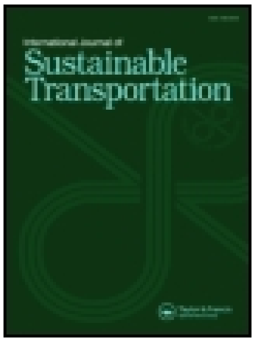

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A review of transit accessibility models: Challenges in developing transit accessibility models

Ali Malekzadeh[a] and Edward Chung[b]

[a]Faculty of Science and Engineering, Queensland University of Technology, Brisbane, Australia; [b]Faculty of Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong

ABSTRACT

The increasing traffic congestion and pollution in cities is seriously threatening the livability and development of urban areas. As a result, the growing importance of transit accessibility is attracting considerable attention among researchers in transport planning, urban geography and sustainable development. To help solve these increasingly serious issues, public transport studies related to transit network design, transit system evaluation, land use, and transport planning in cities require accurate transit accessibility measurements. The past three decades have seen a burgeoning body of research on transit accessibility, and numerous models have been developed to measure transit accessibility for different purposes. This comprehensive review explores the existing transit accessibility models and highlights their practical advantages and drawbacks from different perspectives to help researchers and transport planners employ the most suitable models to counter mounting traffic threats. Accordingly, this review seeks to answer the following questions. What are the major challenges in developing transit accessibility models? What are the potential research directions to address these challenges? Why have different researchers developed different models for measuring transit accessibility in cities? How important is it to estimate travel impedance or attractiveness of opportunities accurately? Finally, what are the important criteria for developing future transit accessibility models? To deliver its outcomes and answer these questions, this paper reviews transit accessibility models under three main categories: system accessibility, system-facilitated accessibility and access to destinations.

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1. Introduction

Evaluating transit accessibility has attracted particular attention from both policymakers and transport planners, as various measurements have been applied recently to assess the results of transport planning in cities. Primary approaches use only access time in their suggested methodology, while contemporary models can usually incorporate different accessibility components.

However, because of the various spatial and temporal dimensions of transit accessibility, and its multimodal nature, finding a measurement to capture all these components accurately is relatively difficult (Lee, 2009; Mavoa, Witten, McCreanor, & O'Sullivan, 2012; Murray, Davis, Stimson, & Ferreira, 1998). On the question of transit accessibility models, it is widely agreed that incorporating different aspects of accessibility can affect the practicality of models and increase their complexity. Detailed models combine different variables with different measuring units, which can make them difficult to understand and use. In contrast, simple models, based on travel time estimations, are easy to analyze and understand, but they are not usually accurate, as they do not capture different aspects of transit accessibility.

This paper presents a thorough assessment of transit accessibility approaches and attempts to find directions for improving the existing models. Consequently, this study clarifies the advantages and limitations of existing approaches and highlights the characteristics of accurate transit accessibility models. Although a number of researchers have published review papers on accessibility measurements (Geurs & Van Wee, 2004; Pirie, 1979; Scheurer & Curtis, 2007; Vale, Saraiva, & Pereira, 2015), none of these studies has focused on transit accessibility models in particular. This research differs from those review papers as it focuses only on transit accessibility models.

In this paper, section 2 describes the accessibility notion and transit accessibility components. Section 3 reviews current transit accessibility measurements and approaches. Section 4 presents the existing challenges in developing transit accessibility models and explores possible directions for developing more accurate models in the future. Finally, section 5 provides a summary and conclusion for this study and illustrates future trends for developing more accurate models.

2. Accessibility concept and transit accessibility definitions

Although the concept of accessibility has been discussed in transportation literature for more than five decades, it is still

CONTACT Edward Chung edward.cs.chung@polyu.edu.hk Faculty of Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong.
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difficult to define and measure (Handy, 2002; Horning, El-Geneidy, & Krizek, 2008; Lei & Church, 2010; Wang, Brown, & Mateo-Babiano, 2013). Accessibility definitions become very important because different accessibility concepts and measurements demonstrate the developers' approaches to accessibility (Jones, 1981; Makri & Folkesson, 1999). As accessibility is studied in various fields, such as socioeconomics, transportation, and urban planning, it can be defined in several ways (Doi, Kii, & Nakanishi, 2008).

The concept of accessibility, which was developed in the 1950s, was acknowledged as an urban growth concept for controlling future urban development (Wegener, 1998). These definitions, however, have not focused on forecasting the development of cities; instead, they have attempted to explain the interaction between land use and transportation strategies, as well as the socioeconomic characteristics of residents (Geertman & Ritsema Van Eck, 1995).

Early accessibility definitions focused only on the attractiveness of opportunities for defining accessibility. Hansen (1959) defined it as "the potential of opportunities for interaction." A number of researchers explained the interaction between land use and transport systems by defining accessibility as "the ease with which any land-use activity can be reached from a location using a particular transport system" (Dalvi & Martin, 1976); "the benefits provided by a transportation/land-use system" (Ben-Akiva & Lerman, 1985); "the number and diversity of places that can be reached within a given travel time and/or cost" (Bertolini, 2005); and "the consumer surplus, or net benefit, that people achieve from using the transport and land-use system" (Leonardi, 1978). Iacono, Krizek, and El-Geneidy (2010) described accessibility as a tool for monitoring land use and the transportation system, and for assessing the effect of proposed policies and decision making on land use or the transport network. Based on this definition, accessibility should describe the benefits of both transport and land-use planning together.

El-Geneidy and Levinson (2006), Burns (1980), Huisman (2005), and Weibull (1980) moved a step forward, involving the effect of "individuals or socioeconomic" variables. Burns (1980) defined accessibility as "the freedom of individuals to decide whether or not to participate in different activities"; Weibull (1980) defined it similarly as the freedom and ability of people to participate in different activities. Huisman (2005) viewed accessibility as "a significant concept employed to understand patterns in the location of facilities and to indicate broad features of the behaviour of people, as well as evaluating the ability of services to meet people's needs." El-Geneidy and Levinson (2006) defined it as "a measure or indicator of the performance of transportation systems in serving individuals living in a community."

Bhat et al. (2000) added a "temporal" aspect to the accessibility definition, describing it as the "ease of an individual to pursue an activity of the desired type, at a desired location, by a desired mode, and at a desired time." They defined accessibility by land-use attractiveness, transport system attributes, travelers' characteristics and temporal aspects of accessibility.

Some of the literature added further dimensions to the accessibility definition by introducing subsidiary notions. Ingram (1971) introduced the concept of "relative accessibility," which is the level of connectivity between two locations, and "integral accessibility," which is the connectivity to all other locations in a given area. Handy (1992) defined "local accessibility" as accessibility to nearby activities, such as small shopping centers and supermarkets, associated with short and frequent trips, and "regional accessibility" as accessibility to large shopping centers and commercial areas associated with long and infrequent trips.

Yet another dimension occurs between 'active accessibility', which is a traveller's desire and ability to participate in different activities located in a given area, and 'passive accessibility', which is the ease of reaching a place by different travellers in a given area (Cascetta, 2013; Hanson, 1995; Miller, 2007; Pirie, 1979). Miller (2007) also added another definition to accessibility by introducing people-based accessibility versus traditional place-based accessibility. In this definition, Miller (2007) defined people-based accessibility as the ability to perform an activity in a place without being physically present through the help of communication technology.

The literature defines transit accessibility in a similar fashion, restricting the mode of travel to public transit and perhaps walking (Hillman & Pool, 1997; Liu & Zhu, 2004; Murray et al., 1998; O'Sullivan, Morrison, & Shearer, 2000). Ikhrata and Michell (1997) described transit accessibility as an evaluation of the transit system from the transit users' point of view. This recent transit accessibility definition emphasize transit users' behavior in the transit system and explain how travelers understand transit services when they use them to reach their destination and to find out which parameters are important from their perspective (e.g., travel time, transit transfers and fares).

Defining and finding an appropriate approach for estimating accessibility is becoming a very important matter, as recent investigations in the U.S show that most planning agencies consider mobility improvement as a way to improve accessibility (Proffitt, Bartholomew, Ewing, & Miller, 2019). Following this approach in the planning of cities ignores the effects of other important accessibility components for improving the accessibility in the cities.

From these definitions, we can derive four main components in transit accessibility approaches: attractiveness of opportunities (land-use), transport, and temporal and individual (socioeconomic) components.

The "attractiveness of opportunities or land use" component describes land-use conditions, including quantity of opportunities, quality of land use, spatial distribution of opportunities, and competition between supply and demand. The "transport" component represents transport supply attributes and the performance of the transport system, such as travel time, cost of travel, reliability and level of comfort. The "temporal" component describes temporal constraints, such as the availability of opportunities at different times, and the time availability for people to take part in various activities (Geurs & Van Wee, 2004). The "individual or socioeconomic" component involves traveler characteristics and

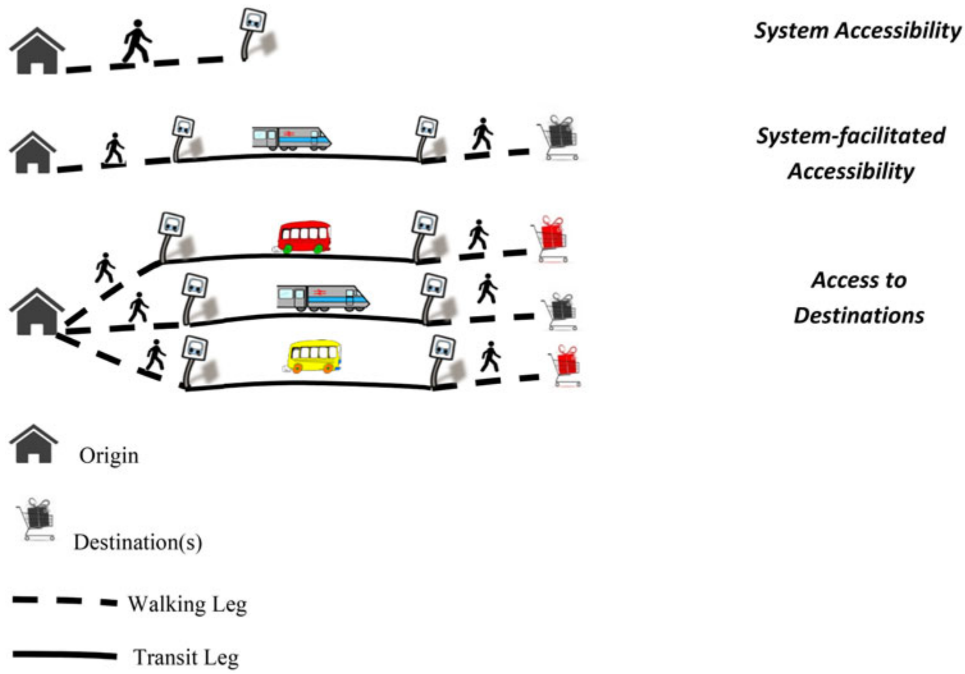

Figure 1. Schematic graph of different approaches for measuring transit accessibility.

abilities, such as the socioeconomic characteristics of individuals and their physical abilities. This component is important, as the ability and preferences of travelers can affect their level of access to the transport system and opportunities (Cervero, Rood, & Appleyard, 1995; Geurs & Van Eck, 2003; Geurs & Van Wee, 2004; Shen, 1998).

3. Methodological approaches to measure transit accessibility

Most transit accessibility approaches can be classified into three main categories. The first group of transit accessibility models deals with physical access to the public transit network, estimating how easy it is for a person to reach public transit stops using different travel modes. These transit accessibility measurements, called “system accessibility” or “access to transit stops,” can evaluate only distance, time or effort to reach a transit network. In other words, these approaches address only the “first-mile” aspect of the transit network. The second type of transit accessibility measurement is called “system-facilitated accessibility.” Compared to the first category, system-facilitated accessibility measures a traveler’s ability to reach an opportunity by incorporating the travel time or cost spent in the transit network. Therefore, these models focus mainly on the performance of the network in estimating accessibility to a single destination. They do not show overall accessibility from a given area to multiple surrounding opportunities. The third type of transit accessibility measurement is called “integral accessibility” or “access to destinations.” While the first two measurement approaches show access to a network or access provided by a transit facility to travel to a destination, the third group, is associated with measuring overall access to a number of possible destinations, reveals how easy it is for residents to travel from an origin to opportunities using public transit (Lei & Church, 2010; Mavoa et al., 2012).

Figure 1 provides a simple explanation of the different transit accessibility measurement categories.

This study exclusively reviews the transit accessibility models which have been developed and examined in real transit networks under these three categories. This research reviews the most innovative and novel models proposed in the most highly cited papers since the concept of transit accessibility was first defined up to the present. Google Scholar was utilized for this purpose. This study also focuses only on transit accessibility methodologies; it does not review other transit accessibility sub-categories, such as social exclusion.

For greater reader value, models were sorted and classified based on practicality and ease of implementation. Each section first evaluates more practical models. Model practicality can be defined as ease of access to the data (using open-source data or transit agency data in comparison to subjectively generated data) and ease of modeling and calculation. Also, to provide a clear review this paper explores the complex models in more detail than models with simpler methodologies.

3.1. System accessibility models (accessibility to transit stops)

Access to transit stops is important because reaching public transit is an important part of the public transit journey (Mavoa et al., 2012). Various models for measuring accessibility to transit stops have been introduced by researchers. These approaches use a variety of measurements, from simple estimation methods, such as distance or cumulative measurements, to more complex measurements, such as gravity or utility-based measurements.

3.1.1. Distance-based system accessibility approaches

The distance-based model is a simple and popular technique in transit accessibility modeling and has been developed by many researchers. The distance measure is the easiest accessibility measurement, as it simply incorporates the distance from a given origin to different opportunities into the model. The distances in these models can be estimated as the average distance to opportunities in a given area or the distance to the closest opportunity. Some studies have proposed simple straight-line (Euclidean) distances; while others have proposed complicated impedance formulations for weighting the distance to opportunities (Geurs & Van Wee, 2004; Makri & Folkesson, 1999).

Foda and Osman (2010) suggested a number of simple distance-based algorithms for measuring transit accessibility at this level. They introduced ideal and actual stop accessibility indices (ISAI and ASAI) and the stop coverage ratio index (SCRI) to measure accessibility to public transit stops.

The ISAI represents accessibility to a transit stop through a nearby pedestrian road network and is calculated by dividing the overall length of the pedestrian road network links located within a walking distance of 400 m by the ideal access coverage area of the bus stop, measured as a circle with a radius of 400 m.

The ASAI is calculated by dividing the overall length of the pedestrian road network links located within walking distance of 400 m by the actual access coverage area of the bus stop, measured on the basis of the geometric area of the pedestrian road network around the bus stop within the given walking distance. In the ASAI, the denominator is not a fixed rate as in the ISAI; it relates to the surrounding road network formation. However, in the ASAI, an index value decrease does not show whether the bus stop is less accessible or if this decrease is because of a greater bus stop access coverage area rather than being an effect of reducing the pedestrian road network length (Foda & Osman, 2008, 2010).

Foda and Osman (2010) also introduced the SCRI to highlight the proportion of the actual access coverage to the ideal access coverage of a transit stop. This index is calculated by dividing the actual access coverage area of the bus stop, measured on the basis of the pedestrian road network paths (geometric area), by the ideal access coverage area, measured as a circle with a radius of 400 m, with the bus stop located in the center of the circle.

Polzin, Pendyala, and Navari (2002) developed another model to improve the accuracy of system accessibility estimations by incorporating travel demand (spatial distribution of population and employment) and the temporal aspects of transit services (e.g., temporary service availability and transit service frequency). This approach, called the Time-of-Day-Based transit accessibility model, has been tested in Tampa, Florida. Although this distance-based approach expanded the definition of physical access by including temporal details, such as time of day, the model again simplified the access distance calculation by defining a pre-determined buffer zone (e.g., 0.5 miles) around the transit routes and utilizing an average tolerable wait time (e.g., 10 min) for all modes of transit services.

Gan, Liu, and Ubaka (2005) also proposed a system accessibility model using the Florida Transit Geographic Information System (FTGIS). Accessibility in this model is defined by the number of people served in the transit catchment area, a three-quarter mile buffer zone around the transit stops. The model was also used for estimating the level of service for different demographic groups.

One of the main drawbacks to these distance-based approaches relates to adopting fixed distance ratios (e.g., 0.25, 0.5, or 0.75 miles) as acceptable and desirable walking distances to transit stops. It is not appropriate to apply fixed-distance values in different case studies as in most cases, the average access and egress distances are different from the adopted distances in these approaches.

The public transport accessibility level (PTAL) is also a well-known distance-based system accessibility model, which has been used in the UK since 1992. The PTAL model incorporates public transport attributes by applying average waiting time based on service frequency and reliability. Walking times are calculated from the origin to all public transit stops in the catchment area. The total access time in this model is converted to an EDF (equivalent doorstep frequency) factor for each destination; the EDF values are then summarized for all routes within the catchment area and for the different transport modes, such as bus and rail, to incorporate the benefits offered by the different routes (Kerrigan & Bull, 1992; Wu & Hine, 2003). To calculate the accessibility index (AI) for a single mode in this model, all EDFs for all available routes need to be summarized with a weighting factor in favor of the route with the maximum EDF value:

$$AI_{\text{mode}} = EDF\ max\ +\ (0.5\ *\ All\ other\ EDFs) \tag{1}$$

The overall accessibility index can then be calculated as the total of the individual accessibility indices for all modes. The PTAL model has the advantage of including choice of routes and transit modes, but traveler behavior cannot be incorporated into the measurement.

Some researchers also incorporate travel demand into the distance-based models by incorporating population into the model.

3.1.2. Gravity-based system accessibility approaches

The gravity-based models propose a weight to opportunities representing their attraction and apply an impedance value (decay function) to reflect their distance from origin. Gravity-based models differ in the method adopted for the decay function calibration, as well as for calculating the attractiveness of opportunities (Dong, Ben-Akiva, Bowman, & Walker, 2006; El-Geneidy & Levinson, 2006; Geertman & Ritsema Van Eck, 1995; Makri & Folkesson, 1999).

A number of studies (e.g., Levinson and Brown-West, 1983) in the context of transit accessibility show that the desirability of using transit services drops sharply after the first 0.06 miles, and gradually diminishes beyond 0.36 miles. To incorporate these deterioration effects into transit accessibility, Zhao, Chow, Li, Ubaka, and Gan (2003) developed a gravity-based system accessibility model to reflect the diminishing trends in transit service use, by increasing the walking distances, as well as both natural and man-made barriers in the walking network. They defined an exponential decay function to capture traveler behavior for accessing transit services. However, these approaches do not successfully capture actual transit user behavior, as people may walk a long way to a transit stop if they have no alternative to reach the transit corridor.

Giannopoulos (1989) also developed another system-facilitated accessibility model based on the gravity approach for train services, defining transit accessibility based on station accessibility. In that model, transit accessibility is defined as a function of the population in the catchment area of the train station and the average travel time to the station, with all available modes as variables in the impedance factor:

$$A_i = \sum_j P_j f(t_{ijm}) \tag{2}$$

$$f(t_{ijm}) = \frac{\sum (t_{ijm})^{-a}}{m} \tag{3}$$

where P_j represents the population in the catchment area, t_{ijm} indicates the travel time to the station by mode m, and m indicates the number of modes.

Their model has an advantage over the existing system accessibility approaches, as it considers the effect of all available modes of travel for accessibility to train stations. The model outcome can also be improved by calibrating the weight of each available mode of travel.

Analysts and researchers in the fields of urban planning, public health and finance (such as Kocher and Lerner (2007) and Chiu et al. (2015)) developed another system accessibility measure in the context of the gravity-based approach, known as "Transit Score". The value of a route is defined as the service level (frequency per week) multiplied by the mode weight (heavy/light rail is weighted 2X, ferry/cable-car/other is 1.5X, and the bus is 1X) and by a distance penalty. This model has several shortcomings, as it uses an arbitrary approach to weigh the transit modes and applies a pre-defined distance decay function to capture public transport performance.

3.1.3. Utility-based system accessibility approaches

The utility-based models are defined based on the "logsum" expression of a random utility model, in which the probability of an individual making a particular choice is related to the utility of all available choices (Ben-Akiva & Lerman, 1985). The theoretical basis of utility models is directly linked to economic theory and is consistent with the key concept of total consumer net benefit. According to this theory, individuals gain utility by proximity to urban opportunities reachable within a given travel expense (Cascetta, 2013; Hansen, 1959). According to the economic benefits theory, people benefit when they have access to opportunities (El-Geneidy & Levinson, 2006).

Rastogi and Rao (2002), and Rastogi and Krishna Rao (2003) introduced and developed a utility-based system accessibility model that considers random utility for access to transit stations, using individual or socioeconomic variables, mode availability (e.g., walking, bicycle and bus), impedance to access to the station in each mode, and the environmental impact of each mode.

Their proposed model, known as the Environmental Transit Accessibility Index (ETAI), takes into account traveler characteristics (individual behavior), environmental effects, and transport attributes to model the accessibility to transit stops. In this model, the choice of access mode for accessing the transit station is determined by the socioeconomic characteristics of the individuals, the impedance to access to the station in each mode, and the environmental impact of each mode in a random utility framework. The model can also consider the choice of access stops by using the average distance to transit service stops (Rastogi & Krishna Rao, 2003).

Although the ETAI model incorporates different variables into the model, it describes only the traveler's access behavior to transit stops; it does not explain the travelers' choice or their perception of the entire transit network.

3.1.4. Discussion of system accessibility approaches

System accessibility indices represent an overview of accessibility to public transport stops; they do not capture public transport features to actual destinations. With the exception of the ETAI model, they typically do not consider difficulties that travelers may experience in getting to public transit. Although these approaches are useful tools for measuring public transit availability, they do not provide a general view about actual transit accessibility in an entire transit network. In most cases, they provide either underestimated or overestimated results for transit accessibility. For example, several cases with long transit travel times to actual (final) destination may be identified as having high system accessibility due to their proximity to the transit system and vice versa.

Table 1 provides a summary of system accessibility models. In this research, model practicality is defined as data availability for the model and ease of implementation in different case studies.

3.2. System-facilitated accessibility

Many researchers (e.g., Lei & Church, 2010; Liu & Zhu, 2004; Leake & Huzayyin, 1979; and Mavoa et al., 2012) have acknowledged the importance of both focusing on accessibility to transit stops and finding accessible areas for traveling by public transit.

Our review of system-facilitated models shows that although these measurements commonly use a distance-based approach to estimate accessibility, they use different methods to estimate distance in the transit system. Liu and Zhu (2004) developed a GIS tool called ACCESS to estimate

Table 1. A summary of system accessibility models.

Developer(s)	Name of model	Type of measurement	Indicators	Travel mode	Trip purpose	Components	Pros and cons	Practicality
London Borough of Hammersmith and Fulham (1992)	PTAL (Public transport accessibility level)	Distance measurement	Walking time, reliability of the service modes, number of services, and the level of services at access points (e.g., waiting time)	Walking to transit stops	—	Transport, temporal (partial)	The key advantage is that it is easy to understand, but it does not capture traveler characteristic	●
Foda & Osman (2008, 2010)	Ideal Stop Accessibility Index (ISAI), Actual Stop Accessibility Index (ASAI), and Stop Coverage Ratio Index (SCRI)	Distance Measurement	Network and Euclidean Distance	Walking to transit stops	—	Transport (partial)	Considers only the pedestrian network to transit stops	●
Hsiao, Lu, Sterling, and Weatherford (1997)	—	Cumulative Model	Euclidean distance and spatial variables (e.g., population and employment)	Walking to transit stops	—	Transport (partial) and land-use demand and supply (partial)	Highlights a strong relationship between transit service ridership and walking access to transit services	●
Polzin et al. (2002)	Time-of-Day–Based transit accessibility model	Cumulative Measurement	Network distance, service frequency, spatial distribution of population and employment	Walking to transit stops	—	Transport, temporal, land-use demand and supply (partial)	Measures the spatial and temporal aspects of transit accessibility	●
Gan, Liu, and Ubaka (2005)	—	Cumulative Measurement	Network distance and population	Walking to transit stops	—	Transport (partial) and land-use demand (partial) and socio-economic characteristics (partial)	Estimates the level of service for different demographic groups of people	●
Zhao et al. (2003)	—	Gravity/ Cumulative Measurement	Network distance and population	Walking to transit stops	—	Transport and land-use demand (partial)	An exponential curve is weighted based on distribution of walking distances to transit stops	●
Giannopoulos (1989)	—	Gravity-based Model	Travel time and population	Walking, cycling or private car to train stations	—	Transport and land-use demand (partial)	Incorporates the effect of all available transport modes for access to train stations	●
Kocher and Lerner (2007)	Transit Score	Gravity-based Model	Transit service features (e.g., frequency per week), transit mode availability (e.g., train, ferry, bus) and network distance	Walking to transit stops	—	Transport	Incorporates the service level of public transport into the model	●
(Rastogi & Krishna Rao, 2003; Rastogi & Rao, 2002)	ETAI (Environmental Transit Accessibility Index)	Utility Measurement	Network distance, environmental effects and transit mode availability	Walking and cycling to transit stops	—	Transport, individual and temporal (partial)	Based on choice of access stops, but impractical in most cases due to difficulties with data collection	○

● Completely satisfactory; ○ Partly satisfactory.

system-facilitated accessibility. This model uses a cumulative platform to measure transit accessibility by measuring the number of residents with access to a particular destination within a specified time or cost. The proposed model calculates the shortest travel time from origin to destination using the distance and average travel speed in each part of the trip (access, in-vehicle and egress). The model also estimates the trip cost and converts it to travel time to calculate travel impedance. Although the model is structured on the shortest network distance algorithm, it does not consider either the waiting time or the frequency of the transit system. More complex measurements in this category incorporate attributes such as transfer time, waiting time and detailed schedule information. For example, Hillman and Pool (1997) introduced a GIS-based tool, ACCMAP, to incorporate the walking time to a stop, the waiting time at the stop, the in-vehicle traveling time, and the frequency of transit services at peak and off-peak times. This model can also be integrated with land use and census data to highlight low-service locations for specific population groups.

Leake and Huzayyin (1979) also introduced a system-facilitated method for measuring transit accessibility based on travel time in the transit system, service frequency and coverage by transit routes. Like Hillman and Pool (1997), they incorporated the temporal aspect of accessibility into the model by measuring accessibility at different periods of time (peak time, off-peak time, weekdays, and weekends).

Tribby and Zandbergen (2012) proposed a high-resolution, multimodal model to incorporate the travelers' behavior into the model. Their model utilizes an ArcGIS platform to estimate the walking time from residential locations to a bus stop, waiting time at the bus stop, travel time on the bus, and any necessary transfers. It incorporates socio-economic data (e.g., low-income group, car-less, older than 65) to identify critical areas for public transport improvement.

Schoon, McDonald, and Lee (1999) improved the accuracy of system- facilitated accessibility by incorporating the time and cost of travel for different travel modes into the model. This model, called Accessibility Indices (AIs), is based on measuring door-to-door travel times and the cost between home and 15 important destinations. They estimated the total travel time as the average travel time of all modes of travel and introduced a travel time index. They also used a similar procedure to estimate the cost index.

Measuring transit accessibility by incorporating traveler stop choice behavior is another system-facilitated accessibility model, developed by Nassir, Hickman, Malekzadeh, and Irannezhad (2015) and Nassir, Hickman, Malekzadeh, and Irannezhad (2016). This proposed model improved public transport accessibility measurement by capturing traveler's behavior, the diversity of public transport modes, and the subjectivity of traveler's decisions in complex transport networks. The results of this measuring method highlighted the importance of considering public transport network characteristics, such as travel time, the number of transfers, access walking and shelter availability, and revealed the importance of public transport diversity in public transport accessibility modeling.

3.2.1. Discussion on system-facilitated accessibility models

Although system accessibility models have the advantage of capturing travelers' difficulties when traveling through the transit system to their destination, they cannot capture the importance of opportunities from the perspective of residents and travelers. So although these models are useful tools for measuring transit accessibility to certain points, such as the CBD or the airport, they cannot capture the effect of land-use supply on transit accessibility.

These models are generally structured on the distance-based approach, which does not allow capture of traveler behavior in the transit system. A brief review of these models is summarized in Table 2.

3.3. Access to destination models

Measuring access to various activities and opportunities is the ultimate goal of the accessibility models. This third category of measurement estimates overall access associated with a number of possible destinations. As previously explained, system-facilitated accessibility models, show the accessible area via public transit, but they do not incorporate the importance of destinations into the model. Several methods have been proposed to measure overall transit accessibility between origin and destinations. We have categorized these accessibility models into three groups: distance-based, gravity-based, and utility-based access to destinations models.

3.3.1. Distance-based access to destinations models

One of the basic models in this category is Land Use and Public Transport Accessibility Indexing (LUPTAI), which was developed by Yigitcanlar, Sipe, Evans, and Pitot (2007). The LUPTAI model is an origin-based model which estimates transit accessibility via walking and the public transport (PT) network and estimates accessibility to five different land uses: employment, health, shopping, financial and education centers. This modeling process includes three main steps: (a) estimating walking accessibility based on walking distance to and from public transit stops; (b) estimating PT accessibility based on PT travel time; and (c) combining both measures and assigning accessibility index values to each defined grid cell. The model also uses population density to highlight areas that have a major inequity of accessibility in relation to population. LUPTAI is based on the Geographical Information System (GIS), which makes the calculations simple, but requires an extensive data set for processing (Davidson, 2008; Yigitcanlar et al., 2007).

Although LUPTAI is a decision support tool enabling local and state governments to optimize land use and transport integration, it has a number of limitations. The model defines arbitrary distance ranges for access walking (e.g., 400, 600, 800, 1,000, and 1,200 m) to evaluate quality of access to transit stops, and utilizes arbitrary service

Table 2. Summary of system-facilitated accessibility models.

Developer(s)	Name of model	Type of measurement	Indicators	Travel mode	Trip purpose	Components	Pros and cons	Practicality
Liu and Zhu (2004)	ACCESS	Cumulative Measurements	Travel time (access, in-vehicle and egress) and cost of trip	Walking and transit	—	Transport (partial)	Does not consider waiting time for transit services	●
Hillman and Pool (1997)	ACCMAP	Distance Measurement	Travel time (access, waiting time, in-vehicle and egress) and traveler census data	Walking and transit	—	Transport, temporal, socioeconomic (partial)	Can be integrated with land-use and census data	●
Leake and Huzayyin (1979)	—	Distance Measurement	Public transport attributes (service frequency, number of routes and number of available modes), and temporal factors (time of day/week)	Walking and transit	Home-based and non-home based accessibility to work, education and other activities	Transport and temporal	Uses the coverage area around the transit routes instead of transit stops	●
Tribby and Zandbergen (2012)	—	Distance Measurement	Travel time (walking time, waiting time, transfer time), peak and off-peak bus travel times, and socioeconomic attributes (e.g., low-income group, car-less, over 65)	Walking and transit	—	Transport, temporal and socioeconomic (partial)	Uses average travel and waiting time, not the actual travel time estimation	●
Schoon et al. (1999)	Accessibility Indices (AI)	Distance Measurement	Travel time (access, egress, in-vehicle and waiting time) and travel cost (fare, toll, car operating and parking costs)	Walking, transit, car and bicycle	15 different destinations	Transport and temporal (partial)	Used to evaluate existing transport policies and find ways to improve public transit services; requires detailed transport data	○
Nassir et al. (2015); Nassir et al. (2016)	Stop Choice Model	Utility Measurement	Travel time, number of transfers, access walking, shelter availability, and transit mode	Walking and transit	—	Transport, socioeconomic and temporal (partial)	Treats the correlation among the public transport mode choices and between stop choices	●

● Completely satisfactory; ○ Partly satisfactory.

frequency to assess the transit service quality. Another drawback to this model relates to estimating the composite index. The model assigns equal weight to all opportunities (i.e., education, health, shopping) to estimate the aggregate accessibility indices, even though travelers may give different values to different activities and destinations.

Mavoa et al. (2012) developed the Public Transit and Walking Accessibility Index (PTWAI) to measure potential access between land parcels as origins and opportunities via public transit (buses, trains and ferries). To improve the modeling results with arbitrary distance ranges, the PTWAI applies a multi-model network, utilizing travel time as network impedance and includes service frequency by estimating the average number of public transit routes through each transit stop. The model applies an additional 10 minutes waiting time at each transit stop. This is considered "arrive to wait" time. The model calculates an average for transit accessibility to 17 different land uses.

One of the main drawbacks of the model relates to its estimated impedance. The waiting times are estimated by averaging the number of trips per hour per stop. This does not consider actual travel frequency or the number of available transit services at each stop. The accessibility index in this model is also structured on the mean of the accessibility index in each land-use category. This method does not consider the importance and preferences of different opportunities from the perspective of travelers, as it gives equal weight to different land uses.

Lei and Church (2010) introduced another distance-based transit accessibility model, based on the Dijkstra algorithm. They developed an algorithm to find the shortest path from a given origin to the possible opportunities. In this algorithm, transit stop choice is made based on the fastest possible journey to destinations, which is not necessarily the closest transit stop with the shortest walking time from a given origin. Although this approach has the advantage of more accurately estimating travel time by incorporating actual transit service frequency and utilizing a shortest path algorithm, the composite transit accessibility index in this approach is defined simply by the summation of accessibility values from the given origin to all possible destinations. Hence, it fails to capture properly the benefit side of accessibility.

To incorporate the temporal aspect of transit accessibility into the model, Farber, Bartholomew, Li, Páez, and Habib (2014) developed a distance-based transit accessibility model by measuring transit accessibility at different times of day. The proposed model utilizes GTFS data and the Dijkstra algorithm to estimate the travel time between all census block centroids to the 10 closest supermarkets. Although this model estimates the travel time at different times of day (6am–10pm), the opening hours of destinations (supermarkets) are not included in the model. Moreover, the model measures transit accessibility to only the 10 closest supermarkets, regardless of their size or attraction.

Owen and Levinson (2015) also proposed a cumulative opportunity measurement to capture the temporal aspect of transit accessibility. This approach measures accessibility every minute by including the access/egress walking time and in-vehicle transit time. The model highlights the accessibility variations over time.

A review of the access to destination approach in this category also shows that although there is broad research on the impacts of unaffordable public transit (Lucas, 2012; Nadeau, 2016), few models incorporate transit fares into their accessibility model (Farber et al., 2014; Geurs, Zondag, De Jong, & de Bok, 2010; Handy & Niemeier, 1997). It is also important to highlight that only a small number of these models incorporate total travel cost (travel time and transit travel fares) into the accessibility model.

The UK Department of Transport introduced a software/model to measure accessibility based on travel time and fares in London. This model was developed further by Ford, Barr, Dawson, and James (2015) to measure accessibility based on generalized costs, including time and fares. The travel fares are calculated based on the flat rate for a bus trip, and on the average price/km for heavy and light rail services.

In a similar study, El-Geneidy et al. (2016) developed cumulative accessibility measures based solely on travel time, solely transit fare, and the generalized combination of travel time and cost. The results show that although there is a significant correlation between accessibility measurement by time and transit fares, the impact of transit fares on transit accessibility is significant, as it affects the accessibility of low-income earners.

Currie (2004) examined a cumulative transit accessibility model based on estimated generalized travel costs to identify regions with poor transport services. This model measures accessibility to 14 different destinations (trip purposes) in five different periods of time (see Table 3). This approach also highlights the importance of including the temporal aspects of accessibility in the model.

A review of these distance-based transit accessibility approaches reveals that although these approaches have improved gradually in recent decades, and provide practical and simple methods for evaluating overall accessibility, they do not capture traveler preferences and behavior in a transit network. To overcome this limitation and incorporate traveler behavior, several researchers have developed access-to-destination models, based on the gravity and utility approaches. These models are briefly discussed in the following sections.

3.3.2. Gravity-based access-to-destination models

Alam, Thompson, and Brown (2010) developed a gravity model for predicting transit accessibility that incorporates traveler preferences, the relative attraction of destinations, and the cost of travel. The impedance or cost vector for traveling between zones is defined based on three parameters: door-to-door transit time between zones, door-to-door highway time between zones, and door-to-door highway distance between zones. The attraction vector is defined by five different variables: population, population density, number of jobs, job density in the destination zone, and the percentage of the destination zone within $1/4$ mile of the bus stop.

Table 3. Summary of access-to-destination accessibility models.

Developer(s)	Name of model	Type of measurement	Indicators	Travel mode	Trip purpose	Components	Pros and cons	Practicality
Mavoa et al. (2012)	PTWAI (Public Transport and Walking Access Index)	Distance Measurement	Walking time, "arrive to wait" time, waiting time, transit time	Walking and transit	Access to 17 land-uses in five main categories (education, financial, health, shopping, and recreation)	Transport (partial) and land-use supply (partial)	The waiting time estimations are not based on actual transit frequency and number of services.	●
Lei and Church (2010)	—	Distance Measurement	Access and egress walking time, waiting time, and in-vehicle time	Walking and transit	Accessibility to work	Transport, temporal and land-use supply (partial)	The model defines accessibility by average access time from origin to destination and vice versa to incorporate temporal aspects of accessibility.	●
Farber et al. (2014)	—	Distance Measurement	Access and egress walking time, waiting time, and in-vehicle time	Walking and transit	Accessibility to supermarkets	Transport, temporal (partial) and land-use supply (partial)	Although, the model includes the temporal aspects by estimating the travel time at different times of day, it does not consider the opening hours of supermarkets; it measures accessibility only to the 10 closest shops regardless of size or attraction.	●
Owen and Levinson (2015)	—	Cumulative/Distance Measurement	Access and egress walking time, waiting time, transfer time, and in-vehicle time	Walking and transit	Accessibility to jobs	Transport, temporal and land-use supply (partial)	Pro: captures temporal aspects of accessibility by measuring accessibility variations over time	●
Ford et al. (2015)	—	Cumulative Measurement	Access and egress walking time, waiting time, transit fares, and in-vehicle time	Auto, cycle, and transit	Accessibility to jobs and services	Transport, and land-use supply (partial)	Applies weight to access, egress and waiting time to reflect the actual perceived cost	●
Currie (2004)	—	Cumulative/Distance Measurement	Access and egress walking time, waiting time, transfer time, in-vehicle time, and transport fares	Transit	Accessibility to CBD, pools, shops, universities, sports, pharmacies, regional shopping centers, main employers, hospitals, food stores, cinemas, child care, and doctors	Transport, temporal and land-use supply (partial)	The accessibility results show the temporal effect by modeling the accessibility model in five different time periods (am peak, inter-peak, evening, Saturday pm and Sunday pm)	●

Bocarejo S and Oviedo H (2012)	—	Gravity Model	Travel time between O-D pairs, transport expenditure between O-D pairs, average income	Multi -modal	Accessibility to jobs	Transport, land-use (supply)	Incorporates the effect of travel cost and time	●
El-Geneidy et al. (2016)	—	Cumulative Measurement	Access and egress walking time, waiting time, transfer time, transit fares, and in-vehicle time	Transit	Accessibility to jobs	Transport, and land-use supply (partial)	Measures accessibility based solely on travel time, solely on transit fare, or a generalized combination of travel time and cost	●
Bhat (1998); Bhat et al. (1999)	Parallel Conductance	Utility Model	In-vehicle time, out-of-vehicle time, cost of all three modes (auto, transit, and walking), and sociodemographic variables (age, gender, income) and employment	Walking, auto, transit	Work, shopping	Transport, land-use (supply and demand) and socioeconomic factors	Estimates the utility of each mode deterministically by the utility of the path with the highest systematic utility	●
Peter Davidson Consulting (2008)	Land Use and Public Transport Accessibility Indexing Model (LUPTAI) – new edition	Utility Model	Walking time to stops, waiting time, transit travel time, walking time from stops to destinations, interchange between the services, and transit fares	Walking and transit	Eleven destinations in four categories (health, shopping, education and employment)	Transport, temporal, land-use (supply and demand)	Defined based on destination choice	●
Algers et al. (1997)	—	Utility Model	Network attributes (cost, in-vehicle time, walking/bicycle travel time, and waiting time), land-use attributes (size and number of employees), and socioeconomic attributes (age, gender, and employment)	Auto, transit, walking, and bicycle	Work, school, business, and shopping trips	Transport, land-use (supply) and socioeconomic factors	Pros: Includes the choice of secondary destinations or trip chains; measures accessibility for three types of travelers: male workers, female workers and household members 12 and above; Cons: Depending on different variables makes the model impractical to for large networks	○

● Completely satisfactory; ○ Partly satisfactory.

In this methodology, transit accessibility between an origin and a destination is defined as:

$$TA_{ij} = \sum_{i=1}^{n} \left[\left(ATN_j^a \right) * \left(F_{ij}^f \right) \right] \quad (4)$$

where ATN_j^a presents the attraction vector of a destination zone and F_{ij}^f indicates the cost or fraction vector for traveling between zones. The accessibility of zone i is defined as the sum of accessibility to all available opportunities:

$$TA_i = \sum_{j=1}^{n} TA_{ij} \quad (5)$$

Bocarejo S and Oviedo H (2012) developed a gravity accessibility model, which measures the impedance function between O-D pairs, based on the cost of travel time and the affordability index. Affordability is measured by the proportion of average transport expenditure and income for each zone. The model applies a modal split in every zone and calculates the weighted average of travel times and costs for all O-D pairs.

Like other gravity-based approaches, these models have difficulty calibrating decay functions (friction variables) and weighing opportunities because of the inherent complexity of the gravity models.

3.3.3. Utility-based access-to-destinations models

As explained above, one of the main drawbacks of the LUPTAI model developed by Yigitcanlar et al. (2007) is to fail to capture travelers' destination preferences. To address this limitation (Davidson, 2008) structured a new version of the LUPTAI model based on a random-utility model for destination choice to account for the attractiveness and relative importance of opportunities.

The generalized cost measure estimates all of the attributes that make the travel difficult from the perception of travelers. The generalized costs include walking time to stops, waiting time, transit travel time, walking time from stops to destinations, walking time for interchange between services, and transit fares. All variables are weighted and converted into a common utility unit (e.g., dollars or minutes).

Bhat (1998), and Bhat, Carini, and Misra (1999) introduced and developed a "parallel conductance" calculation as an alternative logsum technique. This method measures the perceived travel utility by combining travel mode choices (auto, transit and walking) to different destinations. In-vehicle time, out-of-vehicle time, and the cost of all three modes are estimated as utility attributes for modeling the destination choice in this technique. The model includes socio-demographic variables, such as age, gender and income.

Algers, Daly, and Widlert (1997) introduced another destination and mode choice model for measuring transit accessibility to work, school, business and shopping centers. One advantage over the previous choice models is that the proposed method can model the choice of secondary destinations or trip chains. The model incorporates land-use, network and socio-economic variables. To investigate the effect of the socio-economic aspects of the accessibility estimation, the model also measures accessibility for three different household categories (see Table 3).

3.3.4. Discussion on access-to-destination models

As discussed in 3.3.1 above, distance-based access-to-destination approaches do not reflect the relative importance of the different opportunities. They give identical weight to various opportunities with different characteristics (e.g., size and the number of employees). In contrast, gravity-based and utility-based approaches have the advantage of capturing the stochasticity and subjectivity of travelers in their perception of different opportunities. However, they do not capture the subjectivity of travelers in their perception of the transit system. For instance, in these random-utility approaches, the subjectivity of travelers applies only to destination choice, and the impedance part of the model is estimated deterministically (based on the generalized cost of the single shortest path to each destination). Consequently, these models do not fully capture traveler preferences and their subjectivity in the perception of the transit network. A brief outline of these models is given in Table 3.

4. Challenges in developing transit accessibility models

This review reveals that an acceptable and accurate transport accessibility model must both satisfy the theoretical bases and practical criteria. These requirements have led us to identify three main challenges in developing transit accessibility models; collecting data, estimating travel impedance and weighing opportunities.

4.1. Data collection

One of the important areas in transport accessibility modeling is the data feed for the modeling. As in other types of transport modeling, data collection for transit accessibility modeling has several limitations. Although there is a general recognition of accessibility's multifactor nature, modelers usually ignore temporal or individual components in their models because of data collection difficulties and restrictions. This review identifies the following data collection limitations and challenges.

Obtaining high-resolution data is one of the main challenges and limitations in data collection. Transit accessibility models usually need to analyze fine geo-coded data, including high-resolution socio-demographic data, fine-grained geo-referenced census data, and household behavioral data. However, access to this data is severely restricted globally.

The second obstacle affecting data collection rises from inconsistency between the geographical zones in different sets of geo-coded data. For example, the geographic boundaries for different data sets (e.g., census data, travel survey data) often cannot be overlaid on each other, creating difficulties in using various types of spatial data sets that have different sets of geo-coded data. Data collection in large metropolitan regions that have multiple transit authorities or agencies can also be a significant challenge for modelers.

The third limitation stems from dissimilarities in time sequences for collecting different datasets. For example, some datasets are regularly updated every four years (e.g., travel survey data), while other data sets are collected only for specific requirements (e.g., subjective transport surveys), without consistent intervals.

The fourth issue in data collection is that the required data are usually not collected individually for particular research, so they may not contain all the required data records that a modeler needs. For instance, estimating traveler behavior based on household travel survey data may not be an adequate approach for observing traveler route choice behavior; the exposed path choice behavior might not necessarily show the preferred behavior. This issue is highlighted particularly when the transport network offers passengers no other options. Although the current trend shows that authorities try to provide accurate traveler behavioral pattern information, collecting transport users' behavioral data remains a key challenge for accessibility modeling.

The final data collection limitation relates to obtaining qualitative data for modeling. Quantitative data can usually be obtained for the basic characteristics of land use and transportation systems, but qualitative data for particular accessibility features, such as the qualitative characteristics of infrastructure, is very rare. Numerous accessibility studies have acknowledged a significant gap between qualitative data requirements and their availability in urban and transport planning departments (Cerdá, 2009; El-Geneidy & Levinson, 2006; Geurs & Van Wee, 2004; Handy & Clifton, 2001).

Therefore, obtaining high-resolution data, uniformity and consistency in time sequences of collecting travel survey data, consistency in collecting geo-coded information and socio-economic data and also collecting data subjectively for transport modeling can help modelers to improve the accuracy of transit accessibility measurements.

4.2. Estimating travel impedance

Reviewing the existing traditional accessibility models reveals that estimating accurate travel impedance is a critical challenge in transit accessibility modeling. Existing accessibility models typically emphasize impacts that are easy to estimate, at the cost of those that are tricky measure (Breheny, 1978).

Traditional transit accessibility models typically pay no attention to traveler behavior, commonly ignoring the fine details of transit characteristics that are not easy to estimate. For example, transport system reliability is usually a very important consideration for travelers, but most transit accessibility models do not consider these indicators. Taking traveler behavior into account also facilitates understanding of diverse transport user groups' perceptions of the transit network, and so helps modelers find optimal transit policies for improving accessibility for different groups of people. This can improve social equity, urban livability and therefore local economies through the transit network.

In addition, existing transit accessibility models do not usually capture traveler preferences or stochasticity in their perceptions of the transit system. Most models focus only on a single path to the destination to estimate accessibility. Transit accessibility models usually assume that all travelers have similar objectives (e.g., minimum travel time to reach a transit stop or actual destination) and can make the best choice to get to their destination. However, this may not always be the case.

This review reveals that applying utility models to capture traveler behavior and stochasticity, along with capturing transit network disutilities, provides a better understanding of travel impedance from travelers' perspective.

4.3. Weighing the opportunities

This review of the transit accessibility models reveals that the method chosen to calibrate the attractiveness of opportunities can seriously affect the models' results. Guy (1983) illustrated this by comparing the outcomes of accessibility measurements with different attractiveness factors for "local" accessibility to shops and services. These measures resulted in different outcomes and confirmed that the accessibility level varies significantly when the model uses different approaches to weigh opportunities. This review also shows that only destination choice models, such as the "Parallel Conductance" model, propose a practical approach for calibrating the benefit side of accessibility from the travelers' perspective. Other approaches do not provide a robust theoretical method for measuring the effect of the benefit side of accessibility and fail to capture the effect of multiple possible opportunities based on their attractiveness to travelers.

Therefore, applying utility models which consider all the benefits that travelers can gain from choice of destination or land-use supply, can provide more accurate estimation of transit accessibility from the transit users' perspective.

5. Summary

This study reviewed several transit accessibility models in three main categories: system accessibility, system facilitated and access to destination. This review evaluated existing models' advantages and shortcomings and highlighted possible challenges to developing more accurate transit accessibility models. Thus, this research can be helpful for policymakers, urban developers and transport researchers in two ways. It can be used as a useful guideline for adopting an appropriate approaches for transit accessibility measurement in cities as well as providing direction for developing more accurate models by identifying the shortcomings of the existing approaches.

It is important to state that even though defining model accuracy for accessibility measurements is not easy, in general, accessibility models that incorporate and pay attention to all the main accessibility components (transport, travelers, temporal, and land use) can provide a better understanding of transit accessibility from the travelers' perception.

This review also revealed that differences between transit accessibility models derived from differences in interpreting the transit accessibility concept among researchers and differences in the purpose of use of transit accessibility models (Alam et al., 2010; Bhat, 1998; Lei & Church, 2010; Mavoa et al., 2012). This is a very important point as different models in similar case studies, often yield different results due to the inherited dissimilarity of their methodologies.

In short, distance-based and gravity approaches are usually relatively easy to interpret and use, but they do not capture all aspects of transit accessibility. In contrast, utility-based measurements can incorporate all dimensions of transit accessibility, but they are not easy to use in real and dense urban networks.

In the same way, system accessibility models which measure accessibility to transit services are usually easy to interpret and use. However, these approaches do not provide an overview of the difficulties that travelers may experience when commuting. Access to destination approaches, however, can highlight traveler difficulties in accessing different destinations. Again despite this advantage, this approach is generally not easy to use in real networks. Aggregating accessibility output by aggregating the results of different purposes of trips, for example, is yet another challenge in access-to-destination approaches. The aggregated accessibility models discount details in the outcome of the model and this can further reduce model accuracy.

This study also confirmed the existing dilemma among transport planners and policy makers to develop and utilize an appropriate approach for measuring transit accessibility which also has been discussed by Silva, Bertolini, te Brömmelstroet, Milakis, and Papa (2017), Andriessen (2004), Fincham and Clark (2009), and Straatemeier, Bertolini, te Brömmelstroet, and Hoetjes (2010). On the one hand, the scholars try to develop models which are relatively easy to understand (user-friendly) and are applicable in every situation. On the other hand, for truly accurate measurement, they need to adopt a robust theoretical approach to incorporate the effect of different accessibility components such as traveler behavior which generally would not be easy to achieve.

This review also leads to the classification of transit accessibility models into two high-level categories: strategic planning models and operational detail models. Strategic models do not focus on individual preferences. However, they can successfully demonstrate a region's overall transit accessibility, and so are very practical tools for planning and high-level forecasting. These models are also usually relatively user friendly. In contrast, although operational detail models offer more comprehensive and useful focus on transit network details, land-use and traveler characteristics, they are usually difficult to apply in complex transit networks.

The above statement illustrates why there is no agreement among scholars that a single model can fit every situation. Also, it is important to state that usually distance-based and gravity-based measurements (especially in system-accessibility and system-facilitated accessibility categories) are useful strategic planning tools while utility-based approaches (especially in access to destination category) are more applicable to operational detail models.

5.1. Future models

Reviewing the most current approaches shows that there is broad awareness, and an important trend towards capturing travelers' behavior and their stochasticities in estimating travel impedance (Bhat, 1998; Bhat et al., 1999; Nassir et al., 2016; Rastogi & Krishna Rao, 2003). This provides an opportunity to capture various population groups' accessibility prefernces. The use of GTFS (General transit feed specification) data and detailed travel survey data in recent years has also facilitated capturing these important variations in transit networks. However, capturing all these stochasticities and preferences in dense transit networks is a difficult practice.

This study also identified a trend towards developing more disaggregated transit accessibility measurements, in contrast to combined or aggregated models (e.g., combined accessibility measures for different times of day or different types of activity). This approach helps modelers to overcome the complexities of merging disaggregated results and capture detailed information which can be lost in the aggregated models.

ORCID

Edward Chung http://orcid.org/0000-0001-6969-7764

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