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Accessibility measurement techniques in urban studies: a comprehensive review

Elahe Anjomshoaa[*1], Hasanuddin Bin Lamit[2], Arezou Shafaghat[3], Tareef Hayat Khan[1], Sharifah Salwa Bt Syed Mahdzar[1]

[1]*Department of Architecture, Universiti Teknologi Malaysia, Malaysia*

[2]*Department of Landscape Architecture, Universiti Teknologi Malaysia, Malaysia*

[3]*Department of Structure and Material, Universiti Teknologi Malaysia, Malaysia*

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Abstract

The concept of accessibility has been used in a number of scientific fields during the last few decades such as transport planning, urban planning and geography, and plays an important role in policy making. It expresses what possibly the major function of cities is; i.e. providing opportunities for easy interaction or exchange. In this study we attempted to present a comprehensive review on different techniques provided by different experts for measurement of accessibility in literature. First we summarized different accessibility measurement perspectives and components, and then we reviewed the different accessibility measures. A look at the literature revealed a wealth of information regarding the theory and specific construction of accessibility measures, which can help policy makers gain a better understanding of the strengths and weaknesses of each method when they are used for urban planning and management.

***Corresponding Author:** Elahe Anjomshoaa ✉ eanjomshoaa.utm@gmail.com

Introduction

For several decades, accessibility has been the focus of much literature in various fields of study. Accessibility is generally used to refer to the effort, means, or modes, with which a destination can be reached. In particular, the concept of accessibility provides a framework to understand the reciprocal relationships between land use and mobility. Accessibility definitions typically include two elements: (a) an impedance factor that describes transport networks and (b) a factor for the activity or opportunity available at a location (Envall, 2007). Litman (2003) defined accessibility as an ease of reaching the opportunities (i.e. goods, services, activities and facilities) in a destination. According to Litman (2007), it refers to people's ability to use services and opportunities. Baradaran and Ramjerdi (2001) call it 'a state of connectivity'.

During the last few decades, the concept of accessibility has been used in many scientific areas such as transport planning, urban planning, geography, and policy making (Zhang and Zhang , 2015, p. 1139). In urban geography, it is used for explaining town growth, location of facilities and functions, and comparison of land uses (Ingram, 1971). In transportation planning, it commonly refers to real access to goods, services, and destinations (Al Kahtani *et al.*, 2008, p.2). Transport professionals pay particular attention to the quality of the transport connecting place of residence and destination by considering various factors such as time, distance, mode, cost, quality, reliability and levels of service; while land-use planners generally focus on geographic accessibility, such as the distribution of services and destinations and the distances between them (Heinrichs and Bernet, 2014, p.58). In pedestrian planning, accessibility refers to facilities designed to accommodate people with disabilities (Litman, 2016, p.6).

Accessibility to opportunities (economic, recreational, service, and social) within a region is an important component of the quality of life within the region.

Various measures of accessibility have been developed in the last decades. Also, there are several studies that have reviewed accessibility measures but focused on a specific perspective. Some of them are: Song (1996) and Handy & Niemeier (1997) (focusing on location accessibility); Pirie (1979) and Kwan (1998) (focusing on individual accessibility); Koenig (1980) and Niemeier (1997) (focusing on economic benefits of accessibility), Geertman & van Eck (1995), Song (1996), and Handy & Niemeier (1997) (focusing on place accessibility). Considering previous studies, in this paper our purpose is to review, comprehensively, some of the most important accessibility measurement techniques in literature. This article can help policy makers gain a better understanding of the strengths and weaknesses of each method when they are used for urban planning and management. The structure of this article is organized as follows: First we present accessibility measurement perspectives and components (Section 2). Second we review the accessibility measurement methods presented by Hansen (1959), Ingram (1971), Wachs and Kumagai (1973), Weibull (1976), Koenig (1980), Miller (1991), Wang and Timmermans (1996), Kwan (1998), Bhat *et al.* (2000), Baradaran and Ramjerdi (2001), Geurs and van Eck (2003), Apparicio *et al.* (2008), Tal and Handy (2011), and Foti *et al.* (2012) in Section 3. Finally, we present the conclusion of the study in Section 4.

Accessibility Measurement Perspectives and components

According to Geurs and van Wee (2004), there are four types of accessibility measures perspectives: (a) *Infrastructure-based accessibility* or proximity measures analyzing times, congestion and operating speed in the road or rail transport network (i.e., generalized cost to reach activities) (Albacete *et al.*, 2015); (b) *Location-based* (or zonal-level) accessibility measures describe the spatial distribution of opportunities. Measures of place accessibility typically have two parts: a transportation (resistance or impedance) part and an activity (motivation, attraction or utility) part (see Handy and Niemeier, 1997; Kwan, 1998; Koenig, 1980).

The transportation part consists of travel distance, time, or cost for one or more modes of transport, whilst the activity part consists of the amount and location of different types of activities (Makri and Folkesson, 2000, p.4); (c) *Person-based measures* analyzing the availability of the activities for an individual within a given time to participate in activities (see time-space prisms of Hägerstrand, 1970, or activity/action spaces of Axhausen 2007); and (d) *Utility-based accessibility* assuming that people can gain the benefit (economic) from access to spatially distributed activities.

Accessibility has three primary components: Land-use component, transportation component, individual component, and temporal components (Geurs and van Wee, 2004, 128). Table 1 shows a matrix of accessibility measurement perspectives and components adapted from Geurs and van Wee (2004).

Table 1. Accessibility measurement perspectives and components (Geurs and van Wee, 2004).

Measure	Component			
	Transport component	Land-use component	Temporal component	Individual component
Infrastructure-based measures	Travelling speed; vehicle hours lost in congestion	-	Peak-hour period; 24-h period	Trip-based stratification, e.g. home-to-work, business
Location-based measures	Travel time and or costs between locations of activities	Amount and spatial distribution of the demand for and/or supply of opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Stratification of the population (e.g. by income, educational level)
Person-based measures	Travel time between locations of activities	Amount and spatial distribution of supplied opportunities	Temporal constraints for activities and time available for activities	Accessibility is analyzed at individual level
Utility-based measures	Travel costs between locations of activities	Amount and spatial distribution of supplied opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or seasons	Utility is derived at the individual or homogeneous population group level

They argue that "infrastructure-based measures do not include a land-use component; i.e. they are not sensitive to changes in the spatial distribution of activities if service levels (e.g. travel speed, times or costs) remain constant. The temporal component is explicitly treated in person-based measures and is generally not considered in the other perspectives, or treated only implicitly, for example by computing peak and off-peak hour accessibility levels. Person-based and utility-based measures typically focus on the individual component, analyzing accessibility on an individual level. Location based measures typically analyze accessibility on a macro-level, but focus more on incorporating spatial constraints in the supply of opportunities, usually excluded in the other approaches" (Geurs and van Wee, 2004, p. 25 and 26).

In the current study, we follow Geurs and van Wee (2004)'s classification, and use them to classify various methods of determining accessibility methods.

Accessibility Measurement Techniques and Formulas

Hansen's method: Location-based perspective (Potential Measure)

Hansen (1959) defined accessibility as the potential of opportunities for interaction (p.73): "The opportunity which an individual or type of person at given location possesses to take part in a particular activity or set of activities". The indicator that Hansen called a "measurement of accessibility" was later known as a gravity-based or Hansen-type measures which are based on the gravity model and weight opportunities according to a travel impedance function.

Based on Hansen's method for a given subarea i, to all other subareas j, accessibility is measured as

$$A_i = \sum_{j \neq 1} \frac{S_j}{T_{ij}^{b}} \quad (1)$$

Where, S_j = Size of activity in zone j; T_{ij} = Travel time between zones i and j; and b = Exponent describing the effect of travel time between zones. In this formula, for accessibility to employment, b = 2.00; for accessibility to shopping, S_j = annual retail scales; for accessibility to employment, S_j = number of jobs; and for accessibility to a residential activity, S_j = population.

Ingram's method: Location-based perspective (Distance and Contour Measure)

According to Ingram (1971), accessibility is the inherent characteristic or advantage of a place in term of overcoming some form of spatially operating friction source such as time and distance. Ingram distinguished between 'relative' accessibility and 'integral' accessibility. 'Relative' accessibility was taken as the physical separation between two points while 'integral' accessibility was defined as how one point related to all other points in a given area.The integral accessibility of one location is defined as the average of the relative accessibilities at that location:

$$A_i = \frac{\sum_{j=1}^{n} d_{ij}}{n} \quad (2)$$

In equation (2), d_{ij} is the straight line distance between i and j points.Also, relative accessibilities between all possible pairs of points is written as:

$$a_{ij} = 100.e\left(-\left(d_{ij}^{2}.v^{-1}\right)\right) \quad (3)$$

Where a_{ij} = is the relative accessibility of point j at i; and V = average squared distance between all points.

Wachs & Kumagai's method: Location-based perspective (Contour Measure)

Wachs & Kumagai (1973) define accessibility as "the average opportunity which the residents of the area possess to take part in a particular activity or set of activities".

They constructed a Cumulative-opportunity (CUM) index to measure the access to jobs: The number of job sites which can be reached within some minutes of travel time from the zone of residence of this population group.

In Wachs and Kumagai's model, index is computed for each zone based, upon the summation of terms each of which represents the accessibility to appropriate employment on the part of particular occupational and income categories. The value for a particular zone is computed as follows;

$$AI(T)_i = \frac{1}{100} \sum_{i=1}^{J} \sum_{k=1}^{K} P_{ijk} E(T)_{ijk} \quad (4)$$

Where,

$AI(T)_i$ = the accessibility index for zone using a travel time radius of T minutes; j = the income category, j= 1, 2,..., J; k = the occupation category or job class, k= 1, 2, ..., K; P_{ijk} = the proportion of the work force of zone i which is 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 travel from zone i;and 1/100 is a scaling factor" (Liu and Zhou, 2015).

Weibull's method: Location-based perspective (Adapted Potential Measures)

In Weibull (1976)'s model, accessibility is modeled as the potential of opportunities for interaction and can be obtained from a given location by paying a certain space/time-based cost. Weibull considers attraction-accessibility measures in general: An attraction-accessibility measure relative to the chosen distance and attraction characteristics.

Weibull weights attraction by the number of jobs in a zone and related to travel time and car ownership:

$$A_i = \sum_{j=1}^{n} q_t(d_i j)\omega_j / e_j \quad (5)$$

Where:

q_t = 1for d ≤ t and 0 for $d>t$;d_{ij} = Travel time; ω_j = Number of jobs in zone j. In equation (5):

$$e_j = \sum_{k=1}^{n} [p_1(d_{kj}^{a'})h_k^a + p_2(d_{kj}^{b'})h_k^b] \quad (6)$$

Where P is a non-increasing function calculated from empirical data such that: $P(0) = 1, P(x) \rightarrow 0$ and as x → +∞. Also, d is travel time via auto (a') and transit (b'); and h represents population in the zone of car owners (a) and non-car- owners (b) (Bhat *et al.* 2000 , p.21).

The gravity-based accessibility measure proposed by Weibull (1976) at the resident location $i$is written as:

$$A_i = \sum_{j=1}^{n} \frac{S_j d_{ij}^{-\beta}}{V_j} \quad (7)$$

Where;

A_i = The gravity accessibility indicator; n = the total number of healthcare service provider places;S_j = the number of healthcare providers that exist at location j;d_{ij}= the distance between the locations i and j;β = the decay factor, and V_j= the demand for healthcare services at location j (Jamtsho and Corner, 2014, p. 81).

Koenig's method: Utility-based perspective (Logsum Benefit Measure)

Koenig (1980) distinguished two main types of measures: isochronal definition and opportunities. Isochronic definition refers to the number of opportunities that could be reached during a given travel time. Opportunities are weighed by an impedance, a proper decreasing function of travel cost/time to reach these opportunities. Three formulations of accessibility presented by Koenig (1980) are:

$$A_{gravity} = \sum_j O_j \, exp\,(-C_{ij}/x_o) \quad (8)$$

$$A_{utility} = x_o \log \frac{A_i}{A_o} \quad (9)$$

Where:

O_j = Opportunities in zone j; C_{ij}= Time or cost between zones i and j; x_o = Distribution parameter; A_o= Reference value.

$$A_{cum-opp} = \sum_j O_j \, f(C_{ij}) \quad (10)$$

Where:

$A_{cum-opp}$= Accessibility from zone i to the relevant type of opportunities;O_j = Opportunities of that type that are present in zone j (employment places, shop s . . .);C_{ij}= Generalised time/cost for a trip from i to j used; and $f(C_{ij})$ = Impedance function. (Ohmori *et al.*, 1999).

In equation (10), the generalised travel time C_{ij} from i to j by mode m can be calculated as:

$$C_{ij}^m = k^m \theta_{ij}^m + \frac{1}{T} \gamma_{ij}^m \quad (11)$$

Where,

γ_{ij}^m =Monetary cost from i to j by mode m;θ_{ij}^m =Travel time from i to j by mode m;k^m =Discomfort coefficient associated with mode m by the considered people; T = Value of time for the considered people.

Miller's method: Person- based perspective (Space-time measure)

Miller (1991) used space-time prisms model where accessibility is analyzed at the micro level. This model shows the ability of individuals to travel and participate in activities at different locations in an environment. This type of measure is used in time geography. "The prism or potential path space (PPS) presented by Miller (1991) delimits locations for which the probability of being included in an individual's space-time path is greater than zero. The PPS is a three-dimensional entity existing in the region of bounded space time" (Stimson and Golledge, 1997, p.275).

Aspace-time prism model is shown in Figure 1.The person should be at a fixed place located at (x_i,y_i) from z_0 to z_1.

The person can leave this travel origin at time z_1 but should return there at$z_2$while leaves$z_2 - z_1$ = T time units for travel. The considered stop time has not been shown in Figure 1. Considering the traditional potential path space assumption of a constant and uniform velocity of travel *(v),* PPS is obtained by the path deviation from parallel to the axis z in all spatial directions to a slope of *1/v*. This slope is far from the travel origin and positive along the axis z starting at z_1, and far from the travel destination and negative along the axis z starting at z_2 , until both cones meets at time z_1 +*T/2* (Fisher, 2006, p.161).

Wang& Timmermans' method: Activity-based Space-Time measure

The proposed measure by Wang & Timmermans (1996) is individual and location specific. According to them: "People's accessibility is defined as people's perceived value of the extent to which their activity programs can be implemented with ease" (p.10). In this respect, the accessibility of people having activity *a*, and living at home *h*is obtained as:

$$\mathrm{A}_{ha} = \ln[\textstyle\sum_{I=1}^{m_{ah}} \exp(U_I)] \qquad (12)$$

Where, m_{ah}=the number of alternative schedules to carry out activity at home.

In case when people have *different* activities but living at the *same* home, the overall accessibility of all people is determined as:

$$\mathrm{A}_h = \textstyle\sum_{a=1}^{a} \ln[\sum_{I=1}^{m_{ah}} \exp(U_I)] \qquad (13)$$

Also, when people have the *same* activity but living in *different* homes, the average accessibility of people can be:

$$\mathrm{A}_a = \{\textstyle\sum_{h=1}^{H} 1n[\sum_{I=1}^{m_{ah}} exp(U_I)]\}/H \qquad (14)$$

"The accessibility of a location is defined as people's perceived value of the extent to which people's activity programs can be implemented with ease, if this particular location has to be the destination to implement at least one activity in the activity program" (Wang & Timmermans, 1996, p.11). In this regard, the accessibility of place *p* to people having activity *a* living at home *h* is expressed as:

$$\mathrm{A}_{pha} = \ln[\textstyle\sum_{I=1}^{m_{pha}} \exp(U_I)] \qquad (15)$$

Where m_{pha}= the number of alternative schedules to carry out activity at home and place.

In case whenpeople have the *same* activity but lives at *different* homes, the overall accessibility of a place *p* to people can be obtained as:

$$\mathrm{A}_{pa} = \textstyle\sum_{h=1}^{H} \ln[\sum_{I=1}^{m_{ph}} \exp(U_I)] \qquad (16)$$

Furthermore, if people have *different* activities while living at *different* homes, the overall accessibility of a place to people will be determined as:

$$\mathrm{A}_p = \textstyle\sum_{a=1}^{a} \sum_{h=1}^{H} \ln[\sum_{I=1}^{m_{pha}} \exp(U_I)] \qquad (17)$$

Kwan's method : Person- based perspective

Three types of accessibility measures are evaluated in the study of Kwan (1998): gravity-type, cumulative-opportunity, and space-time measures. The gravity-type measure has three impedance functions; inverse power, negative exponential, and modified Gaussian. The second type has six cumulative-opportunity measures, each compute a weighted sum of urban opportunities within 20, 30, and 40 minutes of travel time (Kwan, 1998, p. 199). In cumulative-opportunity measure, Kwan (1998) specified two various impedance functions:(1) the rectangular function presented by Wachs and Kumagai (1973) which gives the same weight to opportunities independent of distance from the origin, and (2) the negative linear function adapted from Black and Conroy (1977) in which opportunities are weighted linearly by the distance from the reference location (Ibid). The third type of accessibility measures include12 space-time measures which consists of three types of indicators extracted from individual daily potential path area (DPPA) (Ibid). Based on Kwan (1998)'s model, following formulas are presented:

Gravity-type, inverse power;$A_i = \sum W_j\, d_{ij}^{-\propto}$ (18)

Gravity-type, exponential; $A_i = \sum W_j\, e^{-\beta d_{ij}}$ (19)

Gravity-type, Gaussian; $A_i = \sum W_j\, e^{-d_{ij}^2/v}$ (20)

Cumulative-opportunity, rectangular;

$A_i = \sum W_j f(d_{ij})$ (21)

$$f(d_{ij}) = \begin{cases} 1, & for\ d_{ij} \leq T \\ 0, & otherwise \end{cases}$$

Cumulative-opportunity, negative linear;

$A_i = \sum W_j f(d_{ij})$ (22)

$$f(d_{ij}) = \begin{cases} (1 - t/T), & for\ d_{ij} \leq T \\ 0, & otherwise \end{cases}$$

Where;

W_j= Weighted area of location j;

d_{ij}= Travel times in minutes between location i and j;

α = 0.8, 1.0, 1.5, 2.0; β = 0.12, 0.15, 0.22, 0.45; v = 10, 40, 100. 180; and T= 20, 30, 40.

Kwan (1998) derived three indices as space-time measures of accessibility based on delimitation of the DPPA and the specification of the feasible opportunity set (FOS): (p.202).

Number of elements of the set FOS which shows the number of opportunities;

Weighted sum of opportunities in the FOS (A_S)

Length of network arcs in the DPPA

$A_S = \sum W_k I(k)$ (23)

Where $I(k)$ is an indicator function such that $I(k) = \begin{cases} 1, & k \in \text{FOS} \\ 0, & otherwise \end{cases}$

Bhat et al's method

According to Bhat *et al.* (2000), "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" (p. 1). They considered five main types of accessibility measures:

A. *Graph theory or spatial separation measures:* They use the distance between a location and other locations in the area as the accessibility value: (Bhat *et al.*, 2001, p.3)

$A_i = \frac{\sum_j d_{ij}}{b}$ (24)

Where d_{ij} is the distance between zones i and j, and b is a general parameter.

B. *Cumulative opportunities measures:* These measures consider the attractiveness of a travel in formulation. They define a travel time and use a number of activities within that time as the accessibility to that unit (Bhat *et al.*, 2000, p.19):

$A_i = \sum_j O_{jt}$ (25)

O_{jt} = Activity in zone j where j is within time t of zone i; t = 15 and 30 minutes. (Bhat *et al.*, 2001, p.13).

C. *Gravity measures:* These types are considered as continuous measures which sum attractions in a study area but reduce them by increasing time or distance from the origin (Bhat *et al.*, 2001, p.3).Using composite impedance:

$A_i = 1n\left[\frac{1}{J}\sum_{j=1}^{J}\left(\frac{O_j^{\alpha}}{C_{ij}^{\mu}}\right)\right]$ (26)

Where:

α, μ = parameters estimated from destination mode choice models for the region under consideration;

O_j = sum of all measures of attractiveness for traffic zone j ;

j= total number of zones in the area;

c (equivalent auto in-vehicle time units)= $IVTT_{auto} + \beta^* OVTT_{auto} + \gamma^* Cost_{parking}$ Where

IVTT stands for in-vehicle-travel time amount, and OVTT= out-of- vehicle-travel time amount

D. *Utility measures:* These measures are in accordance with aperson's perceived profit for different travel choices:

A_n=E$\left[Max_{i \in C}^{U_{in}}\right]$= 1n $\sum_{i \in C} exp(V_{in})$ (27)

"The method of calculating accessibility for an individual n, is the expected value of the maximum of the utilities (U_{in}) over all alternative spatial destinations i in choice set C. The utility is determined by taking the log sum of V_{in}". (Bhat *et al.*, 2002).

E. *Time-space measures:* These measures add a third dimension to the accessibility framework. They consider the time limitation of the persons (Bhat *et al.*, 2001, p.4).

F. In this context, Bhat *et al.* (2000) recognized three types of time limitations: (a) capability limitations: constraints of the activity number that a person can accommodate during a given time; (b) coupling limitations: the requirement for being in specific places at a specific time; and (c) authority limitations: given activities' operational times, or times of transport infrastructure/service components (Scheurer and Curtis, 2007, p.24).

F. Baradaran and Ramjerdi's method

According to Baradaran and Ramjerdi (2001), "the extent of accessibility can also be calculated as the number of different links and modes to which the specific location has access". Baradaran and Ramjerdi (2001) studies three models of accessibility: one model based on travel-cost approach where the measure of accessibility is defined as the connectivity level of the nodes (Equation 28), and two other models are gravity-based models (Equations 29 and 30). For each model, three deterrence functions were examined: linear in travel time (*t*), exponential in travel time, and Box-Cox transformed travel time.

- *Travel-cost approach:*

$$a_1 = \frac{1}{t_{ii}} + \sum_{j \in L} \frac{1}{t_{ij}}, i \neq j$$
$$a_2 = 1/e^{\beta t_{ii}} + \sum_{j \in L} \frac{1}{e^{\beta t_{ij}}}, i \neq j \qquad (28)$$
$$a_3 = \frac{1}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{1}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, i \neq j$$

Where:t_{ii}= the internal travel time at *i*, andt_{ij} = the travel time between locations.

- *Gravity- based approach:* The first group of gravity based approach is Hansen type group:

$$b_1 = \frac{p_i}{t_{ii}} + \sum_{j \in L} \frac{p_j}{t_{ij}}, i \neq j$$
$$b_2 = \frac{p_i}{e^{\beta t_{ii}}} + \sum_{j \in L} \frac{p_j}{e^{\beta t_{ij}}}, i \neq j \qquad (29)$$
$$b_3 = \frac{p_i}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{p_j}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, i \neq j$$

Where, *p* represents population. The second group of gravity-based measures is related to the agglomeration effect which includes:

$$b_1 = \frac{p_i^*}{t_{ii}} + \sum_{j \in L} \frac{p_j^*}{t_{ij}}, i \neq j$$
$$b_2 = \frac{p_i^*}{e^{\beta t_{ii}}} + \sum_{j \in L} \frac{p_j^*}{e^{\beta t_{ij}}}, i \neq j \qquad (30)$$
$$b_3 = \frac{p_i^*}{e^{\delta\left(\frac{t_{ii}^{\theta}-1}{\theta}\right)}} + \sum_{j \in L} \frac{p_j^*}{e^{\delta\left(\frac{t_{ij}^{\theta}-1}{\theta}\right)}}, i \neq j$$

In above equation,p_i^*shows the transformed population of location which is calculated as:

$$p_i^* \mid (t_{ij} \leq 1 hour) = \frac{p_i + \sum_{j \neq i} \Psi_{ij(d)} p_i}{K} \qquad (31)$$

"A location *j* is assumed to be a neighbor of location *i*if t_{ij} is less than or equal to one hour". (Baradaran and Ramjerdi , 2001).

Geurs andvan Eck's method: Location-based perspective

Geurs and van Eck (2003) focused on location-based accessibility measure to assess the job accessibility effects of land-use and transport scenarios. In this regard, they studied accessibility measure based on potential measures:

$$A_i = \sum_{j=1}^{n} D_j F(d_{ij}) \qquad (32)$$

Where, A_i= A measure of accessibility in zone *i* to opportunities *D* in all zones *j*; d_{ij}= the distance between *i* and *j* used, and F= is a distance-decay function. (Geurs and van Eck, 2003, p. 71).

Geurs and van Eck (2003) argued that potential accessibility measures consist of three approaches: In first approach, the effects of competition are incorporated on opportunities by evaluating both the opportunities within reach from origin zone (the supply potential) and the relevant population within reach from the same origin zone (the demand potential), and then they are divided (e.g. see Weibull, 1976).

The second approach is influenced by an accessibility measure developed by Joseph and Bantock (1982) where the accessibility of supply and demand at different places is calculated:

$$\mathrm{A_i} = \sum_{j=1}^{n} \left[\frac{Gp_j}{\sum_{k=1}^{m} P_k \mathrm{F}(d_{jk})}\right] \mathrm{F}(d_{ij}) \quad (33)$$

Where; $\mathrm{A_i}$= The potential accessibility of area i to general practitioners;Gp_j= The number of general practitioners in area j within area i range; p_k= The population in area k within the doctors' catchment area; and $\mathrm{F(d_{ij})}$ = A function of the distance between zones i and j.The third approach is about defining balancing factors of "doubly constrained spatial interaction model". These reverse balancing factors are represented as: (Geurs and van Eck, 2003, p. 72)

$$A_\mathrm{i} = \sum_{j=1}^{n} \frac{1}{B_j} D_\mathrm{j} \,\mathrm{F}(d_{ij}) \quad (34)$$

$$B_\mathrm{j} = \sum_{i=1}^{m} \frac{1}{A_i} O_\mathrm{i} \,\mathrm{F}(d_{ij}) \quad (35)$$

Based on potential accessibility measures, Geurs and van Eck (2003) developed a log-logistic distance-decay function that have the best fit with the observed travel data:

$$\mathrm{F}(d_{ij}) = [1 + \exp(a + b1nd_{ij})]^{-1} \quad (36)$$

Where d_{ij} =travel time between i and j, and a and b are parameters that need to be estimated. (p.76).

Apparicio et al's method: Geographical Accessibility Measure

Apparicio *et al.* (2008) recognized five commonly used spatial accessibility measures: (1) the distance to closest service, (2) the number of services within a certain meters or minutes, (3) the mean distance to all services, (4) the mean distance to a certain number of closest services, and 5) the gravity model (Ngui and Apparicio, 2011). Accessibility measures presented by Apparicio *et al.* (2008), can be written by following formulas:

$$\mathrm{Z_i^a} = \frac{\sum_{b\in i} \mathrm{w_b} (\min|\mathrm{d_{bs}}|)}{\sum_{b\in i} \mathrm{w_b}} \quad (37)$$

Where,Z_i^a= mean distance between census tract i and closest service; w_b= total population of spatial unit b completely within census tract i ; and d_{bs}= distance between spatial unit b and service s. (Apparicio *et al.*, 2008).

$$\mathrm{Z_i^b} = \frac{\sum_{b\in i} \mathrm{W_b} \sum_{j\in S} \mathrm{S_j}}{\sum_{b\in i} \mathrm{W_b}} \quad (38)$$

WhereZ_i^b= mean number of services within n meters or minutes of census tract i; W_b= total population of spatial unit b completely within census tract i ;S = all services; and S_j= number of services within n meters or minutes of spatial unit centroid b with S_j= *1* where $d_{bs} \leq n$ and S_j = *0* where $d_{bs} > n$. (Ibid)

$$\mathrm{Z_i^c} = \frac{\sum_{b\in i} \mathrm{w_b d_{bs}}}{\sum_{b\in i} \mathrm{w_b}} \quad (39)$$

Z_i^c= mean distance between census tract i population and all services;w_b= total population of spatial unit b completely within census tract i; and d_{bs}= distance between spatial unit centroid b and service s. (Ibid)

$$\mathrm{Z_i^d} = \frac{\sum_{b\in i} \mathrm{w_b} \sum_{s} \frac{\mathrm{d_{bs}}}{\mathrm{n}}}{\sum_{b\in i} \mathrm{w_b}} \quad (40)$$

Z_i^d= mean distance between census tract i and n closest services;w_b= total population of spatial unit b completely within census tract i;d_{bs}= distance between spatial unit centroid b and service s (sorted in ascending order); and n= number of closest services to be included in measure. (Ibid)

$$\mathrm{Z_i^e} = \frac{\sum_{b\in i} \mathrm{w_b} \sum_{S} \mathrm{S_{ws} d_{bs}^{-a}}}{\sum_{b\in i} \mathrm{w_b}} \quad (41)$$

Z_i^e= mean value of potential gravity;w_b= total population of spatial unit b completely within census tract i; S = number of services in study area;d_{bs}= distance between spatial unit centroid b and service s;α = friction parameter (usually 1, 1.5 or 2); and S_{ws}= weight given to the service s (e.g. its size). (Ibid).

Tal and Handy's method: Pedestrian Accessibility Measure

According to Tal and Handy (2011), "accessibility is a function of proximity to destinations and the directness of routes to those destinations, or what is generally called network connectivity" (p.1). They studied the effect of the pedestrian network on pedestrian accessibility. In this regard, they identified three network-related measures: (1) Link to Node Ratio (LNR) which is a measure of connectivity independent of origins and destinations. (2) pedsheds which is measured with respect to a specific origin, and (3) Pedestrian Route Directness (PRD) which is measured with respect to a specific origin and destination. (Tal and Handy, 2011, p.4).

LNR is "the ratio of road links (segments of a road between two intersections) to the number of nodes (intersections and sometimes cul-de-sac ends), with higher values indicating a network that provides more route options and more direct connections" (p.4). A pedshed is defined as "the area that can be reached from a given origin by walking along the network for a specified distance as a percentage of the area of a circle with a radius of the same distance" (p.5). PRD is "derived from the second measure and uses the number of households within the pedsheds rather than the number of parcels or the size of the area" (p.5).

Foti et al's method: Distance and Gravity-Based Measures

Foti *et al.* (2012) focus on distance and gravity-based measures and allow a choice of aggregation and decay functions. They use structures and algorithms to compute the proposed accessibility measures: "Efficient algorithms to compute point to point accessibilities, as well as accessibility trees to activities, using a set of weights on the edges of the graph to allow shortest path computations from parcels to activities" (Foti *et al.*, 2012, p. 1). For querying the points of interest (POI), they acted according to Geisberger (2011) who stated that it can be done "with breadth-first search in the unit-distance case or a unidirectional Dijkstra (1959)'s search algorithm for arbitrary edge weights" (Foti *et al.*, 2012, p.6). In this regard, Foti *et al.* (2012) considered the case in which a person is interested in only the *k*-nearest of a categorized POI set (i.e. distinct categories for gas stations, restaurants, etc.). The actual POI locations are mapped to the road network; therefore, the input is a list of vertices. To index the POI locations, Foti *et al.* explored the backward contraction hierarchies search space for each of the inputs. Each encountered vertex has an ordered list based on distance that saves the shortest distances to the POI when they are faced with the search. During the search for the closest POI set, a query calculates the forward search space and examines the list of every encountered vertex. Each list is merged with the sorted result list and the lowest k entries are stored. The search is stopped when the furthest *K*POI in the list is closer to the source vertex compared to any remaining vertex from the search space (p.6 and 7).

Discussion

Based on the literature review, Five approaches for measuring accessibility are classified: travel-cost approach, gravity approach, constraints-based approach, utility-based approach, and composite approach. Accessibility measures in these classes differ in three respects: theoretical foundation, complexity of construction, and demand on data (Baradaran and Ramjerdi, 2001). Although the model presented by Hansen (1959) is not yet sufficiently well refined for estimating purposes, the concept and the approach may be potentially useful tools for metropolitan planning purposes. The Gaussian curve presented by Ingram (1971) is the most applicable of the measures discussed for the quantitative measurement of accessibility. His technique may also be useful in measuring the integral accessibilities of one set of points with respect to another set of points, for example, the accessibility of workplaces to residential locations.

The framework developed by Wachs and Kumagai (1973) is 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. Its data are to illustrate differences in accessibility as a function of spatial location of residence, and socio-economic status. The accessibility measure (axiomatic approach) presented by Weibull (1976) contains as a sub-class called "gravity potentials". Koenig (1980)'s method (behavioral approach) allows a better appraisal of accessibility indicators and precise recommendations are proposed for their practical formulation and use. It suggests that accessibility is a powerful determinant of trip rate. By using Miller (1991)'s method, we can determine the feasibility of current GIS technology to handle the derivation of space-time prism concepts.

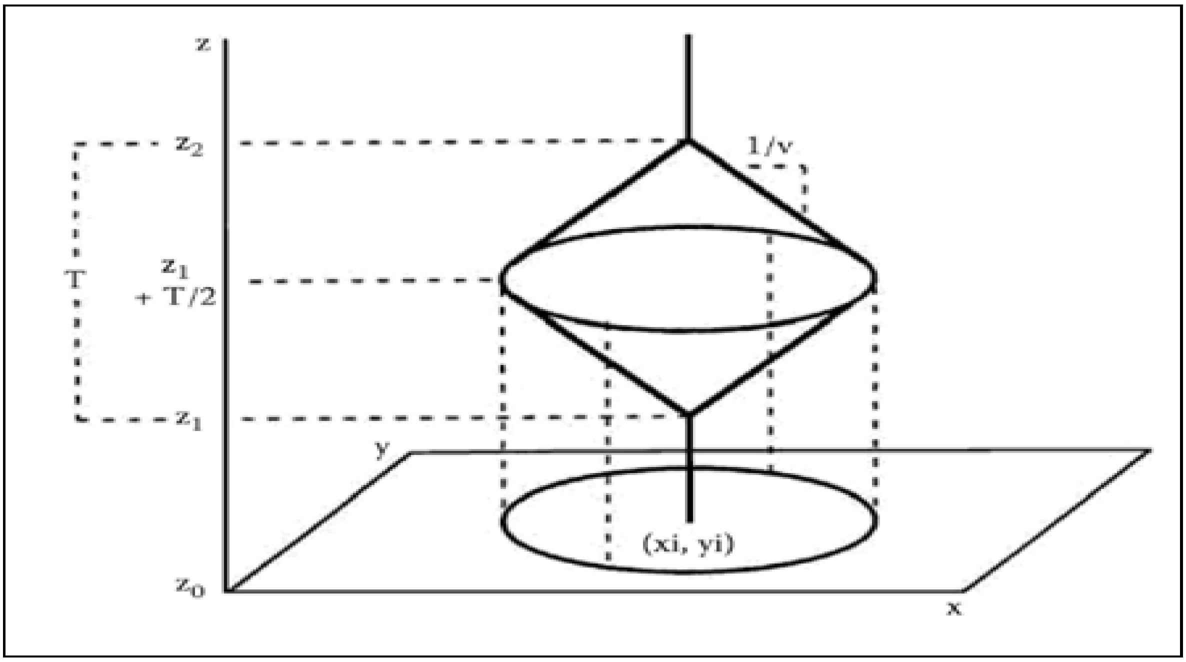

Fig. 1. A Scheme of a space-time prism model adapted from Fisher (2006).

The ability of a GIS to handle data on street networks can provide a realistic operational version of the potential path area, or the spatial extent of an individual's reach given spatial and temporal constraints on movement. The concept presented by Wang and Timmermans (1996) is used to develop measures of accessibility of people and locations. These measures evaluate accessibility in terms of opportunities to participate 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 Kwan (1998)'s method, space-time and integral indices are distinctive types of accessibility measures which reject 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. Results of Kwan (1998) support the findings of earlier studies (Handy and Niemeier 1997) that the accessibility patterns observed in a particular analytical context depend on the type of accessibility measures used even when the analysis is based on individual-level data and nonzonal methods. The method of Bhat *et al.* (2000) was developed for the aggregation of the spatial data.

The technique draws from the multinomial logit model, which is a workhorse of transportation planning. Their proposed accessibility measure and the techniques were incorporated into a software package that offers flexibility to the user in many different areas. Users may input their own data or, if they are in one of the two default areas, may use the information included regarding these areas. Results may be presented as color-coded maps, or as database outputs; when comparing two different runs, results can be displayed with a map showing the differences in accessibility. Although the aggregation method presented by Bhat *et al.* (2000) advances the field, there are many areas requiring attention. First, the different results from using weighted and unweighted aggregation methodologies need to be evaluated more thoroughly. Second, a comparison of the different levels of aggregation for different size study areas needs to be explored. And third, the default data included in the software needs to be expanded to more areas.

According to Baradaran and Ramjerdi (2001), we found out that there are some important issues relevant in modeling accessibility which are: measurement of spatial separation, measurement of attraction masses, choice of demarcation area, unimodality versus multimodality, agglomeration effects, the dimension problem, and time of day. They indicated the importance of the availability of necessary data for the comparison and evaluation of accessibility measures by all identified approaches. Geurs and van Eck (2003)'s method revealed that traditional evaluations of accessibility impacts of land-use and transport policies can be improved by estimating potential accessibility measures. These measures can be easily computed from existing land-use and transport data, and/or models, which are traditionally employed as input for estimating infrastructure-based measures. Also, based on their proposed technique: (1) incorporation of job competition into accessibility estimations significantly affects the results; (2)the interpretability of activity-based accessibility is much improved by estimating the separate influence of land-use changes, infrastructure projects, and congestion on the development of (job) accessibility; (3)incorporating the match between job and educational levels is important in evaluation of job accessibility, and results in more accurate accessibility computations. However, a shortcoming of the study is the aggregate level of analysis; and (4) by the use of activity-based accessibility measures, a land-use scenario with a near-zero average accessibility change may reveal considerable spatial variation in accessibility changes. In Apparicio *et al.* (2008)'s method, in comparison to the most accurate aggregation method (population-weighted mean of the accessibility measure for census blocks with in census tracts), accessibility measures computed from census tract centroids, though not inaccurate, yield important measurement errors for 5% to 10% of census tracts. By using Tal and Handy (2011)'s method, suburban areas with lower housing density and a pedestrian network based on pathways, parks, and greenbelts, can have a higher level of connectivity and accessibility than measured in a more traditional grid network with four-way intersections and small blocks. Accounting for actual pedestrian connectivity, particularly the connections to schools and other public facilities, can lead to both better planning and more accurate research with respect to the conditions that promote walking. They focused on the pedestrian network rather than the bicycle network. More detailed analysis is needed to understand differences between these as well as differences in the networks relevant to bicyclists of different abilities. Finally, by reviewing Foti *et al.* (2012)'s technique, we found some limitations: One major limitation of this work is that it is only a distance and gravity measure based framework. Ideal accessibility measures would be derived from the utility of a log sum in a choice model. Additionally, queries have a single node of origin; to capture space-time prism-style accessibility, the shortest path between two points and a maximum deviation would need to be implemented. Second and perhaps more importantly, this work is a distance-based implementation. It should be expanded to include multi-modal travel times, using congested road network travel times, transit schedule-based travel times, and bike network travel times. These travel times can then be used in lieu of distance in the radius of the accessibility computation.

Conclusion

In this study we reviewed different approaches to the measurement of accessibility in the literature of urban studies. A look at the literature in this study revealed a wealth of information regarding the theory and specific construction of accessibility measures. This can help policy makers gain a better understanding of the strengths and weaknesses of each method when they are used for urban planning and management.

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