where t_a = time in auxiliary modes (pedestrian curves) t_e = waiting time at stops (0.5* headway) t_s = alighting time t_v = time in the vehicle T_g = journey time on an ideal public transit system-straight-line connections and maximum speed
Giannopoulos and Boulougaris (1989) (Ref 57)	$A_i = \sum_j P_j \cdot F(t_{ijm})$ $F(t_{ijm}) = \frac{\sum (t_{ijm})^{-a}}{m}$	P_j = population of settlement j that lies within the "catchment area" of station i t_{ijm} = generalized time by mode m
Guy (1983) (Ref 39)	$A_i = \sum_j S_j d_{ij}^{-b}$ Gaussian form: $A_i = \sum_j S_j \exp\left[-\frac{1}{2}\left(\frac{d_{ij}}{d*}\right)^2\right]$	S_j = "size" of opportunity at j (set at 1.0 pending information about the "size" of shops) d_{ij} = Euclidean distance between home, i, and opportunity j b = constant (calculated for four intervals rising from 1.0 by intervals of 0.5) $d*$ = distance after which access to shops is "awkward"
Handy (1992) (Ref 45)	Local accessibility to commercial activity within a zone $A_i = \frac{E_j^{r,s,o}}{\exp(bt_{ij})}$ A time-discounted number of supermarkets $N_i = \sum_j \exp(-bt_{ij})$	$E^{r,s,o}$ = retail, service, and other employment in zone i t_{ij} = average intrazonal travel time b = distance-decay parameter taken to be 0.1813 (calculated using local travel diary data) i = origin household j = destination supermarket b = distance-decay parameter taken to equal 0.52 (calculated from local travel diaries) t_{ij} = travel time from household i to supermarket j
Hansen (1959) (Ref 52)	$A_i = \sum_{j \neq 1} \frac{S_j}{T_{ij}^b}$	S_j = size of activity in zone j T_{ij} = travel time between zones i and j b = exponent describing the effect of travel time between zones For accessibility to employment, b = 2.00 For accessibility to shopping, S_j = annual retail sales For accessibility to employment, S_j= number of jobs For accessibility to a residential activity, S_j = population

Knox (1978) (Ref 6)	$$A_i = \frac{B_i(t)(\%)}{M_i(\%)}100$$ $$B_i(t) = C_i\frac{B_i}{T_a} + (100 - C_i)\frac{B_i}{T_{tr}}$$ $$B_i = \sum_j\left(\frac{S_j}{D_{ij}^k}\right)$$ $$M_i = \sum_j\left(\frac{P_j}{D_{ij}^k}\right)$$	*B(t)* = zone accessibility (as calculated below) *M* = market potentials (as calculated below) For each zone, these parameters are calculated as a percentage of the highest value in the study area C_i = car-owning percentage of households in the zone *T* = average travel times for a given distance via auto (*c*) and transit (*tr*) S_j = total number of consultation hours at doctors' offices in zone *j* D_{ij} = linear distance between the centroids of zones *i* and *j* *k* = - 1.52 P_j = total population in zone *j*
Kockelman (1997) (Ref 32)	$$A_i = \sum_j\frac{Att_j}{f(t_{ij})}$$	Att_j = attractiveness of zone *j* (sales and services jobs) t_{ij} = travel time between zones *i* and *j*
Koenig (1980) (Ref 25)	$$A_i = \sum_j O_j \exp(-C_{ij}/x_o)$$	O_j = opportunities in zone *j* C_{ij} = time or cost between zones *i* and *j* x_o = distribution parameter
Lee and Goulias (1997) (Ref 33)	$$A_i = \sum_j \exp\left[(d_{ij}/d_*)^2/(-2)\right]$$	d_* = distance from zone *i* where accessibility declines most rapidly
Levinson and Kumar (1994) (Ref 44)	$$A_{mi} = \sum_j\left[f(C_{jim})\,EMP_j\right]$$ $$\overline{A}_m = \sum_i(A_{im}\,HH_i)\Big/\sum_{i=1}^{I}(HH_i)$$	A_{im} = accessibility in residential zone *i* by mode *m* $f(C_{jim})$ = friction factor between zones *i* and *j* by mode *m* EMP_j = employment in zone *j* $\overline{A}_m$ = benefit of network *1* by mode *m* (a countywide weighted average of accessibility indexes) HH_j = households in destination zone *j*
Linneker and Spence (1992) (Ref 56)	$$A_i = \frac{\sum_j P_j}{C_{ij}^a}$$	P_j = market potential of zone *j* C_{ij} = transport costs between zones *i* and *j* *a* = parameter for calibration
Tagore and Sikdar (1996) (Ref 27)	$$A_i = \frac{\sum_j S_j f(t_{ij})\exp(\gamma M_j)}{\sum_j S}$$ $$M_j = \sum_k m_j^k$$ $$m_i^k = \frac{F_i^k}{\sum_j F_j^k}$$ $$f(t_{ij}) = e^{\alpha t_{ij}}(t_{ij})^{\beta}$$	S_j = size of activity in zone *j* $f(t_{ij})$ = calibrated travel deterrence function (shown below) M_j = mobility level of zone *j* γ = coefficient of mobility to be calibrated m_i^k = normalized mobility parameter using mode *k* for zone *i* F_i^k = frequency of occurrence of parameter *k* in zone *i* t_{ij} = travel time α, β = parameters for calibration

6.3 APPLICATIONS OF THE GRAVITY MEASURE OF ACCESSIBILITY

Gravity-type accessibility measures have been used to measure access to medical facilities (Ref 6), grocery stores (Ref 45), railway stations (Ref 57), shopping (Refs 31, 33, 39) and employment (Refs 32, 52, 54, 58).

In addition to using accessibility measures to evaluate access to particular types of activities, researchers have used gravity measures to compare different transportation configurations. Zhang et al. (Ref 53) compare an existing urban situation with the situation following the addition of a proposed light-rail system. Graphical presentations of their findings show wide variations in accessibility across study areas. Other researchers also find gravity-based accessibility measures to be an effective way to track changes over time (Ref 54).

In a recent case study, Handy (Ref 45) applied gravity-based accessibility indices to two pairs of communities (old and new). However, in studying the line between local accessibility and shopping behavior, Handy found an important distinction between the minimum distance to shopping and the variety of possible shopping destinations. This distinction is masked in most forms of accessibility measures.

A variation on accessibility to employment was used by Cervero, Rood, and Appleyard (Ref 54). Instead of using the number of all jobs as the attraction, they investigate whether or not citizens have access to jobs in their income bracket. Their work also considers the local area jobs/housing mix and their changes over time (Table 6.1).

At the national level, Linneker and Spence (Ref 56) use a gravity-type accessibility measure to assess the effect of constructing a federal highway around London. They divide Great Britain into fifteen areas. A study of this magnitude obviously requires the aggregation of a large amount of data. Aggregation is an important issue in many studies. Handy (Ref 45) finds that relations seen at the aggregate level are different from those at the disaggregate level. This can have effects when interpreting accessibilities within and across regions.

Gravity-type accessibility measures are also used as inputs to other modeling projects. Kockelman (Ref 32) uses such a measure as one of three new variables she introduces to travel behavior models to explain vehicle kilometers traveled, automobile ownership, and mode choice. The introduction of accessibility is found to significantly improve performance of the models.

Several researchers criticize the ability of gravity-based accessibility measures to accurately reflect accessibility. One criticism is that many measures assign the same level of accessibility to all individuals in a zone (Ref 59), but this applies to all measures that aggregate at the zonal level. Another difficulty is highlighted by Handy and Niemeier (Ref 22) who discuss the difficulty of constructing a measure that accounts for the possibility that two people in the same place may face different levels of accessibility.

Another point of criticism is the method that some researchers uses to calibrate gravity-based accessibility measures. As mentioned earlier, several researchers found local data useful in calibrating their measures. This technique is not uncommon in other transportation-modeling situations. Agyemang-Duah and Hall (Ref 55) were successful in transferring an ordered-response model to other areas that needed limited changes to the model parameters. Their model includes a gravity-based accessibility measure as one of the variables. They found this method works reasonably well.

A final criticism is that the general form of the gravity model implies a trade-off between attraction and distance. One unit of attraction is equal to one unit of distance (Whitbread as quoted in Ref 20). However, this criticism is specific to simple forms of the gravity measure and is not relevant to general forms of the measure.

CHAPTER 7. UTILITY MEASURE

7.1 THEORY AND GENERAL STRUCTURE OF THE UTILITY MEASURE OF ACCESSIBILITY

Another approach to measure accessibility is with a utility-based measure. This type of measure is based on an individual's perceived utility for different travel choices.

The most general form of this measure is:

$$A_n = E\left[\underset{i \in C}{Max}\, U_{in}\right] = \ln \sum_{i \in C} \exp(V_{in}) \qquad \text{(Eq. 7.1)}$$

That is, for individual *n*, accessibility is defined as the expected value of the maximum of the utilities overall alternative spatial destination *i* in choice set *C*. This is called the logsum of the discrete choice model.

Ben-Akiva and Lerman (Ref 59) prove that the utility form of accessibility meets several criteria described by Weibull (Ref 19). For example, it:

- does not decrease with the addition of alternatives; and
- does not decrease if the mean of any one choice utility increases.

Ben-Akiva and Lerman also argue that because the above expression is the natural logarithm of the denominator of the multinomial logit mode choice model used in travel demand forecasting, it is often available with very little extra computation (Ref 59).

7.2 ALTERNATIVE FORMS OF THE UTILITY MEASURE OF ACCESSIBILITY

Martinez (Ref 60) considers accessibility as the change in the transport user's benefit (Δ *TUB*) as measured by market and transport costs for consumers and producers. In examining a short-run case, where transport costs are reduced, he examines the changes in benefit when the transport user travels to the activity and when the activity travels to the user. He admits that a shortcoming of his approach is the assumption of fixed prices and land use.

Table 7.1 — Formulations of the Utility Measure of Accessibility

Ben-Akiva and Lerman (1979) (Ref 59)		Their formulation of an accessibility measure based on utility theory is used for Eq. 7.1
Martínez (1995) (Ref 60)	Accessibility: $$A = \frac{-1}{\beta_{hp}} \ln\left(g_{hpti}\right)$$ Pseudo-attractiveness: $$A_{pseudo} = \frac{-1}{\beta_{hp}} \ln\left(b_{hptj}\right)$$	h = household p = purpose t = time period i = trip origin j = trip destination g, b_{htij} = balancing factors-consumer and producer surplus
Niemeier (1997) (Ref 58)	$$\Delta A = -\left(\frac{1}{\lambda}\right)\left[\ln \sum_k e^{V k}\right]_{V^1}^{V^2}$$	ΔA = compensating variation (in units of dollars) λ = marginal utility of income V = mean indirect utility k = combined mode-destination choice $V^{1,2}$ = mean indirect utility for scenarios 1, 2
Richardson and Young (1982) (Ref 61)	$$A_i = \ln 2 + \left(B_j + B_k + B_i\right) - \left(C_{ij} + C_{ik} + C_{jk}\right)$$	For the binary choice of tours i through zones j and k B = benefits of activity participation at destination C = cost of travel between two sites
Sweet (1997) (Ref 62)	$$A_{In} = \ln \sum \exp V_{in} - \ln \sum \exp V_i$$	V_{in} = residual utility that varies with both i and n V_i = utility related to intrinsic qualities of the destinations' alternative-specific constant

7.3 APPLICATIONS OF THE UTILITY MEASURE OF ACCESSIBILITY

Ben-Akiva and Lerman (Ref 59) apply their accessibility measure to models of mobility and travel. They describe "mobility" as being an overall attribute of a decision maker characterized by their employment location, residential location, auto ownership, and mode to work (Ref 59:17). Travel choices are short-term decisions of destination, mode, route, and time of day. They argue that there is a choice sequence that a decision maker goes through and use this in their modeling of travel behavior.

Richardson and Young (Ref 61) use the utility approach with a nested logit model to calculate linked-trip accessibility. They consider the binary choice of making a tour in two possible orders. Because the accessibility of a site may be its proximity to someplace other than home (for instance, work), they argue that this type of measure prevents estimation biases that may occur from only considering accessibility to one place (Table 7.1).

Niemeier (Ref 58) uses such measures to evaluate the difference in utility due to policy changes, also called “compensating variation.” This is the amount an individual would have to be compensated in order to be as well off as he or she was before the policy change. Using the marginal rate of substitution between utility and inputs, as shown in Table 7.1, Niemeier calculates trade-offs (e.g., dollars-per-minute decrease in commuting time, dollars-per-increase in job opportunities). Her analysis also shows discrepancies in benefits from increases in auto accessibility across socioeconomic groups. Niemeier also demonstrates that changes in mode have different effects on accessibility to different socioeconomic groups.

One criticism of the utility/logsum approach to measuring accessibility is that not all options are available to all individuals, and there are no natural constraints for the choice set (Ref 59). Similarly, researchers need to be aware of including irrelevant alternatives in the choice set and the consequences thereof, such as decreasing the probability of viable choices (Ref 59). And, an accessibility measure based on utility will only reflect observed behavior and not reflect the benefit of increased choices (Ref 20).

CHAPTER 8. TIME-SPACE MEASURE

8.1 THEORY AND GENERAL STRUCTURE OF THE TIME-SPACE MEASURE OF ACCESSIBILITY

Time-space measures add another dimension to the conceptual framework of accessibility corresponding to the time constraints of individuals under consideration. Early work in this area was conducted in Sweden by T. Hägerstrand (Ref 63). He used a three-dimensional prism of the space and time available to an individual for partaking in activities.

The motivation behind this approach to accessibility is that individuals have only limited time periods during which to undertake activities. As travel times increase, the size of their prisms shrink. The space dimension of this measure is calculated with the accessibility measures described in the previous chapters. Constraints on time are generally divided into three classes (Ref 63):

- capability constraints—related to the limits of human performance (e.g., people need to sleep every day);
- coupling constraints—when an individual needs to be at a particular location at a particular time (e.g., work); and
- authority constraints—higher authorities that inhibit movement or activities (e.g., park curfews).

In recognizing the time-space accessibility of individuals, trip chaining can be better evaluated (Ref 64). This approach follows a trend in trip modeling today, where modelers emphasize trip-activity packages, and not just single trips (Ref 65). Another consequence of modeling accessibility of individuals is the ability to distinguish different members of the same household who may face different levels of accessibility (Ref 66).

Results of this measure can be presented graphically with the choices available to an individual represented by an area that meets certain criteria calculated by other accessibility measures (e.g., meeting a certain level of utility, encompassing a certain number of attractions; see Table 8.1) (Ref 26).

8.2 ALTERNATIVE FORMS OF THE TIME-SPACE MEASURE OF ACCESSIBILITY

Researchers have added refinements to the general measure outlined above. Hall (Ref 67) advocates the use of expected travel time to determine the appropriate prism size. He argues that allowance for uncertainty is a behaviorally appropriate addition to the traditional time-space models. Miller (Ref 26) adds to the types of measures developed above, a time element that is the boundary of the time-space prism. Therefore, his measure (Table 8.1) A_1 calculates the utility within a time-space prism for an individual. His measure A_2 calculates the benefits associated with the activities available within a time-space prism for an individual (Table 8.1).

Table 8.1 – Formulations of the Time-Space Measure of Accessibility

Kwan (1998) (Ref 66)	$A_g = \sum W_i I(i)$ $I(k) = \{1 \; if \; k \in FOS, 0 \; otherwise$	W_j = weighted area of location j 1. Summation of opportunities in the feasible opportunity set (FOS) 2. Weighted sum of opportunities in the FOS = A_g 3. Length of network arcs in the daily potential path area
Miller (1999) (Ref 26)	$A_1 = \frac{1}{\lambda} \ln \sum_{k=1}^{m} \exp\left(a_k^{\alpha} T_k^{\beta} \exp(-\lambda t_k)\right)$ $A_2 = \sum_{k=1}^{m} b_k$ where: $b_k = 0 \; if \; a_k = 0 \; or \; T_k \leq 0$ $\exp\left[\lambda\left(\frac{\alpha}{\lambda} \ln a_k + \frac{\beta}{\lambda} \ln T_k - t_k\right)\right]$ otherwise $A_3 = \max_{\{k\}} [b_k]$	A = accessibility measure a_k = attraction of activity location $T_k = f(t)$ = time available for activity participation t = travel time required m = number of flexible activities b_k = benefit α, β, λ = parameters ≥ 0
Wang and Timmermans (1996) (Ref 64)	$A_{hp} = \ln\left[\sum_{i=1}^{m_{hp}} \exp(U_i)\right]$	A_{hp} = accessibility of people with activity program p, living in household h m_{ph} = number of alternative schedules to implement program p A_h = overall accessibility of people with different activity programs in household h

	$A_h = \sum_{p=1}^{P} A_{hp}$ $A_p = \{\sum_{h=1}^{H} A_{hp}\} \Big/ H$ Accessibility of locations $A_{whp} = \ln\left[\sum_{i=1}^{m_{whp}} \exp(U_i)\right]$ $A_{wp} = \sum_{h=1}^{H} \ln\left[\sum_{i=1}^{m_{wh}} \exp(U_i)\right]$ $A_w = \sum_{p=1}^{P} \sum_{h=1}^{H} A_{whp}$	A_p = average accessibility of people having the same activity program, but living in different households A_{whp} = accessibility of workplace w to people with activity program p, living in household h A_{wp} = overall accessibility of workplace w to people with same activity program and different households A_w = overall accessibility of workplace w to people with different activity programs and different households

8.3 APPLICATIONS OF THE TIME-SPACE MEASURE OF ACCESSIBILITY

Burns (Ref 68) uses a time-space accessibility measure in order to evaluate multiple case studies. Several of these involve the effects of changes in the transportation system and in attractions on accessibility for individuals. Others have considered the effect of discounting distance (in a gravity-type of application) and the effect of clustering activities. One conclusion from Burns' work is the importance of temporal strategies (such as flex-time) over velocity strategies (such as increasing road speeds) in increasing accessibility (Ref 68). Similarly, Hall (Ref 67) finds an optimal size of clustered activities. This is based on the type of attraction and applies primarily to hard-to-locate items.

Because this method depends heavily on technology, new solutions are being developed all the time. For example, Lee and McNally (Ref 69) find that more and more geocoded databases are available with relevant information, electronic versions of the yellow pages are becoming more available, and geographic information systems can be coded to perform algorithms that reduce program complexity.

The main criticism of space-time measures is that, owing to a high level of disaggregation, they are difficult to aggregate (Refs 21, 26), and it is difficult to look at the effects of changes on the larger scale, such as in land use and the transportation system (Refs 21, 68). For example, a difficult parameter to determine is the time limit for individuals in a zone.

CHAPTER 9. EMPIRICAL COMPARISONS

Instead of discussing theoretical benefits of different types of accessibility measures, some researchers have applied different measures in order to compare the results. One researcher cautions that different measures can lead to different conclusions (Ref 39). This approach highlights the statement that "different situations and purposes demand different approaches" (Ref 22: 1181).

In order to compare different accessibility measures, Guy (Ref 39) normalizes each type of measure and then compares them (Table 9.1). For the gravity measures, he uses several different values of the exponent. In comparing several measures of one point in time, strong correlation was found. In the dynamic case, considering measures across time, mean accessibility values followed the trend being evaluated (the loss of shopping opportunities in the area), but the median accessibility values were inconsistent. Guy also pays special attention to extremes in the data (e.g., the 10th percentile case) to examine how the different accessibility measures characterize their situation.

In another research project, Koenig (Ref 25) partitions his data by two levels of car availability and three age groups. He then evaluates changes in accessibility to these groups, based on two proposed road projects. In computing his A_i and U_i measures (Table 9.1), he finds good convergence between the two. He attributes this to the similarity of the variables.

A comprehensive comparison of accessibility measures was conducted by Kwan (Ref 66) using twelve gravity-type measures, six cumulative-opportunity measures, and twelve space-time measures. The twelve gravity-type measures are further broken down into three types of impedance functions: inverse power, negative exponential, and modified Gaussian. The twelve time-space measures are divided by gender, as shown in Table 9.1. Based on a sample of travel diary information, research data are partitioned further on the basis of tour lengths (short and long). Accessibility is then measured by the number of opportunities or by a weighted area.

Kwan (Ref 66) finds the gravity and cumulative-opportunity measures to generally have good correlation with each other and poor correlation with the space-time measures.

The different accessibility measures also are compared in terms of the three-dimensional surfaces they imply for the study area. Gravity and cumulative-opportunity measures produce distinctive spatial patterns, while the space-time contours are "somewhat haphazard" (Ref 66: 208). The different impedance functions used in the different measures primarily affect the size of peaks and troughs.

Song (Ref 70) looks at nine different accessibility measures to explain population densities, as shown in Table 9.1. Statistical, non-nested testing is conducted to find a measure with the best explanatory power. Of the types of measures tested (i.e., distance to CBD, gravity, cumulative opportunities, and network distance), gravity measures were found to best explain the data.

Table 9.1 — Formulations from Empirical Comparison Research

Guy (1983) (Ref 39)	$A_i = \sum_j S_j d_{ij}^{-b}$ The Gaussian form: $A_i = \sum_j S_j \exp\left[-\frac{1}{2}\left(\frac{d_{ij}}{d*}\right)^2\right]$ $A_i = \sum_k d_{ij(k)} E_k \Big/ \sum_k E_k$ $A_i = O_i(D)\left[D - \left(\sum_{j=1}^{O_i(D)} d_{ij} \Big/ O_i(D)\right)\right]$	S_j = "size" of opportunity at j (set at 1.0 pending information about the "size" of shops) d_{ij} = straight-line distance between home, i, and opportunity j b = constant (calculated for four intervals rising from 1.0 by intervals of 0.5) d_* = distance after which access to shops is "awkward" $d_{ij(k)}$ = Euclidean distance to a shop j in which good k is available E_k = mean expenditure per household on good k $O_i(D)$ = total number of opportunities available to home i within distance D from the home d_{ij} = straight-line distance between home i and opportunity j
Koenig (1980) (Ref 25)	$A_{gravity} = \sum_j O_j \exp(-C_{ij}/x_o)$ $A_{utility} = x_o \log \frac{A_i}{A_o}$	O_j = opportunities of type under consideration in zone j C_{ij} = time or cost for trip from i to j x_o = distribution parameter

	$$A_{cum-opp} = \sum_j O_{ij}$$ where: $$C_{ij}^m = k^m t_{ij}^m + \frac{1}{vot} c_{ij}^m$$	A_o = reference value k^m = discomfort associated with mode m by the group considered t_{ij}^m = travel time from i to j by mode m vot = value of time of group considered c_{ij}^m = travel cost from i to j by mode m
Kwan (1998) (Ref 66)	Gravity-type, inverse power $$A_i = \sum W_j d_{ij}^{-\alpha}$$ Gravity-type, exponential $$A_i = \sum_j W_j e^{-\beta d_{ij}}$$ Gravity-type, Gaussian $$A_i = \sum_j W_j e^{-d_{ij}^2 / \nu}$$ Cumulative opportunity, rectangular $$A_i = \sum W_j f(d_{ij})$$ Cumulative opportunity, negative linear $$A_i = \sum W_j f(d_{ij})$$	Weighted average of opportunities based on building height W_j = weighted area of location j d_{ij} = travel time in minutes between locations i and j α = 0.8, 1.0, 1.5, 2.0 β = 0.12, 0.15, 0.22, 0.45 ν = 10, 40, 100, 180 $f(d_{ij})$ = 1 for $d_{ij} \le$ T ; 0 otherwise $f(d_{ij})$ = (1-t/T) for $d_{ij} \le$ T ; 0 otherwise T = 20, 30, 40
Song (1996) (Ref 70)	$$A_i = \frac{\sum_{j \ne i} E_j d_{ij}^{-1}}{E}$$ $$A_i = \frac{\sum_{j \ne i} E_j d_{ij}^{-\lambda}}{E}$$ $$A_i = \frac{\sum_{j \ne i} E_j e^{-\lambda d_{ij}}}{E}$$	E = total employment in region d_{ij} = distance between two points $\overline{d}_i$ = average distance measures WAD = weighted average distance (note: distance to the CBD was also used as a measure)

Song (1996) (Ref 70) (continued)	$$A_i = \frac{\sum_{j \neq i} E_j e^{-\lambda d_{ij}^2}}{E}$$ $$A_i = \frac{\sum_{d_{ij} \leq d_o} E_j}{E}$$ $$\bar{d}_i = \frac{\sum_{j \neq i} d_{ij}}{n-1}$$ $$WAD_i = \frac{\sum_{j \neq i} E_j d_{ij}}{\sum_{i \neq j} E_j}$$	

CHAPTER 10. APPLICATION OF ACCESSIBILITY MEASURES

At the case-study level, accessibility measures have been used to characterize the potential impacts of transportation projects, track changes in accessibility over time, unite the effects of land use and the transportation system, illustrate differences in various land use patterns, and highlight discrepancies between population groups (Refs 10, 22, 42, 46). Such case-study applications were discussed in the various sections above. This section concentrates on applications for planning and the use of factor analysis to indicate the importance of accessibility in transportation modeling.

10.1 APPLICATIONS ABROAD

In the United Kingdom the motivation for developing an accessibility measure comes from implementation of Local Agenda 21. After the 1992 United Nations-sponsored Earth Summit, several nations adopted policies to promote sustainability. In the U.K., the policy affecting accessibility is Planning Policy Guidance Note 13 (PPG13) on Transport:

> 4.23 Local authorities should establish 'accessibility profiles' for public transport in order to determine those sites which could meet the policy goals set out in this guidance. These accessibility profiles should relate both to access to public transport from housing and access from public transport to employment and other destination. The profiles should reflect the catchment area served and the likely quality of service. (Ref 15)

In response to the ensuing demand for "accessibility profiles," a private consultant developed a GIS-based program called ACCMAP to evaluate projects and identify areas with high and low accessibility (Ref 16). This program uses several different accessibility measures, including gravity and cumulative opportunities, and then graphically shows the net change in accessibility due to proposed changes.

In the Netherlands, there are three main policy areas where accessibility is being used as a tool in:

- influencing mode choice;
- facilitating the ability to participate in nonwork activities; and
- characterizing conditions for economic growth (Ref 14).

Researchers conclude that these different situations require different types of accessibility measures. In the case of sitting businesses and services, mobility profiles of companies are matched with accessibility profiles of locations. Locations are rated as the following: A—highly accessible to public transport; Al-reasonably accessible by public transport and poorly accessible by car; B—accessible to both public transport and by car; C—accessible by car; and R—poorly accessible by both public transport and car (Refs 8, 71). These accessibility measures are derived primarily by proximity to public transport stops, urban arterial roads, and highway exit ramps.

Using eleven company types, researchers looked at several Dutch cities to categorize the employed population by the above rating system. They found relatively few jobs located at A/Al type sites (Ref 8). They then proposed two policy strategies—improving infrastructure for companies at their current locations and implementation of land use planning for new companies. The researchers anticipate public criticism for regulating the location of companies.

In Ibrid, Jordan, a strictly qualitative, graphic accessibility assessment was conducted for several types of public facilities (Ref 72). The region of service was determined for several public facilities (schools, health centers, fire stations, libraries, post offices, police stations, mosques, and public transport) and circles were drawn around the different sources. Areas with substantial overlap were highly accessible, and areas with little or no coverage were under-served. For some types of facilities, they found that there were a sufficient number of services, based on per capita need, but they were not distributed in a way that served the whole community.

10.2 APPLICATIONS IN THE UNITED STATES

Accessibility measures are seeing increased use in United States transportation planning. Locally, planning organizations are required by the Intermodal Surface Transportation Efficiency Act of 1991 to develop pertinent performance measures of accessibility (Ref 73). One organization describes this as looking at the transportation system from the perspective of the users (Ref 1). Accessibility is described as a type of measure that provides “the closest linkage to the ultimate purpose of the transportation system” (Ref 73: 61).

In practice, cumulative-opportunity measures are the most prevalent. Southern California (Ref 1), Albany, New York (Ref 73), and Florida are using an accessibility-to-employment measure to evaluate transportation projects. Minnesota is using a variation that measures what proportion of the population has more than one mode choice (Ref 73).

Southern California Association of Governments chose a measure that could be used with available data. It is one of several new performance measures for evaluating transportation systems from a user’s perspective. Limitations of this measure include counting of work-based trips of zero time (work at home) which may skew results.

Finally, the Oregon Transportation Plan includes policies regarding accessibility but little guidance. Out of concern that accessibility measures may “double count” other parameters of the transportation system, the minimum interpretation of the policy guidance is being followed (Ref 74).

10.3 FACTOR ANALYSIS

The method of factor analysis takes a completely different approach to the characterization of accessibility. Researchers use this technique to show how accessibility affects travel behavior (Refs 75, 76) and to include spatial interaction in trip modeling (Ref 76). Accessibility-type variables are added to traditional trip modeling. These variables may be the number of attractions, a Shimbel Index (discussed in Chapter 4), or the time or distance to the CBD (Ref 76). After a model is run, factor analysis techniques are used to determine the “natural” grouping of variables and determine their explanatory power in the final model.

Ma and Goulias (Ref 75) partition their data by different types of travelers and find that not all accessibility measures affect every group equally. Vickerman (Ref 76) cautions that there may be a correlation between accessibility measures and other variables that reflect urban structure.

CHAPTER 11. CONCLUSIONS

Because the goal of this project is the development of a measure that is disaggregated by mode, time of day, trip purpose, and spatial area, use of these parameters in the accessibility literature is of particular interest. Although no previous studies have aimed for as comprehensive and ambitious an approach to measuring accessibility as the one proposed in this study, they do provide important insights for this research. Lessons learned from this review can be grouped into two areas: theory and implementation.

11.1 THEORIES BEHIND ACCESSIBILITY MEASURES

Accessibility is a way to characterize the ease of reaching activities. That ease is determined by a combination of the transportation system, which determines the physical connections between activities, and land use patterns, which determine the locations and intensity of activities. Most researchers agree that any accessibility measure should reflect changes in both the transportation system and land use patterns.

Researchers also agree on several other characteristics of accessibility measures. A basic set of criteria were first put forth by Weibull in 1976. These criteria are:

- the order of opportunities should not affect the value of the measure;
- the measure should not increase with increasing distances or decrease with increasing attractions; and
- opportunities with zero value should not contribute to the measure.

Another well-supported criterion for an accessibility measure is that introduction of a new mode should not decrease the accessibility of an area (Ref 28); some argue that the introduction of a new mode, and thus a new choice for travelers, should always increase accessibility.

Researchers also generally agree that accessibility measures should have a behavioral basis, although there is not always agreement on exactly what this basis must be. More sophisticated measures are structurally consistent with travel choice theory, but even the most simple measures can be calibrated to observed patterns of travel. However, some researchers raise the question of the appropriateness of relying on revealed travel behavior as a basis for accessibility measures, given that such behavior is constrained by the available choices and may not be indicative of preferences and desires. Practical considerations often come into play in the resolution of these alternative approaches; technical feasibility and the need for ease of interpretation, for example, may necessitate the use of measures less directly reflective of travel behavior theory.

Under the basic criteria outlined above, the graph theory and spatial separation approach to measuring accessibility are inadequate for the purpose of this project for two reasons. One weakness is their inability to account for land use patterns. Without an element of attraction, these measures are more accurately characterized as mobility measures rather than accessibility measures. Secondly, an increase in choices, either of attractions or travel modes, does not increase the level of accessibility. Therefore, on theoretical grounds, graph theory and spatial separation measures are problematic for this project. The other forms of accessibility measures-cumulative-opportunities, gravity, and utility measures-generally meet these criteria.

11.2 IMPLEMENTATION OF AN ACCESSIBILITY MEASURE

Differences among the accessibility measures used by researchers derive at least partly from differences in the purposes for which the measures are used. Many researchers have studied the influence of accessibility on individual and household transportation patterns and agree that accessibility is an important variable in transportation modeling (Refs 22, 32, 34, 35, 77). Accessibility measures also have been used frequently in models that predict the impact of transportation investments on development and in industrial and residential location choice models (Refs 14, 16, 71, 78). Accessibility measures have been (and are increasingly) used to study equity of access to jobs and basic services between different segments of the population (Refs 10, 50, 79). Although the concept of accessibility employed in different studies may be essentially the same, the operationalization of the accessibility measure may vary in ways appropriate to the specific application.

Wilson (Ref 30) outlines several questions that need to be answered before an accessibility measure can be developed, and practical as well as theoretical considerations generally dictate the answers to these questions. His questions are the following:

- What is the degree and type of disaggregation desired?
- How are origins and destinations defined?
- How is attraction measured?
- How is impedance measured?

The generic form of the cumulative-opportunity measure counts how many attractions are available within a certain travel time or distance. In this case, there is no distinction between attractions near to and far from the origin under consideration. To address this shortcoming, researchers have made refinements in a variety of ways. Black and Conroy (Ref 47) use the area under the cumulative-opportunities curve as the accessibility measure. Weibull (Ref 18) weighs attractions by the number of jobs in a zone and a demand potential (Table 5.1). Handy also develops a measure that is somewhere between a cumulative-opportunities measure and a gravity measure—she sums impedances without an explicit attraction factor. Many researchers find cumulative opportunities an effective measure for evaluating accessibility for a particular trip purpose or for a particular population subgroup (Refs 1, 10, 43, 44, 46, 47). Advantages of such forms include ease of interpretation and limited data requirements; disadvantages include the lack of an explicit behavioral basis.

Gravity measures explicitly weight attractions with travel time or impedance functions that give less weight to more distant attractions. The parameters used in these models can vary widely (Table 6.1). Several researchers discuss the characterization of the impedance function. Behaviorally, a Gaussian-type decay is preferred-this gives an advantage to near attractions and quickly falls off with travel cost (Refs 5, 33). Calibration of the steepest change in the slope is determined empirically.

The literature's discussion of the characterization of attractiveness is more limited. The gravity measure is typically applied at the zonal level, an approach that assigns a uniform attractiveness to a zone and the same accessibility to all the individuals within it (Ref 59). Although gravity measures are less easy to interpret and generally require more data than cumulative-opportunities measures, they also overcome many of the cumulative-opportunities measures' limitations.

An alternative to these measures is a utility or logsum accessibility value. Based on microeconomic theory, these measures evaluate accessibility at the individual (or household) level and assumes that individuals will choose options to maximize their well-being. This approach offers a more sophisticated and theoretically sound treatment of travel behavior by using observed travel choices to accurately value impedance and attractiveness factors. In addition, these models easily incorporate socioeconomic variables to reflect differences between individuals in the valuation of these factors. Niemeier (Ref 58) argues that the dollar value of change in utility is an appropriate way to introduce accessibility into cost-benefit analyses. Utility measures require more detailed data, but are directly derived from travel behavior theory.

Empirical comparisons of accessibility measures are mixed as to the consistency of results between different forms of measures applied to the same data. One researcher found good correlation between the measures used (Ref 25), another found correlation among some measures and not others (Ref 66), and a third found poor correlation (Ref 39). This points to the need for having a clear definition of the use of a measure prior to its construction. A clear understanding of the research objectives is also important.

No previous studies have accomplished—or even attempted—what this study has set out to do, namely, to develop disaggregate measures of accessibility along four dimensions (mode, time of day, activity type, spatial detail) and a methodology for aggregating along any one or combination of these dimensions for use in transportation planning at the local, regional, and state levels. Work previously done on accessibility measures will provide a sound basis for the work attempted in this study.

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APPENDIX A – ABSTRACTS FROM LITERATURE REVIEW

Theories and Overviews

Bach, L., 1981, "The Problem of Aggregation and Distance for Analyses of Accessibility and Access Opportunity in Location-Allocation Models," *Environment and Planning A*, 13, 955–978.

(Author's abstract) The acceptability of information stemming from analyses of accessibility and access opportunity for social, educational, and cultural infrastructure facilities largely depends on two factors: exactness and efficiency. Both of these factors are influenced by the databases available for the analyses. This paper will focus on the problem of data requirements for spatial distributions of demand as well as on data requirements for spatial distances with respect to the exactness of the results of analyses and on the efficiency of preparing analyses. The effects of different levels of aggregation and of different types of distance measures are investigated. (37 Refs)

Ewing, R., 1995, "Measuring Transportation Performance," *Transportation Quarterly*, 49(1), 9–104.

The land use-transportation system is just that-a system-but it is seldom planned or managed as such. Instead, roads are viewed in isolation, and system performance is measured by levels of service on individual roadways. Operating speed becomes the essential element in transportation planning. The emphasis on speed encourages excess travel and contributes to urban sprawl, undermining society's environmental, energy, and growth management goals. In Florida and Washington state, the search is on for better ways to measure transportation system performance. Adding impetus is the neotraditional planning movement, which has rejected speed as the ultimate measure of performance but only hinted at what might replace it. A paradigm shift in performance measurement-from speed to personal mobility, accessibility, livability, and sustainability-is argued. Alternative performance measures used around the United States are identified and assessed preliminarily. Growth management systems of the future will almost certainly rely on multiple measures, not discarding speed but giving weight to other considerations as well. (32 Refs)

Hanson, S., 1986, "Dimensions of the Urban Transportation Problem," *The Geography of Urban Transportation*, ed. Hanson S., The Guilford Press, New York, 3–23.

The author discusses the difference between accessibility and mobility. She also discusses the importance of an accessibility measure to quantify the change in accessibility over time and the potential change from the implementation of a transportation project. The difference between accessibility of places and accessibility of people and the different implications are clearly noted. A few samples of accessibility are given using a gravity measure: Uppsala, Sweden and Milwaukee, Wisconsin. The author then generally discusses factors affecting urban travel and the policy implications of having an accessibility measure. (20 Refs)

Hazel, G. M., 1988, "The Development of a Disaggregate Trip Generation Model for the Strategic Planning Control of Large Foodstores. 2. Measuring Accessibility and Designing the Trip Generation Model," *Traffic Engineering and Control*, 29(2), 95–103.

(Author's abstract) This paper begins by examining the effect of accessibility on the generation and distribution of private-car trips to large foodstores. This is seen as comprising two parts that have been entitled personal accessibility and spatial accessibility. The latter term is made up of two factors, an attraction factor and a spatial deterrence factor. It is argued that personal accessibility relates to the shopping trip rate of the household and should be contained within the trip generation model while spatial accessibility is contained within the distribution model.

The personal accessibility term is subdivided into three factors: the availability of the car, the availability of the household shopper and the availability of the store. The size of the time period when all three coincide is a measure of the personal accessibility of the household to carry out this type of shopping. This concept of shopping accessibility is combined with the theoretical postulates developed from consumer behavior to formulate the conceptual framework of the study. (38 Refs)

Hilbers, H. D., and Verroen, E. J., 1993, "Measuring Accessibility, A Key Factor for Successful Transport and Land-Use Planning Strategies," *Environmental Issues: Proceedings of Seminar A* held at the PTRC European Transport, Highways and Planning 21st Summer Annual Meeting, P363.

(Author's abstract) The evaluation of the accessibility of a location is highly related to the objectives that have to be achieved. In this study of INRO-TNO, a classification of methods for analyzing accessibility is elaborated for three important policy goals in transport planning: stimulating economic growth, influencing mode choice and safeguarding conditions for personal development. On the basis of this, the four most promising methods are worked out: access characteristics (for instanced circles around railway stations), methods based on graph theory, potential accessibility (for instance number of accessible jobs within a certain maximum travel time) and actual accessibility (for instance the percentage of trips with high quality alternatives for car use). The case studies that are carried out with these four methods underline the importance of selecting the most appropriate method for the policy question at hand. The methods developed in this study can support an effective integration of land-use and transport planning. (15 Refs)

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

(Author's abstract) Both perceptual and measurable specifications of accessibility are reviewed and their relevance to transport planning established. The wide variety of analytical forms that can be used to quantify different aspects of accessibility are categorized and grouped by conceptual basis. The different forms of accessibility index are then related to underlying theories which link consumer demand, evaluation and accessibility. (76 Refs)

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

(Author's abstract) An attempt is made to clarify some of the confusion about the notion of accessibility by examining the limitations, strengths, and conceptual bases of distance, topological, gravity, and cumulative-opportunity measures of accessibility. In their aggregate and disaggregate states the measures are practical, enabling measurement into the future and measurement with a minimum of data, but the assumption that all nodes are potential destinations and that all origins are known severely restrict the meaning and use of the measures. Time-space measures of accessibility do not make these assumptions although they are data hungry, retrospective, and share with the other measures the narrow conception of accessibility as a property of the built environment. It is proposed that accessibility be thought of as a vacancy in an activity routine and that it be measured in terms of the disruption involved in creating it. (52 Refs)

Pooler, J. A., 1995, "The Use of Spatial Separation in the Measurement of Transportation Accessibility," *Transportation Research A*, 29A(6), 421–427.

(Author's abstract) In a recent article, Allen *et al.* (1993) introduce what they call a new transportation accessibility measure. The present paper raises some questions about the history of the measure and its novelty. It is argued that accessibility indices have a longer history than the authors suggest and that the proposed index of accessibility, being the average distance among a set of locations, is neither new, nor worthy of the claims made for it. In addition, some questions are raised about the associated empirical results. (60 Refs)

Voges, E. M., and Naudé, A. H., 1983, "Accessibility in Urban Areas: An Overview of Different Indicators," Technical Report RT/21/83, National Institute for Transport and Road Research, CSIR, South Africa.

(Author's abstract) The purpose of this report is to review and evaluate different measures of accessibility, with a view to suggesting methods for evaluating the planning of land use-transport systems, and the spatial pattern of supply of community facilities and employment opportunities. The main body of the report consists of a literature study of different measures such as cumulative opportunity -, network -, gravity -, utility -, and time-space type formulations. The advantages and disadvantages of each are discussed and evaluated against operational and theoretical criteria. (30 Refs)

Weibull, J. W., 1976, "An Axiomatic Approach to the Measurement of Accessibility," *Regional Science and Urban Economics*, 6, 357–379.

(Author's abstract) In this paper an axiomatic approach is developed for the task of measuring accessibility. The general mathematical form of a measure satisfying the postulated axioms is derived. This class of measure contains as a sub-class the so-called gravity potentials. A measure of the accessibility to employment opportunities is presented with applications to the Stockholm region. Finally some ideas on further development of accessibility measures are discussed. (11 Refs)

Weibull, J. W., 1980, "On the Numerical Measurement of Accessibility," *Environment and Planning A*, 12, 53–67.

(Author's abstract) The aim of this paper is to clarify the validity of a fairly broad range of numerical indicators of accessibility. To this purpose a measurement-theoretic framework is presented, where accessibility is considered as a property of configurations of opportunities for spatial interaction. Within this framework, a few established indicators of accessibility are discussed and notions of separable, additive and maxitive indicators are introduced. An analysis is given of the validity of numerical indicators in general and of separable, additive and maxitive indicators in particular. (22 Refs – accessibility, 10 Refs – measurement)

Spatial Separation Models

Allen, W. B., Liu, D., and Singer, S., 1993, "Accessibility Measures of U.S. Metropolitan Areas," *Transportation Research B*, 27B, 439–449.

(Author's abstract) This paper constructs an accessibility index that captures the overall transportation access levels of an area. This index is formulated as a natural extension of the existing relative and integral accessibility measures. Theoretical modeling and empirical tests demonstrate that the index has a convergence property and can be calculated accurately without incurring very high costs. Regression analyses show that the index captures the overall accessibility levels of areas very well. Using this index, the overall access levels of the sixty largest U.S. metropolitan areas are calculated. (19 Refs) [For critique, see Pooler.]

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

(Author's abstract) The measurement of physical separation between the zones of a sub-divided study area is a common necessity in regional analysis. It is obligatory when the concept of accessibility is intrinsic to the analysis and on these occasions distance is commonly used as the unity of physical separation. Whilst an air line distance matrix might prove suitable at the regional scale, it is necessary to use more sophisticated measures when working at the urban scale because physical constraints play a dominant role in dictating the actual separation between zones. This paper presents a method of arriving at an accurate distance matrix at the urban scale using abstract network patterns incorporating the geographical constraints. This obviates the need for expensive digitization and analysis of the road network as a pre-requisite in the compilation of the distance matrix. (9 Refs)

Dupuy, G., and Stransky, V., 1996, "Cities and Highway Networks in Europe," *Journal of Transport Geography*, 4(2), 107–121.

(Author's abstract) The highway system — a communications network on a national or international scale *par excellence* — is here examined in light of the relationships that it makes possible between cities (or poles) of European significance. The 'rank' of each of these cities, in terms of accessibility to the other poles, can be calculated mathematically and a hierarchy of these cities can thus be established. While the position of a given city within this hierarchy is linked to physical and human geography (natural barriers in the first case; boundary effects, extremely variable density according to country and region in the second), it is also linked to the characteristics (especially topological) of the national highway systems. (27 Refs)

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

(Author's abstract) The importance of the concept of accessibility in the literature of urban studies requires that a method be found of describing quantitatively the accessibility at a point. The paper is concerned with, firstly, a set of definitions related to the concept of accessibility. A distinction is made between the relative accessibility between two points and the integral, or total, accessibility at a point. Secondly, various operational forms of these definitions are illustrated with reference to the Hamilton, Ontario, urban area. The derivation of the various measures that are developed is discussed. A measure based on the normal, or Gaussian curve is recommended as the most suitable for determining the integral accessibility at a given point. (12 Refs)

Kirby, H. R., 1976, "Accessibility Indices for Abstract Road Networks," *Regional Studies*, 10, 479–482.

(Author's abstract) A measure of the accessibility of a point to other points in a region is the average over-the-road distance. Baxter and Lenzi (1975) examined the variation of such an index with the distance of the point from the town center, for certain hypothetical road networks in a circular town. However, for a square grid network, they considered only the special case of a point on a road through the town center. The object of this paper is to give results applicable to the general case, for a variety of homogeneous grid networks. It is shown that the appropriate result is obtained by multiplying the accessibility index for direct (air line) routing by the route factor for the network concerned. (7 Refs)

Leake, G. R., and Huzayyin, A. S., 1979, "Accessibility Measures and Their Suitability for Use in Trip Generation Models," *Traffic Engineering and Control*, 20(12), 566 – 572.

The authors are interested in developing an accessibility measure that reflects changes in the transport network and consequently in trip generation. Accessibility measures used in the past and their weaknesses are discussed. Requirements for an accessibility measure in general and for one that would fit into trip generation models are outlined. A suite of measures for public, private, and "all mode" accessibility are developed and evaluated. The authors conclude that for certain trip types the inclusion of an accessibility measure into the trip production model improves its explanatory power. (23 Refs)

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

(Quoted from the author's paper) The objective of the following study is to provide a comprehensive measure and evaluation of [transportation costs as location determinant], intraurban network accessibility. The derivation of the accessibility index consists of three analytical phases. The first phase uses finite graph theory to define the geometric structure of the test networks [Indianapolis and Columbus]. The second phase utilizes flow analysis to provide dynamic criteria of network accessibility. The third phase employs principal components analysis to group variables generated in phases one and two, and to identify spatial regularities in the accessibility pattern. (14 Refs)

Savigear, F., 1967, "A Quantitative Measure of Accessibility," *Town Planning Review*, 38, 64–72.

This paper uses the inverse of the weighted mean average travel time between zones as measure of accessibility (weighted with respect to travel demand to a zone). The author discusses factors that influence accessibility such as zone size and time of day. The author seems to be particularly interested in the effect of parking availability on accessibility but after much discussion concludes there are insufficient data to include it in a measure. Using origin-destination and travel time data an accessibility measure for Oxford, England, is calculated for the existing network alone and with proposed changes. (8 Refs)

Cumulative-Opportunities Models

Allen, Jr., W. G., and Perincherry, V., 1996, "Two-Stage Vehicle Availability Model," *Transportation Research Record 1556*, 16–21.

(Author's abstract) It is well accepted that travel forecasting models benefit from the stratification of travel markets by socioeconomic levels. The number of vehicles available is a key indicator of that level. The number of vehicles available is a key indicator of that level. Using this variable requires that the proportion of households by vehicles available be forecast for each zone. An improved submodel for forecasting vehicle availability by incorporating transit accessibility and land use indicators along with the usual demographic variables is described. This model uses a two-stage approach. The first stage is similar to many other models in current use. In the first step, a lookup table is used to identify an initial estimate of the proportion of 0-vehicle, 1-vehicle, 2-vehicle, and 3+-vehicle household on the basis on the household's size (1-4+), number of workers (0-3+), and income quartile (1-4). This lookup table has 52 cells, with each cell containing the four proportions by vehicles available. Census Public Use Microdata Sample data were used to create this lookup table. The second stage applies an incremental logit model to the initial proportions. In this step, the effects of transit accessibility and land use form on vehicle availability are modeled. Accessibility and density measures are used to calculate a "disutility" measure, which is then used to modify the initial percentages. Good transit service and high development density are associated with lower vehicle ownership. Vehicle availability models of this type recently have been successfully calibrated for the Washington, D.C., and Seattle, Washington, areas. (7 Refs)

Black, J., and Conroy, M., 1977, "Accessibility Measures and the Social Evaluation of Urban Structure," *Environment and Planning A*, 9, 1013 - 1031.

(Author's abstract) The measurement of accessibility and travel patterns in urban areas is described. The methodology presented includes graphical measures of physical accessibility, a numerical index of accessibility that is consistent with graphical measures, residents' accessibility weighted by transport availability and travel behavior. Some empirical results are presented for access and travel to male and female jobs in Sydney, with the use of data collected for the 1971 Census of Population and for the Sydney Area

Transportation Study. The consequences of some alternative arrangements of land use and plans to improve public transport on residents' accessibility are investigated. It is argued that accessibility measures are a useful aid to planners and policymakers in the social evaluation of urban structure. (21 Refs and appendix)

Black, J. A., Kuranami, C., and Rimmer, P. J., 1982, "Macroaccessibility and Mesoaccessibility: A Case Study of Sapporo, Japan," *Environment and Planning A*, 14, 1355–1376.

(Author's abstract) Accessibility measures are presented which provide a means of understanding the internal spatial structure of radically different urban forms and of assessing the impact on residents of land-use and transport policies. It discusses the results of the application to Sapporo in Japan of a set of measures intended for the comparison of accessibility patterns between, within, and across cities in the Pacific Rim countries. After detailing an appropriate conceptual framework attention is focused on measuring the opportunities various groups have of participating in urban activities. Mesoaccessibility and macroaccessibility measures are both used for this purpose. First, Sapporo is put into its regional and national context. Then the mesoaccessibility measures are presented as a means of understanding the local area impact of national and metropolitan level policies. Macroaccessibility measures are illustrated with specific reference to the labour market in 1975 before they are applied as a means of 'teasing out' the distributional consequences of the proposed Sapporo regional land-use and transport plan for 1995. The implications of the results of these analyses for Japanese planners are specified, and a reassessment is made of the accessibility measure as the basis for comparative urban studies in the Pacific Rim. (43 Refs)

Breheny, M. J., 1978, "The Measurement of Spatial Opportunity in Strategic Planning," *Regional Studies*, 12, 463–479.

(Author's abstract) In recent years interest in accessibility has increased due both to the energy crisis and to the realisation that accessibility affects the real income of different groups in the community. The more common measures of accessibility, namely those based on travel-behaviour and potential, are, however, seen to have a number of shortcomings in this context. Measures of 'spatial opportunity' are proposed which omit some of these shortcomings and have the added advantage of simplicity. The nature of these measures is demonstrated through their practical application on data for Gloucestershire. Examples are shown of the use of the measures to give both sectoral and geographical disaggregation in analytical and forecast situations. (31 Refs)

Guy, C. M., 1983, "The Assessment of Access to Local Shopping Opportunities: A Comparison of Accessibility Measures," *Environment and Planning B: Planning and Design*, 10, 219–238.

(Author's abstract) In this paper the author describes an application of certain accessibility measures in the assessment of access to local shopping opportunities. The measures used here include one developed by the author to represent access to immediately local convenience shopping outlets ('shortest distance'), and three which have been suggested by other authors in connection with more general transport policy evaluation exercises ('cumulative opportunity,' 'gravity' and 'Gaussian'). These measures are applied to the assessment access to local shopping opportunities in part of

Reading, Berkshire, using data collected by the author in 1974. Access is measured on a point-to-point basis (between shops and a systematic sample of homes). Considerable contrasts are shown to exist between sets of access measures. Changes in accessibility between 1974 and 1978 in the study area are then briefly considered, and it is shown again that different accessibility measures suggest somewhat different conclusions. (28 Refs)

Handy, S. L., and Niemeier, D. A., 1997, "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A*, 29, 1175–1194.

(Author's abstract) Accessibility is an important characteristic of metropolitan areas and is often reflected in transportation and land-use planning goals. But the concept of accessibility has rarely been translated into performance measures by which policies are evaluated, despite a substantial literature on the concept. This paper is an attempt to bridge the gap between academic literature and the practical application of such measures and provide a framework for the development of accessibility measures. Issues that planners must address in developing an accessibility measure are outlined, and two case studies suggestive of the range of possible approaches are presented. (50 Refs)

[Case studies use gravity, cumulative opportunities and utility measures.]

Hanson, S., and Schwab, M., 1987, "Accessibility and Intraurban Travel," *Environment and Planning A*, 19, 735–748.

(Author's abstract) This paper contains an examination of the fundamental assumption underlying the use of accessibility indicators: that an individual's travel behavior is related to his or her location vis-a-vis the distribution of potential activity sites. First, the conceptual and measurement issues surrounding accessibility and its relationship to travel are reviewed; then, an access measure for individuals is formulated. Using data from the Uppsala (Sweden) Household Travel Survey and controlling for sex, automobile availability, and employment status, the authors explore the relationship between home- and work-based accessibility and five aspects of an individual's travel: mode use, trip frequencies and travel distance for discretionary purposes, trip complexity, travel in conjunction with the journey to work, and size of the activity space. From the results it can be seen that although all of these travel characteristics are related to accessibility to some degree, the travel-accessibility relationship is not as strong as deductive formulations have implied. High accessibility levels are associated with higher proportions of travel by nonmotorized means, lower levels of automobile use, reduced travel distances for certain discretionary trip purposes, and smaller individual activity spaces. Furthermore, the density of activity sites around the workplace affects the distances travelled by employed people for discretionary purposes. Overall, accessibility level has a greater impact on mode use and travel distance than it does on discretionary trip frequency. This result was unexpected in light of the strong trip frequency – accessibility relationship posited frequently in the literature. (37 Refs)

Hardcastle, D., and Cleeve, I., 1995, "Accessibility Modelling Using GIS," *Geographic Information Systems: Proceedings of Seminar N* held at the PTRC European Transport Forum, University of Warwick, England, P400.

The authors have developed a model using GIS (ARC/INFO) to graphically present accessibility data for transportation projects. Using land use and census data, isochrones can be created that can show the number of households with access to a particular point within a certain time frame by a particular mode. (1 Ref.)

Ikhrata, H., and Michell, P., 1997, "Technical Report of Southern California Association of Governments' Transportation Performance Indicators," *Transportation Research Record 1606,* 103–114.

(Author's abstract) The overall goal of the staff of the Southern California Association of Governments (SCAG) is to develop specific, quantifiable, and easily understandable performance indicators for the region's transportation system that better inform elected officials and policy boards of the broad array of choices for investing public and private funds. SCAG's performance indicators are intended to capture the important relationships between transportation and a diversity of public policy concerns. The seven performance indicators used in the preparation of the 1997 Regional Transportation Plan (RTP) are mobility, accessibility [to jobs], environment, cost-effectiveness, reliability, safety, and customer satisfaction. SCAG applies these performance indicators to each of its 13 subregions and to the region as a whole. The federal Intermodal Surface Transportation Efficiency Act of 1991 and Clean Air Act Amendments of 1990, and SCAG's 1994 Regional Mobility Element, set the stage for the abandonment of the old and popular level of service measure. SCAG's performance indicators approach the concept of performance from the perspective of the users of the transportation system, in contrast to traditional approaches that focused more on the facilities and vehicles. SCAG is currently at approximately the midpoint in the development of the 1997 RTP and therefore has considerable practice in working with the performance indicators. This experience confirms the value of performance indicators as a planning tool. (1 Ref.)

McKenzie, R. P., c.1984, "The Measurement of Accessibility to Employment," TSU Ref 245, Transport Studies Unit Oxford University.

The author gives a brief discussion of the different types of accessibility measures developed over the past several years. He then argues that the cumulative-opportunities model is the best, especially as it relates to his two criteria for an appropriate accessibility measure. It takes into account land use, transportation system supply and low reliance on observed behavior. The author then describes a computer model he has developed that calculates the cumulative opportunities to employment. The arbitrariness of picking a "cut-off" point is discussed. (90 Refs)

Mowforth, M. R. N., 1989, "Trends in Accessibility to Employment in Greater London, 1971-1981," *Transportation Planning and Technology*, 13, 85–110.

(Author's abstract) The paper reports on an analysis of trends in accessibility to employment for users of public transport in the Greater London conurbation from 1971 to 1981. Indicators of accessibility are calculated for different groups of the workforce in terms of their preparedness to travel and the number and location of jobs in their categories of employment. These are respectively estimated from a cumulative distribution of generalised costs typically borne by each group of workers in the Greater London Transportation Survey (GLTS) area and from Census employment data. Data for 1971 and 1981 together reflect the substantial changes that took place in the structure and location of employment in London between the two years. (18 Refs)

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

(Author's abstract) Improving the quality of urban life requires not only the provision of employment, medical, education, and recreational opportunities but also a convenient means of access to these facilities for all citizens. This study reports on a prototypical application of a new methodology, called Special Area Analysis (SAA), designed to assess the quality of accessibility in metropolitan areas. Starting with a definition of accessibility in functional terms, this SAA develops measures that focus on the level of accessibility afforded by Boston's present, planned, and programmed urban transportation systems to such essential urban activity centers as major employment districts, medical, recreational, and educational facilities, the central business district, and the airport. In addition, the methodology is applied toward an evaluation of accessibility afforded to specific population subgroups such as low-income and zero-car households. This study demonstrates that the SAA methodology is a useful evaluation tool for use by metropolitan area transportation planning agencies. (1 Ref.)

Wachs, M., and Kumagi, T. G., 1973, "Physical Accessibility as a Social Indicator," *Socio-Economic Planning Science*, 7**,** 437–456.

(Author's abstract) A discussion is presented of the ways in which accessibility to employment and urban services constitutes an important measure of the quality of urban living, and how accessibility might, therefore, be included as an important component of a 'social report' for a city or region. A conceptual framework is introduced for measuring accessibility in terms of the ease with which a citizen may reach a variety of opportunities for employment and services. This framework is interpreted as an approach to evaluating transportation and regional plans which differs from approaches based upon travel volumes and travel times which are currently employed in urban transportation planning and evaluation. The use of the proposed measures of accessibility is illustrated with data on accessibility to employment and health care facilities in Los Angeles, and these data are interpreted to illustrate differences in accessibility as a function of spatial location of residence, and socio-economic status. (13 Refs)

[The authors discuss the potential aggregation and disaggregation properties of this measure.]

Weibull, J. W., 1976, "An Axiomatic Approach to the Measurement of Accessibility," *Regional Science and Urban Economics*, 6, 357–379.

(Author's abstract) In this paper an axiomatic approach is developed for the task of measuring accessibility. The general mathematical form of a measure satisfying the postulated axioms is derived. This class of measure contains as a sub-class the so-called gravity potentials. A measure of the accessibility to employment opportunities is presented with applications to the Stockholm region. Finally some ideas on further development of accessibility measures are discussed. (11 Refs)

Wickstrom, G. V., 1971, "Defining Balanced Transportation — A Question of Opportunity," *Traffic Quarterly*, 25, 337–350.

The author advocates evaluating the user standard of the total transportation system and not just one mode. This standard should be in terms of opportunities available and minimum standards should be set for subpopulations. It may be best for this to be a standard that is normalized to 100. This would then show where transportation services are needed. The needs of an area could be served by either improving transportation or providing the needed service (e.g., health care). This measure is proposed to be a cumulative-opportunities measure with a cut off of 45 minutes. This measure is then applied to six areas in the Washington, D.C. area. (1 Ref footnoted)

Gravity-Type Models

Agyemang-Duah, K., and Hall, F. L., 1997, "Spatial Transferability of an Ordered Response Model of Trip Generation," *Transportation Research A*, 31(5), 389–402.

(Author's abstract) This paper documents analysis of the spatial transferability of an ordered response model, a type of discrete choice model which maintains the ordinal nature in the dependent variable in situations where there are more than two responses. The analysis focuses on shopping trip generation in Metropolitan Toronto. The paper investigates the performance of a directly transferred ordered response model (without updating the transferred coefficients) and assesses the effectiveness of a technique for revising the constant terms and scalars in the model by using small-sample data from the region to which the model is to be applied. The results of this spatial transferability analysis show that a directly transferred ordered response model perform reasonably well in predicting the aggregate shares in the application (new) context. Revising the constant terms and the scalars in the model substantially improves the predictive capability of the transferred model. (14 Refs) [Accessibility (combining destination attractiveness and travel time) is a variable in the model developed.]

Bhat, C. R., Carini, J. P., and Misra, R., 1999, "Modeling the Generation and Organization of Household Activity Stops," *Transportation Research Record*, 1676, 153–161.

(Author's abstract) This paper proposes a model for household stop generation and organization that accommodates the ordinal discrete nature of stop-making and incorporates a comprehensive policy-sensitive measure of accessibility. The model is applied to examine household shopping stop-making behavior using a Boston area household travel survey. The empirical results provide useful insights into the effect of household characteristics and accessibility to shopping opportunities on shopping stop behavior. The application of the model is demonstrated by examining the effect of an increase in highway costs and changes in land-use patterns on shopping stop generation and organization. (21 Refs)

Bhat, C. R., Govindarajan, A., and Pulugurta, V., 1998, "Disaggregate Attraction-End Choice Modeling," *Transportation Research Record*, 1645, 60–68.

(Author's abstract) The ability of travel demand models to provide good forecasts requires that they be casual, that is; the models should represent the travel decisions made by individuals (and households) and should incorporate important demographic and policy sensitive explanatory variables. This recognition has led to a shift from the aggregate modeling paradigm to the disaggregate modeling paradigm, as evident in the widespread use of disaggregate trip production and mode choice models in practice. However, this shift toward disaggregate procedures has not yet influenced the fundamental specification of trip attraction and distribution models employed in practice. This research develops (and estimates) disaggregate attraction-end choice models that will facilitate the replacement of the aggregate trip attraction and distribution models currently in use. The research also compares the proposed disaggregate attraction-end choice model with the disaggregate equivalent of the gravity model. (30 Refs)

Black, J. A., Kuranami, C., and Rimmer, P. J., 1982, "Macroaccessibility and Mesoaccessibility: A Case Study of Sapporo, Japan," *Environment and Planning A*, 14, 1355–1376.

(Author's abstract) Accessibility measures are presented which provide a means of understanding the internal spatial structure of radically different urban forms and of assessing the impact on residents of land-use and transport policies. It discusses the results of the application to Sapporo in Japan of a set of measures intended for the comparison of accessibility patterns between, within, and across cities in the Pacific Rim countries. After detailing an appropriate conceptual framework attention is focussed on measuring the opportunities various groups have of participating in urban activities. Mesoaccessibility and macroaccessibility measures are both used for this purpose. First, Sapporo is put into its regional and national context. Then the mesoaccessibility measures are presented as a means of understanding the local area impact of national and metropolitan level policies. Macroaccessibility measures are illustrated with specific reference to the labour market in 1975 before they are applied as a means of 'teasing out' the distributional consequences of the proposed Sapporo regional land-use and transport plan for 1995. The implications of the results of these analyses for Japanese planners are specified, and a reassessment is made of the accessibility measure as the basis for comparative urban studies in the Pacific Rim. (43 Refs)

Carrothers, G. A. P., 1956, "A Historical Review of the Gravity and Potential Concepts of the Human Interaction," *Journal of the American Institute of Planners*, Spring 1956, 94–102.

This is an early paper that reviews past work regarding the gravity potential theory of human interaction. The author is looking at measuring the possibility of interaction and proposes one way of presenting the data as "contours of equal potential." Postulating that because gravity can be modified for the social sciences, the author tries to modify other scientific equations. (83 Refs)

Cervero, R., Rood, T., and Appleyard, B., 1999 "Tracking Accessibility: Employment and Housing Opportunities in the San Francisco Bay Area," *Environment and Planning A*, 31, 1259–1278.

(Author's abstract) Shifts in job accessibility reflect, in part, the degree to which land use and transportation decisions help to bring job opportunities closer to labor forces. In this paper we argue for the wider use of accessibility indicators as part of the long-range transportation planning process. As a case example, changes in job accessibility indices are traced for the San Francisco Bay Area from 1980 to 1990, computed for 100 residential areas and the region's 22 largest employment centers. Indices are refined based on occupational match indicators that weigh the consistency between residents' employment roles and labor-force occupational characteristics at workplaces. The analysis reveals that peripheral areas tend to be the least job accessible. Moreover, employment centers that are home to highly skilled professional workers are generally the most accessible when occupational matching is accounted for. This is thought to reflect the existence of housing markets that are more responsive to the preferences of upper-income workers. Our analyses show that residents of low-income, inner-city neighborhoods generally face the greatest occupational mismatches. Through a path analysis, the variable 'race' was found to be far more strongly associated with unemployment than was job accessibility, however, even after controlling for educational levels and other factors. We conclude that an important purpose of tracking changes in accessibility is to provide feedback on the degree to which resource allocation decisions in the urban transportation field are helping to redress serious inequities in accessibility to jobs, medical facilities, and other important destinations. (28 Refs)

Davidson, K. B., 1977, "Accessibility in Transport/Land-Use Modelling and Assessment," *Environment and Planning A*, 9, 1401–1416.

(Author's abstract) The relationship between accessibility and urban density is examined both conceptually and experimentally. A linear relationship between the logarithm of density and centrality, a derivative of accessibility, is calibrated. It is shown that centrality can be used to measure the utility of location in the context of the land-use/transport system. This provides a basis for evaluating land-use/transport changes by using only data readily available from transportation studies. (16 Refs)

Davidson, K. B., c.1980, "Accessibility and Isolation in Transport Network Evaluation," Davidson Transport Consulting, Australia.

(Author's abstract) Accessibility is generally understood to describe the ease with which a place may be reached from elsewhere. It is defined as the ease with which a person at a point may gain access, via the transport system (or whatever modes or sub-systems of it are nominated), to all other places in a defined area, taking into account their varying attractiveness and the perceived cost of getting to them. A location with high accessibility will tend for most purposes to be more attractive than one with low accessibility and hence to be more highly valued. This is not to say that accessibility is the sole determinant of a location's value: rather that it is one determinant so any change in accessibility should change the location's value.

Thus it can generally be said that one way to promote a regional or urban development of an area is to increase its accessibility. Taking an action which reduces, relatively or absolutely, an area's accessibility will have social justice implications, particularly if it is an area which is already suffering some other disability.

Accessibility so defined can be seen to be a joint consequence of the transport system and the distribution of activities (e.g. population or employment are simple measures of activity). A change in either the transport system of the distribution of activities will change the value of accessibility and the value will change differently for different places. Herein is the power of the concept in that the impact, on regional or urban development or social disadvantage, of any change to the road system (or any policy designed to change the distribution of activities) can be measured. This power is enhanced if it is possible to develop a measure of accessibility, which is also a formal measure of utility, thus allowing it to be inserted directly into evaluation equations. (3 Refs)

Echeverría Jadraque, D., Monzón de Cáceres, A., Cristobal Pinto, C., and Martín Duque, D., 1996, "Accessibility Levels Conferred by Public Transport in Madrid Metropolitan Area," *Transportation Planning Methods: Proceedings of Seminar E* held at the PTRC European Transport Forum, Brunel University, England, P404-2.

The authors define an accessibility measure based on the number of trips attracted to a zone and the exponent of the time to travel there via public transportation. This is compared to an ideal transportation network and the results are presented graphically. (17 Refs)

Giannopoulos, G. A., and Boulougaris, G. A., 1989, "Definition of Accessibility for Railway Stations and its Impact on Railway Passenger Demand," *Transportation Planning and Technology*, 13, 111–120.

(Author's abstract) This paper addresses the notion of accessibility of railway stations and its relation to the number of passengers using these stations. It first gives a discussion on the notion of accessibility and it presents the special factors and the issues involved in its definition for (intercity) railway stations. Of the large number of possible definitions of an Accessibility Index, it goes on to choose the form that statistically explains better the changes in the number of passengers using a station. The methodology followed in order to do this, can be used as a guideline for determining the type of index that would best explain the data in other similar situations. Having selected an Accessibility Index for railway stations, a simple regression model has been made, that connects this accessibility index to the number of passengers using the station. The type of this relation, its statistical characteristics, and its sensitivity are then discussed and some useful overall conclusion reached. The data used and a first application of the results, which is also briefly described in the paper refer to the railway network of Greece. (15 Refs)

Guy, C. M., 1983, "The Assessment of Access to Local Shopping Opportunities: A Comparison of Accessibility Measures," *Environment and Planning B: Planning and Design*, 10, 219–238.

(Author's abstract) In this paper the author describes an application of certain accessibility measures in the assessment of access to local shopping opportunities. The measures used here include one developed by the author to represent access to immediately local convenience shopping outlets ('shortest distance'), and three which have been suggested by other authors in connection with more general transport policy evaluation exercises ('cumulative opportunity', 'gravity' and 'Gaussian'). These measures are applied to the assessment access to local shopping opportunities in part of Reading, Berkshire, using data collected by the author in 1974. Access is measured on a point-to-point basis (between shops and a systematic sample of homes). Considerable contrasts are shown to exist between sets of access measures. Changes in accessibility between 1974 and 1978 in the study area are then briefly considered, and it is shown again that different accessibility measures suggest somewhat different conclusions. (28 Refs)

Handy, S. L., 1993, "Regional Versus Local Accessibility: Neo-Traditional Development and its Implications for Non-Work Travel," *Built Environment*, 18(4), 253–267.

Four communities with different characteristics are evaluated in order to determine the affect of land use on nonwork trips. The four communities were chosen based on their different levels of local and regional accessibility. The exponential form of a gravity-based accessibility indicator was used in the determination. To test the influence of different land use patterns, shopping frequencies in the four communities are compared across the different levels of local and regional accessibility. While accessibility was found to affect travel patterns, at the aggregate level the evidence is inconclusive.

Handy, S. L., and Niemeier, D. A., 1997, "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A*, 29, 1175–1194.

(Author's abstract) Accessibility is an important characteristic of metropolitan areas and is often reflected in transportation and land-use planning goals. But the concept of accessibility has rarely been translated into performance measures by which policies are evaluated, despite a substantial literature on the concept. This paper is an attempt to bridge the gap between academic literature and the practical application of such measures and provide a framework for the development of accessibility measures. Issues that planners must address in developing an accessibility measure are outlined, and two case studies suggestive of the range of possible approaches are presented. (50 Refs)

[Case studies use gravity, cumulative opportunities and utility measures.]

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

This is the earliest paper typically cited by researchers looking at the application of the gravity model. The author uses a residential land use model to empirically develop a measure of the "intensity of the possibility of interaction." He describes the general characteristics of an accessibility measure as being proportional to the size of the attraction and inversely proportional to the distance of separation. Different exponents are developed for different activities (e.g., work, shopping) and a map with contours of equal accessibility is developed. (5 Refs footnoted)

Knox, P. L., 1978, "The Intraurban Ecology of Primary Medical Care: Patterns of Accessibility and Their Policy Implications," *Environment and Planning A*, 10, 415–435.

(Author's abstract) Patterns of intraurban accessibility to primary medical care in four major Scottish cities are examined in the context of existing public policy and against the background of intraurban patterns of community well-being. Certain regularities are observed in the spatial ecology of family doctors' surgeries, and the notion of an 'inverse care law' is discussed. A modified interaction model is introduced and used to analyse local accessibility to primary care facilities. Results indicate that disparities in accessibility tend to compound many other patterns of socioeconomic disadvantage. The formulation of public policies concerned with medical deprivation and area deprivation is discussed in the light of these results. (71 Ref.)

Kockelman, K. M., 1997, "Travel Behavior as Function of Accessibility, Land Use Mixing, and Land Use Balance," *Transportation Research Record 1607*, 116–125.

(Author's abstract) The relative significance and influence of a variety of measures of urban form on household vehicle kilometers traveled, automobile ownership, and mode choice were investigated. The travel data came from the 1990 San Francisco Bay Area travel surveys, and the land use data were largely constructed from hectare-level descriptions provided by the Association of Bay Area Governments. After demographic characteristics were controlled for, the measures of accessibility, land use mixing, and land use balance – computed for trip makers' home neighborhoods and at trip ends – proved to be highly statistically significant and influential in their impact on all measures of travel behavior. In many cases, balance, mix, and accessibility were found to be more relevant (as measured by elasticities) than several household and traveler characteristics that often form a basis for travel behavior prediction. In contrast, under all but the vehicle ownership models, the impact of density was negligible after accessibility was controlled. (38 Refs)

Koenig, J. G., 1980, "Indicators of Urban Accessibility: Theory and Application," *Transportation*, 9, 145–172.

(Author's abstract) The concept of accessibility and its related indictors have been in use for a long time, with still diverging interpretations of their significance and formulation. In this paper, a review is made of various existing theoretical bases, with special emphasis on recent behavioural approaches. It is suggested that this theoretical framework now allows a better appraisal of accessibility indicators and precise recommendations are proposed for their practical formulation and use. Various examples are given, especially for disaggregate analysis where a calculation "for a given person" is proposed instead of the conventional calculation "by a given mode." Finally the relations between accessibility and trip rate are examined; from a study made in French cities, it is suggested that accessibility is a powerful determinant of trip rate. (16 Refs)

Lee, M. S., and Goulias, K. G., 1997, "Accessibility Indicators for Transportation Planning Using GIS," presented at the 76th Annual Transportation Research Board Meeting.

(Author's abstract) In this paper a method to create GIS-based accessibility indicators is presented. The method allows to create person-by-person and store-by-store (disaggregate) accessibility indicators but also to derive a zonal summary (aggregate) indicators that can be used in more traditional transportation planning applications. These indicators have also been used as explanatory variables in person-based transportation planning models illustrating the relationship between accessibility and shopping behavior, which in turn can be used in the trip generation models in the usual travel demand forecasting process. In this study the use of network shortest path, Gaussian function, parameter value 4.856, and employment intensity as attraction measures created an accessibility with the best behavioral foundation. The study also shows that building GIS-based accessibility indicators is feasible and provides better information than aggregate accessibility indicators. (21 Refs)

Levinson, D., and Kumar, A., 1994, "Multimodal Trip Distribution: Structure and Application," *Transportation Research Record 1466*, 124–131.

(Author's abstract) A multimodal trip distribution function estimated and validated for the metropolitan Washington, D.C., region is presented. In addition a methodology for measuring accessibility, which is used as a measure of effectiveness of networks, using the impedance curves in the distribution model is described. This methodology is applied at the strategic planning level to alternative high-occupancy vehicle alignments to select alignments for further study and right-of-way preservation. (35 Refs)

Linneker, B. J., and Spence, N. A., 1992, "An Accessibility Analysis of the Impact of the M25 London Orbital Motorway on Britain," *Regional Studies*, 26(1), 31–47.

(Author's abstract) The M25 London Orbital Motorway seems certain to have affected the general levels of accessibility in Britain. The scale and nature of these accessibility changes are however much less clear and the aims of the paper are to attempt to specify them. The methodology involves calibration of market potential measures in both a with-road and without-road case using exogenously determined route minimization between regional zones. Time, distance and cost impedance functions are calculated for both HGV's and cars. The results point to significant accessibility changes but not always in the direction anticipated. Much depends on the nature of the impedance function, the mode of travel and location of the impact. (25 Refs)

Tagore, M. R., and Sikdar, P. K., 1996, "A New Accessibility Measure Accounting Mobility Parameters," *Volume 1: Travel Behaviour*, Proceedings of the 7th World Conference, World Transport Research, Elsevier Science Ltd., 305–315.

(Author's abstract) Accessibility is one of the basic determinants of urban form. In all previous measures of accessibility, mobility parameters have not been included. In this paper, an accessibility index taking account of the mobility of individuals has been developed and applied to Greater Bombay, the commercial capital of India. (12 Refs)

Weibull, J. W., 1976, "An Axiomatic Approach to the Measurement of Accessibility," *Regional Science and Urban Economics*, 6, 357 – 379.

(Author's abstract) In this paper an axiomatic approach is developed for the task of measuring accessibility. The general mathematical form of a measure satisfying the postulated axioms is derived. This class of measure contains as a sub-class the so-called gravity potentials. A measure of the accessibility to employment opportunities is presented with applications to the Stockholm region. Finally, some ideas on further development of accessibility measures are discussed. (11 Refs)

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

(Author's abstract) This paper shows that the gravity model is not a single model but that there is a whole family of spatial interaction models. The properties of this family are outlined in some detail. Basic concepts of such models can be developed in a variety of ways, and these are illustrated. The paper then outlines a number of other theoretical developments, and is particularly concerned with the disaggregation of such models, with the incorporation of time variables, and the relation of spatial interaction, to

more general, models. Uses of spatial interaction models are outlined briefly and the final section of the paper draws a number of conclusions and presents a summary. (65 Refs)
[The author briefly mentions the utility of accessibility. He says that the entropy maximizing method is a statistical averaging method. The author cautions against having an attraction factor that is dependent on zone size. There is discussion about disaggregation (p. 17)]

Zakaria, T., 1974, "Urban Transportation Accessibility Measures: Modifications and Uses," *Traffic Quarterly*, 28, 467–479.

The author defines accessibility as a way to understand the interaction between land use and the transportation system. The author discusses the gravity model and a model based on the probability of intervening opportunities. Three ways that accessibility can be used in transportation planning are discussed: quantification of the developmental advantages of a zone, traffic modeling, and the evaluation of transportation systems. (17 Refs footnoted)

Zhang, M., Shen, Q., and Sussman, J., 1998, "Job Accessibility in the San Juan Metropolitan Region: Implications for Rail Transit Benefit Analysis," *Transportation Research Record 1618*, 22–31.

(Author's abstract) Public transportation investment is made primarily because of its potential social and economic benefits. Properly identifying and measuring these benefits has been the central concern in rail transit investment. The social aspects of the benefits, however, have not been well examined. In this research on the potential benefits of Tren Urbano (a new rail transit system proposed in San Juan, Puerto Rico), accessibility measures are utilized as a key analytical tool. An analysis of Tren Urbano's effects on employment accessibility in the region is presented. The results show that there is a need for lower-income workers to improve their accessibility to jobs. Tren Urban will enhance employment accessibility at the regional level and for all income groups as well. The results also reveal spatial inequity in the distribution of the potential benefits, even though the eventual outcome will be dependent on the actual distribution of ridership. Efforts should be made to channel the potential benefits of transportation investment toward socially targeted populations. Integrating the rail system with other transit modes and formulating favorable land use policies are critical to enhance accessibility. (32 Refs)

Logsum/Utility Models

Algers, S., Daly, A., and Widlert, S., 1997, "Modelling Travel Behaviour to Support Policy Making in Stockholm," *Understanding Travel Behaviour in an Era of Change* eds. Stopher, P. and Lee-Gosselin, M., Oxford: Elsevier Science Ltd., 547–569.

(Author's abstract) This [paper] presents the structure of a system of traffic models that has been developed in Stockholm and describes some of the major results that have been obtained. The system will be used for policy analysis by different regional planning authorities in Stockholm County, where many important planning issues are currently being considered. The model system allows for linkages between different choice levels and takes into account a number of possible choices that have not normally been included in the model systems. It also takes into account different household interactions, for example, concerning the allocation of the car between household members and the selection of household members to do the shopping. The model system also incorporates the effect of various constraints [such as accessibility].

The system includes models for work, school, business, shopping, social visits, and other trip purposes. The models are based on a detailed home-interview survey and are estimated using maximum-likelihood methods. The models are being implemented in a forecasting program that runs on microcomputers to produce summary information and trip matrices for assignment. (8 Refs)

Ben-Akiva, M., and Lerman, S., 1979, "Disaggregate Travel and Mobility Choice Models and Measures of Accessibility" *Behavioral Travel Modeling*, eds. Hensher, D. and Stopher, P., London: Croom Helm, 654–679.

(Author's abstract) Existing measures of accessibility are not based on an explicit behavioral theory. This paper proposes an accessibility measure which is consistent with the application of random utility models to individuals' decision processes. The proposed measure is the expected maximum utility that a consumer derives from a given situation. The paper presents the properties and advantages of this measure and its derivation for the special cases of the multinomial logit and probit choice models.

Given the multi-dimensional nature of the travel and mobility choices, this measure is also shown to provide a logically consistent linkage between component models in a complete model system of travel and mobility choices. This use of this measure is demonstrated for joint and sequential logit models. Finally, the paper addresses key problem areas in the state-of-the-art of spatial choice modeling which directly affect the development of measures of accessibility defined over a large set of spatial alternatives. (34 Refs)

Handy, S. L., and Niemeier, D. A., 1997, "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A*, 29, 1175–1194.

(Author's abstract) Accessibility is an important characteristic of metropolitan areas and is often reflected in transportation and land-use planning goals. But the concept of accessibility has rarely been translated into performance measures by which policies are evaluated, despite a substantial literature on the concept. This paper is an attempt to bridge the gap between academic literature and the practical application of such measures and provide a framework for the development of accessibility measures. Issues that planners must address in developing an accessibility measure are outlined, and two case studies suggestive of the range of possible approaches are presented. (50 Refs) [Case studies use gravity, cumulative opportunities and utility measures.]

Martínez, F. J., 1995, "Access: The Transport-Land Use Economic Link," *Transportation Research B*, 29(6), 457–470.

(Author's abstract) The notion of access has evolved from a physical measure of trip interaction to a more economic concept associated with transport benefits. This paper follows the economic interpretation forward in order to understand the potentiality of access as a consistent economic link between the land use system and the transport system. Consistency is achieved in an economic approach based upon the argument that trips are made *only if* the benefit derived from making contact with other activities exceeds the transport generalized cost. This framework provides economic measure of access, as evidence of impact on origin and destination of trips, which can be calculated from the analysis of the transport system in some relevant cases. This paper analyses (sic) how to calculate measures of access from transport demand models and how to allocate transport access measures in land-use transport interaction modeling. (21 Refs)

Niemeier, D. A., 1997, "Accessibility: An Evaluation Using Consumer Welfare," *Transportation*, 24, 377–396.

(Author's abstract) This study explores the worth consumers place on mode-destination accessibility for the AM journey to work trip. To accomplish this, a multinomial mode-destination choice model is estimated and the denominator of the specified logit model is used as an estimate of mode-destination accessibility. To improve the interpretability of this measure, compensating variation is them applied to convert the mode-destination accessibility to units of dollars per AM journey to work trip. The model is estimated using travel survey data from the Puget Sound Region in Washington state. It is reasonable t assume, for example, that the worth placed on mode-destination accessibility varies by mode, by destination, and by market segment (e.g. low income, high income). Less intuitive, however, are the magnitude and direction of these variations. This paper presents a methodological approach, followed by an empirical evaluation, for examining the worth of the journey to work mode-destination accessibility. The results have important policy implications and also provide a mechanism for incorporating a monetary value for accessibility in future cost-benefit analyses. (34 Refs)

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

(Author's abstract) The concept of accessibility has been variously interpreted as being the "nearness to places," the "nearness to activities" and more recently "the ease of participating in activities." With each of these qualitative interpretations, there has also been a variety of quantitative definitions of accessibility. This paper shows that many of the proposed definitions of accessibility can in fact be gathered to form a spectrum of accessibility measures. These measures differ with respect to the factors included in their formulation and their degree of behavioural interpretation.

Existing measures of accessibility are shown to be deficient in one major aspect. That is, they assume that for any one measure of accessibility there is but one origin of trips. Thus, in estimating the accessibility of a point within a region it is assumed that all potential trips, which contribute to the accessibility of that point, start from that single point. In view of the considerable amount of evidence demonstrating the widespread, and increasing, occurrence, of trip-linking such a proposition must be viewed as being rather doubtful.

In light of this, the paper proceeds to develop a measure of accessibility which explicitly accounts for the linking of trips. The implications of this measure, compared to a conventional unlinked-trip accessibility measure, are discussed as are some problems which are foreseen in the practical implementation of such a measure. (17 Refs)

Sweet, R. J., 1997, "An Aggregate Measure of Travel Utility," *Transportation Research B*, 31(5), 403–416.

(Author's abstract) The paper examines the effect of separating the total utility associated with a choice into components associated with the choice itself and with the transaction or travel involved in realising the choice. It derives an aggregate measure of transaction utility based on the logit model of choice and an interpretation is given in terms of random utility theory. The main interest lies in exploring aggregate measures of the transaction utility, since these can be used to generate costs for an aggregate model which will be consistent with the parent disaggregate model and can also be used to form the basis of such summary measures of travel as accessibility indices. Finally, the transaction component is used to identify the travel component of a consumers' surplus measure of benefit and thus enable the consumers' surplus to be disaggregated into travel and locational benefits.

Time-Space Models

Burns, L. D., 1979, *Transportation, Temporal, and Spatial Components of Accessibility*, Lexington Books, Lexington, Massachusetts.

The author discusses the benefits of the time-space model of accessibility and analyzes eight different types of transportation improvement programs. This type of accessibility measure is argued to be the best because: 1) it is relative to individuals and not locations; 2) it incorporates spatial and temporal locations; 3) the value-weighted mapping responds to individual behavior; and 4) it is analytically flexible. Suggestions for future research include taking into account the realities of the transportation system and income and sociological constraints. (44 Refs)

Hall, R. W., 1983, "Travel Outcome and Performance: The Effect of Uncertainty on Accessibility," *Transportation Research B*, 17B(4), 275–290.

(Author's abstract) An accessibility model is a conceptual tool which explains the interdependencies between the transportation infrastructure and human activities. Traditionally, theorists have based their accessibility models upon deterministic approximations. However, uncertainty in itself can affect whether an activity is accessible, and affect how one measures accessibility. In the first section of this paper, it is shown that travel time randomness interacts with the scheduling of activities to define the region which is accessible to a traveler. In the second section, a problem is considered where a traveler must search among opportunities to locate a certain activity he desires. It is found that there exists an optimal cluster size which minimizes travel cost, the size being a decreasing function of the probability of locating the activity of any single opportunity. (14 Refs)

Kwan, M., 1998, "Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-based Framework," *Geographical Analysis*, 30(3), 191–216.

(Author's abstract) Conventional integral measures of accessibility, although valuable as indicators of place accessibility, have several limitations when used to evaluate individual accessibility. Two alternatives for overcoming some of the difficulties involved are explored in this study. One is to adapt these measures for evaluating individual accessibility using a disaggregate, nonzonal approach. The other is to develop different types of measures based on an alternative conceptual framework. To pursue the former alternative, this study specifies and examines eighteen gravity-type and cumulative-opportunity accessibility measures using a point-based spatial framework. For the latter option, twelve space-time accessibility measures are developed based on the construct of a prism-constrained feasible opportunity set. This paper compares the relationships and spatial patterns of these thirty measures using network-based GIS procedures. Travel diary data collected in Columbus, Ohio, and a digital data set of 10,727 selected land parcels were used for all computation. Results of this study indicate that space-time and integral indices are distinctive types of accessibility measures which reflect different dimensions of the accessibility experience of individuals. Since space-time measures are more capable of capturing interpersonal differences, especially the effect of space-time constraints, they are more "gender sensitive" and helpful for unraveling gender/ethnic differences in accessibility. An important methodological implication is that whether accessibility is observed to be important or different between individuals depends heavily on whether the measure used is capable of revealing the kind of differences the analyst intends to observe. (86 Refs)

Lee, M. S., and McNally, M. G., 1998, ***Application of Space-Time Prisms for the Measurement of Accessibility*** Institute of Transportation Studies, University of California, Irvine, Report Number UCI-ITS-AS-WP-98-2.

(Author's abstract) The space-time prisms envisioned by Hägerstrand enclose the locations a person can reach by taking into account various time constraints. This concept has been applied on occasions to measure accessibility. It was argued that the potential of applying this approach in spatial analysis was limited by data availability and computing power. Taking advantage of technological advances, a procedure utilizing a Geographic Information System (GIS) is developed to locate facilities within time-space prisms. Data from Portland, Oregon are applied to demonstrate how the proposed procedure can be used to measure accessibility to health care facilities. The potential of the procedure for measuring accessibility from the activity-based perspective is discussed. (15 Refs)

Miller, H.J., 1999, "Measuring Space-Time Accessibility Benefits within Transportation Networks: Basic Theory and Computational Procedures," *Geographical Analysis*, 31(2), 187–212.

(Author's abstract) Accessibility is a fundamental but often neglected concept in transportation analysis and planning. Three complementary views of accessibility have evolved in the literature. The first is a constraints-oriented approach, best implemented by Hägerstrand's space-time prisms. The second perspective follows a spatial interaction framework and derives "attraction –accessibility measures" that compares destinations' attractiveness with the travel costs required. A third approach measures the benefit provided to individuals by the transportation/land-use system. This paper reconciles the three complementary approaches by deriving space-time accessibility and benefit measures that are consistent with the rigorous Weibull Axiomatic framework for accessibility measures. This research also develops computational procedures for calculating these measures within network structures. This provides realistic accessibility measures that reflect the locations, distances, and travel velocities allowed by an urban transportation network. Since their computational burdens are reasonable, they can be applied at the urban scale using GIS. (55 Refs)

Wang, D., and Timmermans, H., 1996, "Activity-Based Measures of Accessibility for Transportation Policy Analysis," *Transportation Planning Methods: Proceedings of Seminar E* held at the PTRC European Transport Forum, Brunel University, England, P404–2.

(Author's abstract) This paper introduced a concept of expected maximum utility of alternative activity schedules. The concept was used to develop measures of accessibility locations. [Based primarily on a time-space model.] These measures evaluate accessibility in terms of opportunities to participate [in] activities, by taking into account physical and institutional constraints and people's travel behavior and preference on activity schedules. Therefore, they are able to overcome the drawbacks of the trip-based measures and represent the advanced development of activity-based measures.

In the near future, the developed measures will be applied in a case study, to test their applicability in assessing transport policies. (12 Refs)

Factor Analysis

Ma, J., and Goulias, K. G., 1996, "Multivariate Marginal Frequency Analysis of Activity and Travel Patterns in First Four Waves of Puget Sound Transportation Panel," *Transportation Research Record 1556*, 67–76.

(Author's abstract) An analysis of activity and travel patterns that explicitly accounts for transportation level of service via composite accessibility measures, land use type, and density around residence and workplace of survey participants in the Seattle region is presented. Using the Puget Sound Transportation Panel (PSTP) data, individuals' activity and travel patterns are first grouped into a few relatively homogeneous behavioral groups using cluster analysis. This is done to reduce the great diversity in individuals' behavior into a few representative patterns of behavior using activity and travel indicators simultaneously. Taking the contextual analysis approach, four-level multilevel models that include temporal, spatial, household, and person effects are constructed. The derived accessibility measures of individuals' residence and workplace are then included in the four-level pattern selection models to study the relationship between individuals' characteristics and their activity and travel pattern choices. The analysis is done by separating employed from unemployed persons and provides evidence that level of service and land use are strong determinants of activity participation and trip making. Their effect, however, depends on the person's employment status. (18 Refs)

Vickerman, R. W., 1974, "Accessibility, Attraction, and Potential: A Review of Some Concepts and Their Use in Determining Mobility," *Environment and Planning A*, 6, 675–691.

The paper starts off with an overview of graph theory and the gravity model approach to accessibility. The author then creates four accessibility indices using graph theory and distance, and two indices he calls "attraction-accessibility" for shopping and leisure that are developed with the gravity model. Using these six measures and twenty-four other variables, the author uses regression analysis to develop trip generation equations by mode for shopping and leisure. Factor analysis of the results provides seven components that account for 80% of the variation. An admitted weakness is the inability to reveal latent demand. (50 Refs)

Empirical Comparisons

Guy, C. M., 1983, "The Assessment of Access to Local Shopping Opportunities: A Comparison of Accessibility Measures," *Environment and Planning B: Planning and Design*, 10, 219–238.

(Author's abstract) In this paper the author describes an application of certain accessibility measures in the assessment of access to local shopping opportunities. The measures used here include one developed by the author to represent access to immediately local convenience shopping outlets ('shortest distance'), and three which have been suggested by other authors in connection with more general transport policy evaluation exercises ('cumulative opportunity,' 'gravity' and 'Gaussian'). These measures are applied to the assessment access to local shopping opportunities in part of Reading, Berkshire, using data collected by the author in 1974. Access is measured on a point-to-point basis (between shops and a systematic sample of homes). Considerable contrasts are shown to exist between sets of access measures. Changes in accessibility between 1974 and 1978 in the study area are then briefly considered, and it is shown again that different accessibility measures suggest somewhat different conclusions. (28 Refs)

Koenig, J. G., 1980, "Indicators of Urban Accessibility: Theory and Application," *Transportation*, 9, 145–172.

(Author's abstract) The concept of accessibility and its related indictors have been in use for a long time, with still diverging interpretations of their significance and formulation. In this paper, a review is made of various existing theoretical bases, with special emphasis on recent behavioural approaches. It is suggested that this theoretical framework now allows a better appraisal of accessibility indicators and precise recommendations are proposed for their practical formulation and use. Various examples are given, especially for disaggregate analysis where a calculation "for a given person" is proposed instead of the conventional calculation "by a given mode." Finally the relations between accessibility and trip rate are examined; from a study made in French cities, it is suggested that accessibility is a powerful determinant of trip rate. (16 Refs)

Song, S., 1996, "Some Tests of Alternative Accessibility Measures: A Population Density Approach," *Land Economics*, 72(4), 474–482.

(Author's abstract) This paper presents nine alternative accessibility measures and evaluates their usefulness in explaining population distribution. It first evaluates these measures by using the criterion of maximum explanatory power in standard regression analysis. It then performs non-nested tests on these nine measures. The paper concludes that gravity-type accessibility measures generally perform better than other measures. The most commonly used measure, size of opportunity weighted by the reciprocal of distance, is not statistically surpassed by any other measures. Cumulative opportunity within the average commuting distance and the distance to the central business district are the poorest accessibility measures. (22 Refs)

Other Papers

Al-Sahili, K., and Aboul-Ella, M., 1992, "Accessibility of Public Services in Irbid, Jordan," *Journal of Urban Planning and Development*, 118(1), 1 – 12.

(Author's abstract) The city of Ibrid, Jordan, is divided into 17 zones to examine the accessibility of the location of the public facilities by zone. The educational, health, postal, mosque, public park, fire, police, library and bank services in Irbid are analyzed, as is the accessibility to public transport, to know how good the locations of these facilities is to the public. A descriptive measure, rather than a quantitative one, is used in the analysis. A circle of the maximum walking distance is drawn around each facility representing the service area for that facility, and zones ranging from completely served by these facilities to completely unserved are described. The analysis shows that the central zones had redundant services for many uses, while others are partially served or even unserved. The public transport network compensated for the majority of the deficiencies in the accessibility over the zones. The analysis shows that the availability of good services tends to vary inversely with the needs of the population served. (14 Refs)

Beardwood, J. E., 1990, "The Evaluation of Benefits in Constrained and Congested Situations," *Traffic Engineering and Control*, 31(4), 228, 230–1, 234–5.

(Author's abstract) Strategic-level transport models such as the London LTS are constructed to take account of road and rail congestion and often additionally assume doubly-constrained trip ends. In these circumstances the use of the traditional benefit formulae can lead to severe anomalies. A simple example of this occurs when easier travel into (but not out of) a district forces those living there to make longer journeys than before without themselves receiving any increased benefit. Current practice can attribute more benefit to these 'unwilling' travellers than to those genuinely advantaged by the changes.

A new formulation is proposed which takes better account of the constraints experienced by travellers in such situations. It is designed not only to be compatible with existing evaluations in unconstrained situations, but also to reflect common-sense expectations in more complex cases. Since it is based on accessibilities this system has the additional advantage of being location- rather than person-based, and thus offers the prospect of coping more helpfully with cases of population change. (4 Refs)

Franklin, J. P., and Niemeier, D. A., 1998, *The Prioritization of Mobility Improvements Using a Multicriteria Prioritization Algorithm*, University of California, Davis, Report Number FHWA-OR-RD-99-01.

(Author's abstract) A prioritization process has been prepared by the University of California, Davis, for use by the Oregon Department of Transportation (ODOT) in selecting multimodal mobility improvement projects to fund, given a budget constraint. The process involves first, the evaluation of projects using a set of criteria, incorporating such factors as cost-efficiency and modal integration, and second, the processing of the evaluation scores through a ranking algorithm. The ranking algorithm presented is the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). TOPSIS has been previously implemented by the Washington State Department of Transportation

(WSDOT), and due to issues that arose, modifications were made to the methodology in TOPSIS that were specific to the criteria used by WSDOT. Due to differing policy goals, these criteria are different from those recommended for ODOT. However, the issues that arose would apply to an ODOT implementation. TOPSIS was demonstrated using a sample set of project scores that were collected, and using several scenarios in which the evaluation criteria are weighted in different proportions, yielding unsurprising results. A process for determining final weights was demonstrated during a meeting of the Oregon Transportation Commission. Recommendations for further study are presented. (4 Refs)

Helling, A., 1998, "Changing Intra-Metropolitan Accessibility in the U.S.: Evidence from Atlanta," *Progress in Planning*, 49(2), eds. Diamond, D., and Massam, B. H. Elsevier Science Ltd.

(Author's abstract) Other authors have argued that accessibility has been increasing over time, as well as becoming more homogeneous in U.S. metropolitan areas. Together these developments are thought to have reduced its policy importance. This case study illustrates that this was not entirely the case in Atlanta in the late 1980s. Overall accessibility declined at the end of the decade, rather than continuing its steady increase, and its influence on residential density at the tract level (the access-density gradient) also changed direction. However, accessibility's explanatory power did decline from 1980 to 1990 in Atlanta, as expected. It seems likely therefore that accessibility will continue to be valuable as an indicator of metropolitan transportation systems' performance, as well as allowing planners to better anticipate change and to be more aware of its consequences. (80 Refs)

Hillman, R., and Pool, G., 1997, "GIS-based Innovations for Modelling Public Transport Accessibility," *Traffic Engineering and Control*, 30(10), 554–559.

(Author's abstract) Transport policy is increasingly focused on promoting sustainable transport schemes and, in particular, shifting dependence from the private car towards the increased use of public transport. The effective implementation of this process is facilitated by information about the transport networks that are managed and the effects of changes to those networks. Increasingly the measurement of public transport accessibility is viewed as a useful tool in this planning process. This provides information on the ease, or otherwise, of travel between two points — and may take into consideration factors such as walking to a network access point, travel through the network, interchanges and access to the intended destinations.

GIS provides an excellent environment for the modelling of accessibility. Transport data are inherently spatial in nature and the GIS provides access to additional data such as geodemographic and land-use data-sets. This enables the planner not only to look at the basic travel times between points, but also to assess the utility of specific destinations to specific user groups. This paper examines how a software system called ACCMAP has been implemented to measure accessibility for Local Authorities and Operators. Examples are drawn from a variety of applications including development control and public transport network planning. Data issues in developing and maintaining public transport databases are investigated. (0 Refs)

Meyer, M. D., 1995, ***Alternative Performance Measures for Transportation Planning: Evolution Toward Multimodal Planning***, Georgia Institute of Technology, prepared for the U.S. Dept. of Transportation, Report Number FTA-GA-26-7000.

(Author's abstract) This report presents the results of a research project that examined the incorporation of mobility and accessibility concerns into transportation planning. The questions addressed include: how is system performance defined, and who defines it?; what is the difference between an "output" and an "outcome"?; what are the most appropriate performance measures and how should they be used?; what are the implications of performance based planning on data collection and on the types of analysis tools that are available to transportation planners?; and how do performance measures relate to goals, objectives, and measures effectiveness? This research was based on extensive case studies of State transportation agency, metropolitan planning organization (MPO), and transit agency planning efforts that were characteristic of the performance-based planning process suggested by ISTEA. In particular, potential MPO case studies were identified through a telephone survey of the largest 50 MPO's in the country. In addition, on-going research and planning efforts at the State and national levels were monitored for application in this research. The key findings which include: mobility and accessibility should be important measures of system performance; travel time and modal availability should be the foundation for mobility measures; accessibility measures should be incorporated into project, plan, and system evaluation approaches; and market segmentation and distributional affects of mobility and accessibility changes should be part of measuring system performance (sic). (39 Refs)

Verroen, E. J., and Hilbers, H. D., c.1996, "Urban Planning and Mobility, Some Dutch Experiences," TNO Institute for Infrastructure, Netherlands.

One of the main goals of current Dutch transportation policy is to reduce growth in car traffic. A promising way to achieve this is to encourage use of public transport through better coordination between the planning of transportation facilities and land-use, in particular employment. The amount of traffic generated and the use of different transportation modes depends heavily on the characteristics and location of companies. A promising and innovative land use strategy exploits the differences between companies as to the mobility they generate. In order to establish optimal locations for each type of company, several types of locations are distinguished into three basic location types.

This paper presents the key results of various empirical studies carried out by INRO-TNO that constitute the basis of this location planning instrument. In the paper, we will present the developed typology of companies and location. The effectiveness of the location planning instrument will be demonstrated on the basis of a simulation study in The Hague. Based on the experiences so far, the value of this planning instrument is evaluated. Suggestions for further refinements are described (20 Refs)