A Systematic Review of Scientific Literature on Accessibility Measurements and the Treatment of Automated Vehicles

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Urban and Regional Planning

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December 10, 2019

Blacksburg, Virginia

Keywords: Review, Accessibility Measure, Automated Vehicles, Transportation, Planning.

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ABSTRACT

Accessibility plays an important role in a number of scientific fields, and significant advances in measuring accessibility have been made over the past two decades. However, since the comprehensive review of accessibility measures conducted by Geurs and van Wee in 2004, no attempt has been made to update their study. In addition, the emergence of Automated Vehicles (AVs) is expected to dramatically impact accessibility. Therefore, based on the relevant assessment criteria proposed by Geurs and van Wee (2004) (i.e., theoretical basis, interpretability, operationalization, and usability), this research reviews: (1) progress made over the past two decades on measuring accessibility; and (2) how accessibility measures have incorporated the impacts of AVs. A total of 495 papers and books were identified through a search of Scopus, Web of Science, and EBSCOhost in May 2019. The results found that the existing accessibility measures have been further refined, and new measures have been created by leveraging more advanced behavior theories and/or models. In addition, the operationalization of almost all of the measures has become easier due to more readily available data and more advanced implementation tools. As a result of these changes, accessibility measures are becoming more usable and can more accurately assess social, economic, and environmental impacts. However, the interpretation of these measures is becoming more difficult due to the incorporation of more complicated theories and models. Interestingly, very few papers discussed AVs in the context of accessibility measures. Finally, as a result of this study, future research opportunities are identified.

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General Abstract

The concept of accessibility plays an important role in a number of scientific fields (e.g., transportation planning, environmental conservation, and economic development, etc.), and a change in accessibility can have a direct impact on an individual's quality of life. Transportation accessibility is a function of the connectivity between origins (e.g., a home) and destinations (e.g., a place of employment). Significant advances in measuring accessibility have been made over the past two decades. However, since the comprehensive review of accessibility measures conducted by Geurs and van Wee in 2004, no attempt has been made to update their study. In addition, the emergence of Automated Vehicles (AVs) is expected to dramatically impact accessibility. Therefore, based on the relevant assessment criteria proposed by Geurs and van Wee (2004) (i.e., theoretical basis, interpretability, operationalization, and usability), this research reviews: (1) progress made over the past two decades on measuring accessibility; and (2) how accessibility measures have incorporated the impacts of AVs. The theoretical basis refers to whether an accessibility measure is developed based on solid theories or models, and whether the measure is sensitive to: (a) opportunity changes (e.g., changes in the location of jobs); (b) transport cost changes (e.g., travel time changes); (c) temporal changes (e.g., the change of travel options throughout different times-of-day); and (d) individual changes (e.g., how residents' travel behavior changes due to the emergence of a new subway line). Interpretability refers to how easy an accessibility measure can be explained and understood by planners, engineers, and decision makers. Operationalization refers to how easy it is to use a measure in practice. Finally, usability refers to whether the results of an accessibility measure can be used to assess social, economic, and environmental impacts. A total of 495 papers and books were identified through a search of Scopus, Web of Science, and EBSCOhost in May 2019. The results found that existing accessibility measures have been further refined, and new measures have been created by leveraging more advanced behavior theories and/or models. In addition, the operationalization of almost all of the measures has become easier due to more readily available data and more advanced implementation tools. As a result of these changes, accessibility measures are becoming more usable and can more accurately assess social, economic, and environmental impacts. However, the interpretation of these measures is becoming more difficult due to the incorporation of more complicated theories and models. Interestingly, very few papers discussed AVs in the context of accessibility measures. Finally, as a result of this study, future research opportunities are identified.

Acknowledgements

First of all, I would like to offer my sincere thanks to my academic advisor Ralph Hall, who have guided me through the whole process of my thesis with great patience and time devotion. What I have gained from our cooperation is not only an understanding of research methodology and skills, but also the courage and confidence to address unexpected and tough problems. In addition, I would also like to thank my committee members Wenwen Zhang and David Bieri for their support and valuable insight to this work.

I'd like to thank my family and friends who offered me help, encouragement, and patience throughout this endeavor. I could not have done this without your support! Lastly, I would like to thank those who have provided me with valuable comments, suggestions, and assistance during the preparation of this thesis: Qiong Wang, Aishwarya Borate, Ralph Buehler, and Leigh Bower.

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CHAPTER 1: Introduction

1.1 Current transport system

Transportation interacts with, and plays an important role in, a board range of scientific fields such as geography, land use planning, economic development, public health administration, and environmental conservation (Le Vine, Lee-Gosselin, Sivakumar, & Polak, 2013a; Peter Rickaby, 1985; Polo, Acosta, Ferreira, & Dias, 2015; S. Song, 1996; Verburg, Ellis, & Letourneau, 2011). There are many ways to classify the transportation system. A widely accepted approach is to classify the system by mode of transport, which generally includes three major types - i.e., air, land, and water transportation. Transportation accessibility is a function of the connectivity between origins and destinations. For each mode of transportation, a critical element is access, which reflects the ability of individuals to reach their desired destinations through existing transportation services (Karst T. Geurs & van Wee, 2004). The level of accessibility is an important indicator of a resident's quality of life (Nahdalina, Hadiwardoyo, & Nahry, 2017; Rodrigues, Tobias, & Ramos, 2016), which means that accessibility considerations are one of the major factors influencing planning and management decision making processes.

In order to study accessibility indicators, two questions need to be asked: (1) what is accessibility? And (2) how can the concept of accessibility be translated into performance measures and conveniently apply to policy-related research?

For the first question, the concept of accessibility varies based on its application. For example, researchers have applied accessibility to study the "potential of opportunities for interaction" (Hansen, 1959), the "freedom of individuals to decide whether or not to participate in different activities" (L.D. Burns, 1979), the "benefits provided by a transportation/land-use system" (Ben-Akiva & Lerman, 1985), the "extent to which [the] land-use and transport system enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport model(s)" (Karst T. Geurs & van Wee, 2004), and "How easy it is to live a satisfactory life with the help of the transport system" (Lättman, Olsson, & Friman, 2016). The last concept has been recently revised, and is now known as "perceived accessibility" versus "objective accessibility", which was used previously (ibid.).

Geurs and van Wee (2004) identified four components from different definitions and practical measures of accessibility, which are theoretically important for measuring accessibility. They are: (1) the *land-use component*, which reflects the characteristics of the land-use system - ideally this component should account for both the supply of, and demand for, opportunities, and the competition effects resulted from their confrontation; (2) the *transportation component*, which describes the transport cost for a person or group to overcome the distance impedance from an origin to a destination by a specific transport mode - ideally, the cost should include the amount of time, monetary expenditure, and effort over the travel process (e.g., level of reliability, comfort, and safety); (3) the *temporal component*, which reflects the temporal constraint, particularly, the availability of opportunities, transport options, and participation of specific activities at different times of the day; and (4) the *individual component*, which describes the *needs* (depending on age, income, educational level, household situation, etc.), *abilities* (depending on an individual's physical condition, availability of travel modes, etc.), and *opportunities* (depending on an individual's income, travel budget, educational level, etc.) of individuals (Karst T. Geurs & van Wee, 2004).

Based on the different definitions of accessibility, four broad categories of accessibility measures have been identified and summarized by (Karst T. Geurs & van Wee, 2004):

- **Infrastructure-based measures** analyze the (observed or simulated) performance or service level of transport infrastructure (e.g., the travel time to work by public transit) (ibid.).
- **Location-based measures** analyze accessibility at locations, typically on a macro-level. The measures correspond to the definition of "potential of opportunities for interaction", assessing the level of interaction between origins and spatially distributed activities. Competition effects with supply or demand capacity restrictions could be incorporated in the more complex location-based measures (see section 3.2.3) (ibid.).
- **Personal-based measures** analyze accessibility of individual with a series of environment and individual constraints (e.g., the location and start/end time of mandatory activities, the time budgets for discretionary activities and travel speed allowed by the traffic conditions), and corresponds to the definition of the "freedom of individuals to decide whether or not to participate in different activities" (ibid.).
- **Utility-based measures** analyze the utility or economic benefits that people obtain from participating in the spatially distributed activities based on economic theories. These types of measures correspond to the accessibility definition of "benefits provided by a transportation/land-use system" (ibid.).

A broad range of relevant criteria have been given by Geurs and van Wee (2004) to analyze the usefulness and limitations of the accessibility measures. For example, an accessibility measure should ideally take all components and elements within these components into account to be considered as **theoretically sound**, and thus, be sensitive to the changes of all components. In addition, keeping all other conditions constant, the accessibility measure should behave as expected.

From a macro-level perspective, the transport cost and demand for opportunities with certain supply restrictions should run in an opposite direction to the level of accessibility - e.g., as transport costs decrease, accessibility to any activity should increase. Further, the number of opportunities should run in the same direction as the level of accessibility - e.g., when the number of opportunities increases anywhere, the accessibility to that type of activity should increase from any place (Karst T. Geurs & van Wee, 2004).

From an individual perspective, if an individual cannot reach certain activities within his/her time budget, an increase in the number of activities available should have no influence on the level of accessibility of the individual. In the same vain, an individual with an insufficient ability (e.g., no driver license) would not see an increase in their accessibility if driving to a destination were made easier (ibid.).

Operationalization is the ease with which an accessibility measure can be used in practice, this should consider the availability of data, models and techniques, and time and budget.

The criterion of **interpretability and communicability** highlights the importance of the explainable and communicable components of an accessibility measure(s) during the decision making process. The measure(s) should be understandable by researchers, planners, and policy makers (ibid.).

Accessibility measures can be used as a **social indicator** if the measures can detect changes in social and economic opportunities for individuals (or social groups) - i.e., the essential sources for human existence such as jobs, food, health and social services, social equity impacts, etc. (ibid.).

Accessibility measures may be used as an **economic benefit indicator** if they can be directly linked to an economic theory, or may serve as an input for the calculation of direct economic benefits (e.g., the travel-cost savings from infrastructure projects) or indirect economic benefits (e.g., productivity gains of firms and distributional effects that can be linked with an infrastructure project) of land-use/transport changes (ibid.).

Accessibility measures could be used as an **environmental indicator** if the measure can link changes in environmental costs/pollution/emissions to land use/transport changes. Notably, the environmental costs are separated from the economic benefit indicator due to the importance of analyzing environmental impacts for sustainable development.

From the development of accessibility measures, the topic of translating the concepts of accessibility into performance measures that can be more conveniently applied and communicable to policy-related research has been a longstanding research agenda (F. J. Martínez & Araya, 2000; Miller & Miller, 1991; Shen, 1998; Sweet, 1997; Vickerman, 1974; WICKSTROM, 1971; Wilson, 1971). To date, even though after six decades of measuring accessibility, the debate on how to make the concept of accessibility more usable and communicable in practice continues. However, some developments have been made in the past two decades, including but not limited to theoretical advances (Chorus & de Jong, 2011; A. M. El-Geneidy & Levinson, 2011), refinements of how to measure performance (Alam, 2009; H. M. Kim & Kwan, 2003), the development of more accurate accessibility models (Tomasiello, Giannotti, Arbex, & Davis, 2019), and the extension of the usability of the accessibility indicators to evaluate performances of plans and policies, including social, economic, and environmental impacts (Nahdalina et al., 2017; Vasconcelos & Farias, 2012).

1.2 Automated Vehicles - A New Dimension to Accessibility

The development of Intelligent Communication Technology (ICU), automation, and (hybrid-) electric engines have had a substantial and significant influence on our daily life. These technologies have induced a new wave of development of driverless vehicles in the last decade, with the expectations of reducing accidents (Faisal, Yigitcanlar, Kamruzzaman, & Currie, 2019; Khondaker & Kattan, 2015), congestion (Helbing, Schönhof, Treiber, & Kesting, 2008; Khondaker & Kattan, 2015), energy consumption (Arbib & Seba, 2017; Stephens et al., 2016), and achieving a more equitable transport system (Claypool, Bin-Nun, & Gerlach, 2017). Given the promising future of driverless, or autonomous vehicles (AVs), technology, there are a growing number of companies working to advance and commercialize the technology, such as Google (Poczter & Jankovic, 2013) and Tesla (Siddiqui, 2019), as well as cities (e.g., Boston) (City-Data, 2019). Litman (2019) forecasts that most vehicles will be capable of autonomous driving by the 2040s or 2050s. Therefore, transportation planners should be proactively preparing for this future and working to understand and mitigate the challenges posed by this technology while embracing the benefits (Todd Litman, 2019).

According to the U.S. Department of Transportation, automation is defined as "Vehicles that have at least some aspects of safety-critical control functions (such as steering, throttle, or braking) that occur without driver input. Vehicle automation is divided into six levels, which denote increasing autonomous capability" (U.S. Department of Transportation, 2018) (Figure 1).

Autonomous vehicles (AVs) are a subset of automation at Levels 4 and 5. Level 4 automation means that humans are not driving the vehicle in defined areas and under certain conditions. A human driver must take control outside of those conditions. Level 5 means that humans do not drive the vehicle under all operating circumstances.

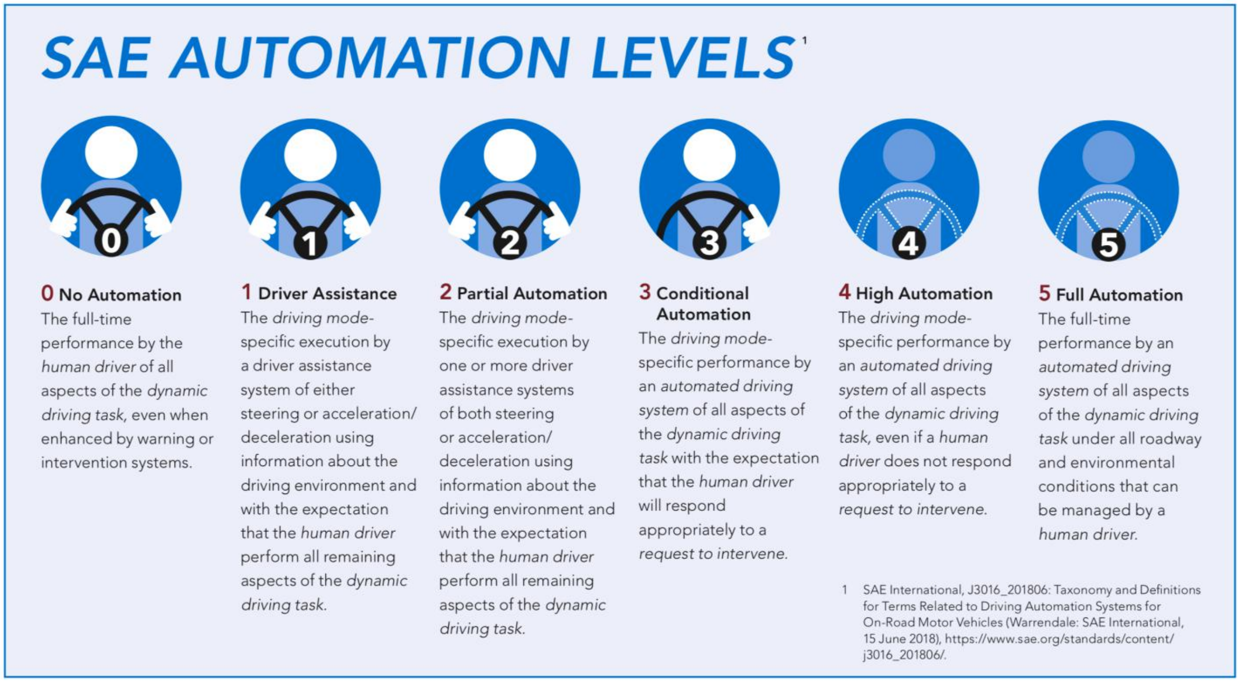

Figure 1: Level of Automation of Vehicles. *Source*: U.S. Department of Transportation 2018, p. vi.

With regard to automation, highly automated vehicles are expected to fundamentally change accessibility (U.S. Department of Transportation, 2018), because, from a transport perspective, they should reduce human error and make vehicle travel more reliable (Helbing et al., 2008; Le Vine & Polak, 2014). In addition, they hold the potential to make travel cheaper (Johnson, Walker, & Peak Car, 2017; Stephens et al., 2016), safer (Khondaker & Kattan, 2015), more comfortable (Bellem, Schönenberg, Krems, & Schrauf, 2016; Elbanhawi, Simic, & Jazar, 2015), and more environmentally sustainable (Khondaker & Kattan, 2015). Automated vehicles could increase the accessibility of people who cannot drive cars, such as children, old people, and the disabled (Claypool et al., 2017). From a land-use perspective, depending on the scenario and planning policies, substantially reduced general transportation costs might trigger a large amount of additional travel demand, and boost another wave of urban sprawl (Anderson et al., 2016), or induce a more compact urban form (Anderson et al., 2016; Milakis, Kroesen, & van

Wee, 2018). Each automated vehicle scenario holds the potential to change the land-use landscape dramatically. From a temporal perspective, since travelers might be able to accomplish some activities on the move, certain temporal restrictions of activities (e.g., fixed working places and time, or activities close times) might be overcome (Milakis et al., 2018). From an individual perspective, many studies have found that the value of time will decrease to some extent when passengers ride in a highly automated vehicle, which means passengers might be more tolerable to longer travel times or distance when participating in activities (Kolarova, Steck, Cyganski, & Trommer, 2018; Montgomery, 2018), triggering travel mode shifts (Bösch, Becker, Becker, & Axhausen, 2018). Given the revolutionary impacts of the emerging automated technology on accessibility, this review also includes the application and usability of accessibility measurements that consider automated transportation services.

Building upon a thorough review of accessibility by Geurs and van Wee (Karst T. Geurs & van Wee, 2004), this paper reviews and discusses recent improvements to existing accessibility measures, along with their usability and application. The paper also studies how automated vehicles might impact accessibility measures.

CHAPTER 2: Methodology

To explore recent developments in measuring accessibility with a focus on vehicle automation, three electronic databases were searched – i.e., Scopus, Web of Science (WoS), and EBSCOhost. Scopus includes a greater number of social sciences journals than the other two databases, WoS covers more historical papers (Mongeon & Paul-Hus, 2016), and EBSCOhost is the primary search engine at the authors' academic institution, and covers a broad range of literature, including books and thesis that may contribute important resources for this review.

By considering the search features of these three databases, the relevant search terms were identified by reviewing the 31 articles listed in Geurs and van Wee (2004). Two steps were followed to develop the search terms. The first step focused on identifying how comprehensive each database was by searching for all of the 31 papers included in Geurs and van Wee (2004). This step, conducted in May 2019, found that of the 31 references, 22 out of 31 could be found in EBSCOhost, 21 in WoS, and 20 in Scopus. The second step developed search terms to maximize the chance of finding the reference papers but with the trade-off of trying to capture a manageable number of new "hit" papers (i.e., the total number of papers returned from a search) on each search platform. Searches on Scopus and EBSCOhost were based on fields, abstract, and title, while the search on WoS was only based on fields and title due to the absence of an abstract option. Given the search conditions in the three platforms described, search terms were developed based on fields, abstract, and title. The final list of search terms are as follow (Figure 2):

- Field: accessibility OR transportation OR transportation planning OR environmental studies OR regional and urban planning OR geography.

- Abstract: (accessibility OR access) AND (measure* OR measuring OR evaluation OR evaluating OR approach* OR assessing OR assessment OR assessed OR examined OR examining OR tested OR determinant OR model*).
- Title: accessibility AND (autonomous OR driver-less OR self-driving OR automated OR measure* OR measuring OR evaluation OR assessment OR modeling OR models OR model OR indicator OR implication* OR approach OR approaches OR concept* OR characteristics).

The search terms developed reflected a balance of finding the reference articles in Geurs and van Wee (2004) and identifying new research on accessibility. When these terms were applied, 12 of the reference articles were found out of total 22 on EBSCOhost, 17 out of 21 on WoS, and 13 out of 20 on Scopus.

Next, the search terms were applied in three databases. The process for selecting relevant articles from these searches to review is shown in Figure 2. By reading the abstracts and full papers where necessary, articles that were considered to fall outside the scope of transportation, urban planning, environmental study, regional planning, and geography were excluded. Papers that were non-English and not available from the author's university library were also excluded. Papers that included measures or models that did not contribute to the evaluation of accessibility were excluded as well. The list of articles identified for review consisted of 475 items. However, during the review of the papers identified, an additional 20 relevant papers were discovered that did not appear in the search results. Therefore, these papers were included in the final list of articles for review, increasing the total number to 495 articles.

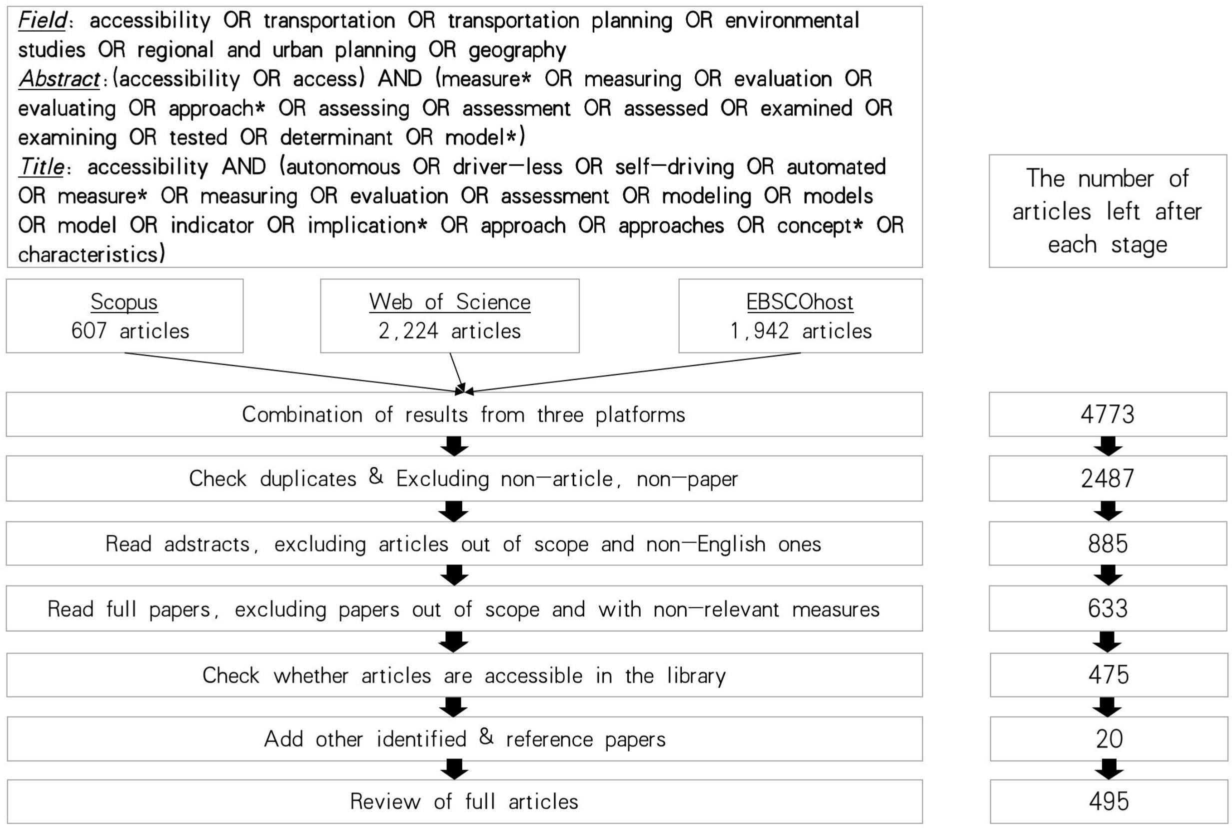

Figure 2: Search Framework for Articles of Review

CHAPTER 3: Results

The relevant findings from this study are summarized in Table 1. There are four classifications of accessibility measures - i.e., land use, transport, temporal, and individual components. For each type of accessibility measure identified by Geurs and van Wee (2004), the upper row presents the previous findings, whereas the lower row presents the updated findings from this research. The numbers shown in the updated rows refer to the number of new paper(s) identified that improved the corresponding accessibility measure. For example, the contour measure has a total of 41 new articles that were identified, of which 2 papers improve the transport component, 1 improves the demand of land-use component, 0 improve the supply of land-use component, 7 improve temporal component, and 7 improve the individual component. In addition, of the 41 new articles, 3 papers use the results of the contour measure as an input to assess economic impacts. The number of new papers identified for social, environmental, and automated vehicle impacts were 37, 0, and 1, respectively. Moreover, the contour measure is in general relatively easy to interpret and operate.

For the new accessibility measures that were created after the Geurs and van Wee (2004) paper, new labels have been added to the table and summary information is provided in each row. For example, there are 4 new papers identified for the "Place-rank" measure (model), which explicitly includes the demand and supply of the land-use component, but implicitly involves transport, and individual components, because the transport cost and impedance function (individual component) are embedded into this flow-based measure, which is sensitive to the changes of transport costs and people's travel patterns (see Section 3.2.5). However, papers on the "Two-step Floating Catchment Area-Extended" measure should be regarded as an update to the "Two-step Floating Catchment Area-Basic" measure.

Table 1: Summary of review of accessibility measures

Accessibility measures	Applications	Components					Operationalization	Interpretation	Usability for evaluation			
		Transport	Land-use		Temporal	Individual			Low level of automated vehicles (AVs)			High level of AVs
			demand	supply					Economic impacts	Social impacts	Environmental impacts	
Infrastructure-based	Old articles: Linneker and Spence (1992)	±	-	-	±	-	Easy	Easy	Potentially usable	Not usable	N/A	N/A
	Updated: Total 31 new papers	8	0	0	5	9	Easy	Easy	24	1	1	1
Location-based												
Contour	Old articles: Wickstrom (1971), Wachs and Kumagai (1973); Black and Conroy (1977), Guy (1983)	±	±	-	±	-	Easy	Easy	Not usable	Not Usable	N/A	N/A
	Updated: Total 41 new papers	2	1	0	7	7	Easy	Easy	3	37	0	1
Potential	Old articles: Stewart (1947), Vickerman (1974); Linneker and Spence (1992), Handy (1993)	+	+	-	±	±	Easy	Moderate	Potentially usable	Usable	N/A	N/A
	Updated: Total 77 new papers	10	2	1	2	12	Easy	Moderate	33	43	2	1
Adapted potential	Old articles: Weibull (1976), Shen (1998), Knox (1978); Joseph and Ban- tock (1982), Van Wee et al. (2001)	+	+	+	±	±	Easy	Moderate	Potentially usable	Usable	N/A	N/A
	Updated: Total 21 new papers	2	0	2	1	1	Easy	Moderate	0	17	1	0
Two-step Floating Catchment Area- Basic*	Total 8 new papers	±	+	+	±	-	Easy	Easy	0	8	0	0
Two-step Floating Catchment Area- Extended*	Total 44 new papers	10	37	37	5	33	Easy	Moderate	5	34	0	0

Accessibility measures	Applications	Components					Operationalization	Interpretation	Usability for evaluation			
		Transport	Land-use		Temporal	Individual			Low level of automated vehicles (AVs)			High level of AVs
			demand	supply					Economic impacts	Social impacts	Environmental impacts	
Balancing factors	Old articles: Wilson (1970, 1971), Geurs and Ritsema van Eck (2001, 2003)	+	+	+	±	±	Easy	Moderate	Potentially usable	Usable	N/A	N/A
	Updated: Total 15 new papers	0	0	0	0	0	Easy	Moderate	3	7	0	0
Place-Rank*	Total 4 new papers	+	+	+	±	+	Easy	Moderate	0	3	1	0
Radiation Model*	Total 3 new papers	±	+	-	±	±	Easy	Moderate	3	1	0	0
Person-based	Old articles: Miller (1991), Kwan (1998), Recker et al. (2001)	+	+	-	+	+	Difficult	Difficult	Not usable	Usable	N/A	N/A
	Updated: Total 32 new papers	6	11	0	7	8	Difficult	Moderate	1	27	0	0
Utility-based												
Logsum benefit	Old articles: Koenig (1980), Sweet (1997), Niemeier (1997); Handy and Niemeier (1997)	+	+	-	-	±	Easy	Moderate	Usable	Usable	N/A	N/A
	Updated: Total 18 new papers	0	0	0	0	0	Easy	Moderate	9	5	1	1
Regret-Minimization based*	Total 1 new paper	+	+	-	±	+	Difficult	Difficult	1	0	0	0
Space-time	Old articles: Miller (1999)	+	+	-	+	+	Difficult	Moderate	Usable	Usable	N/A	N/A
	Updated: Total 8 new paper	3	1	0	3	5	Difficult	Moderate	7	0	0	0
Balancing factor benefit	Old articles: Martınez (1995), Martınez and Araya (2000)	+	+	+	-	±	Easy	Moderate	Usable	Usable	N/A	N/A
	Updated: No new paper identified	0	0	0	0	0	Easy	Moderate	0	0	0	0

For ‘Accessibility Measure’, ‘*’ = the new type of measure;
For ‘Component’, ‘-’ = criterion not satisfied; ‘±’ = criterion partly satisfied; ‘+’ = criterion satisfied;
For ‘Operationalization’ and ‘Interpretation’, ‘Easy’ = easy to operate/interpret; ‘Moderate'' = moderate to operate/interpret’; ‘Difficult’ = difficult to operate/interpret.
For ‘Usability’, ‘Usable’ = usable, ‘Potential Usable’ = potentially usable, ‘Not Usable’ = not usable as inputs for impact assessment; ‘N/A’ = criterion not be included previously.

Thus, the numbers shown in the row of the Extended measure should be read in the same way as, for example, the row for the updated Contour measure.

The findings summarized in Table 1 are discussed in more detail in the following sections.

3.1 Infrastructure-based Measures

3.1.1 Previous progress (Background)

Infrastructure-based accessibility measures are used to represent the functioning and performance of the transport system, e.g,. the travel speed, travel time, the level of congestion, etc. (Karst T. Geurs & van Wee, 2004) . Over the past several decades, these indicators have played an important role in transportation planning in a variety of countries (e.g., the United States, Netherlands, United Kingdom, etc.) (K.T Geurs & Eck, 2001; Karst T. Geurs & van Wee, 2004) . Therefore, these indicators tend to be thoroughly understood by researchers and policy makers, and many accessibility models are built around them. However, the theoretical disadvantages of infrastructure-based accessibility measures are the separation of the transport and land use systems, their inability to carefully manage temporal constraints, and limitations in incorporating individual features. Thus, the measures were not very useful as indicators to evaluate social impacts (ibid.).

3.1.2 Improvements

Theoretical Basis

The literature discussing infrastructure-based measures consists of mainly two types of transportation network: road network accessibility and transit network accessibility.

For road network accessibility measures, in addition to the traditional time-distance and travel time cost measures, a new accessibility indicator has been created that integrates travel options to represent the road network's *robustness* and *reliability* (Liao & van Wee, 2017).

In contrast, the transit network has received intensive attention since it is considered to be more sustainable than private cars as a travel mode. The transit accessibility literature can be generally grouped into three areas (Mavoa, Witten, McCreanor, & O'Sullivan, 2012; Saghapour, Moridpour, & Thompson, 2016), and two out of the three fall into the infrastructure-based accessibility measures. These are: (1) access to transit stop(s); and (2) the ease of movement between origin and destination stations/stops. For the first category, most studies focus on physical access to transit stops, and accessibility was calculated as: (1) the travel time/distance with or without impedance functions (individual component) (Chandra, Bari, Devarasetty, & Vadali, 2013; Huang, Ding, & Li, 2009; Nassir, Hickman, Malekzadeh, & Irannezhad, 2016); (2) the percentage of area in an administrative unit (e.g., census tract) that is covered by transit, measured based on a radius from transit stops (Mamun & Lownes, 2011); and (3) the density of stops in a given area (Saghapour et al., 2016). For the second category - i.e., the assessment of the ease of travel between transit stops - the travel time/distance were weighted with distance-decay functions with or without considering attractiveness of stops (Cai, Wang, & Chen, 2017; H. Kim, Lee, Park, & Song, 2018; W. Li, Luo, Zhou, & Zhang, 2018). As for the improvement of transport cost evaluation, besides in-vehicle travel time used previously, more variables were incorporated for measuring accessibility, such as waiting time, difficulty of transfers, transit frequency, to list just a few (Cai et al., 2017; W. Li et al., 2018; X. Li & Zheng, 2016). Further, some studies were able to measure the accessibility change during different times of day (Barton & Behe, 2017; Cai et al., 2017; W. Li et al., 2018).

However, while some improvements have been made relating to the transport, temporal, and individual components, these improvements focus on the transport system itself, and do not build connections with the land use system. Thus, the infrastructure-based measures still bear the same shortcomings as previously identified.

Operation

The operation of accessibility measures can be classified by the procedure of: (1) obtaining data; and (2) processing data. Improvements related to obtaining data can be found in many papers that use public open sources that can be obtained either by directly downloading the data sources (e.g., the Victorian Government open (Victoria Data)) (Chandra et al., 2013; Saghapour et al., 2016; J. Wang, Deng, Song, & Tian, 2016), or by programming scripts to access the data (e.g., Python, JavaScript) (Møller-Jensen, Kofie, & Allotey, 2012; W. Yang, Chen, Cao, Li, & Li, 2017). Importantly, GPS data are now used which can enhance the assessment of transport cost estimates with real-time travel speed (Cai et al., 2017; Ding, Zhang, & Li, 2018), and the measurement of temporal accessibility change during a day (Cai et al., 2017; Ding et al., 2018). As for the data processing, while ArcGIS is the major implementation platform, other options were also available, including open source processing platforms (e.g., the Travel O-D point Intelligent Query System (TIQS) open platform that based on the Baidu map) (W. Yang et al., 2017).

Usability

With regards to the usability of the accessibility indicator, the majority of applications still remain focused on assessing economic impacts. However, there was one study that successfully used the infrastructure-based accessibility indicator to measure environmental impacts (Vicente & Martín, 2006).

AV Accessibility Impact

Kim et al. (2015) evaluated the travel impact of AVs in Atlanta by using activity-based modeling. To calculate travel time changes, the approach developed a feedback loop that included a mechanism to generate internal demand. The travel time from the urban center to the suburb was defined as accessibility, which assessed the changes under four different scenarios. The travel time variance before and after the introduction of AVs measured the impacts of AVs on accessibility (K. Kim, Rousseau, Freedman, & Nicholson, 2015).

3.2 Location-based Measures

3.2.1 Contour

Previous progress (Background)

A contour measure, also known as an isochronic measure, cumulative opportunities, proximity count, or daily accessibility, counts the number of opportunities that can be reached within a given travel cost (e.g., distance or travel time, fixed costs), or measures the travel cost required to access a fixed number of opportunities (fixed opportunities) (Karst T. Geurs & van Wee, 2004). In general, the former approach is more popular and, thus, it will be discussed as a representative measure in the rest of this section. With regard to its formulation, this measure can be expressed in the following form:

$$A_{ik} = \sum_j W_{jk} f(c_{ij}) \tag{1}$$

$$f(c_{ij}) = \begin{cases} 1 & \text{if } c_{ij} \leq \gamma(\text{threshold value}) \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

This measure of accessibility is a function of the number of opportunities W_{jk} of type k at location j, and the cost of moving between i and j (c_{ij}), as perceived/experienced by person at location i.

Many researchers agree that the advantages of this measure include its convenience of communication and operation (K.T Geurs & Eck, 2001). Regarding operation (i.e., the isochronic or isodistance measure), two important steps have been identified based on its definition and application (Boisjoly & El-Geneidy, 2016; Paez, Mercado, Farber, Morency, & Roorda, 2010): (1) the selection of bandwidth for the catchment area; and (2) the treatment of opportunities within the area - e.g., counting all opportunities inside the catchment area.

However, some theoretical disadvantages have been identified in early studies (K.T Geurs & Eck, 2001; Karst T. Geurs & van Wee, 2004). Under the framework of operation, in the first step, the selections of bandwidth of interest were generally arbitrary without taking transport and individual components into account, e.g., the travel speed variation due to the varying traffic flow, and the different location travel pattern due to different social characteristics of residents. In the second step, the early studies deemed that all opportunities are equally desirable regardless of the type of opportunities (land use component) and the opening hours in a day (temporal component). Additionally, all opportunities were equally reachable within the catchment area, which lacked a differentiation between the adjacent and remote opportunities (individual component).

Improvements

Theoretical Basis

From a theoretical perspective, building on the aforementioned operation framework, advancements have been made in: (1) the estimation of flexible bandwidths; and (2) the estimation of opportunities based on individual needs and satisfactions.

The improvement of the estimation of flexible bandwidth is based on both individual and temporal dimensions. From an individual perspective, Paez et al. (2010) proposed the use of flexible bandwidths in the analysis of accessibility to take into account the individual circumstances of travelers. Further, they proposed a mechanism for selecting flexible bandwidths "based on the use of empirically-based estimates of average trip length," which "is deemed to be a function of a set of explanatory factors selected for their theoretical, practical, or policy relevance" (Paez et al., 2010). In addition to the private car mode of travel, another paper from Páez's group proposed an estimation model for transit (Páez, Mercado, Farber, Morency, & Roorda, 2010). From a temporal perspective, the estimation of the bandwidths flexibly vary according to different transport system conditions throughout a day. Boisjoly and El-Geneidy (2016), Lei et al. (2012), and Owen and Levinson (2015) assessed location accessibility by capturing the number of job opportunities reachable by public transit in an area of a given travel time during different period times of a day (Boisjoly & El-Geneidy, 2016; Lei, Chen, & Goulias, 2012; Owen & Levinson, 2015).

In the step of opportunity estimation, two major advancements have been identified: (1) considering the deterrence effect of distance on opportunities (individual component) by either classifying opportunities into different influenced-by-distance groups through kernel density estimation (Q. Li, Zhang, Wang, & Zeng, 2011), or using a continuous distance impedance function for all opportunities (Salze et al., 2011); and (2) introducing a new behavioral definition of accessibility - *perceived opportunity* - that estimates the expected number of opportunities (the demand side of the land use component) that are perceived as a potential alternative to satisfy the needs of an individual (or a group) (individual component) under one's (their) space-time constraint(s) (temporal component) (Cascetta, Cartenì, & Montanino, 2013, 2016). There are two identified models to assess the individual needs and satisfaction of opportunities. Kulkarni et al. (2000) applied the percolation model to explain the process that leads to the development of perceived bonds (satisfaction) of opportunities (Kulkarni, Stough, & Haynes, 2000). Whereas Cascetta et al. (2013, 2016) used a regression model to assess needs as the probability that an opportunity can be perceived and reached among all opportunities within the catchment area (Cascetta et al., 2013, 2016).

Interpretation

While theoretical progress has been made over the last two decades, the interpretation of the contour measure has become more complex than before due to the incorporation of a new behavioral accessibility definition and regression models for more accurate accessibility results.

Operation

The improvements in the operational dimension can be grouped into two aspects: (1) implementation tools; and (2) databases.

In selecting the catchment area step, a growing number of tools (e.g., MetropAccess Travel Time Matrix (M-TTM), AccessMod) including online platforms (e.g., OpenTripPlanner, UrbanAccess) were developed to more conveniently generate the travel time matrix (Blanchard & Waddell, 2017a; Owen & Levinson, 2015), and thus, draw the boundary around the catchment area. As for the databases, some high resolution travel data has been used (e.g., the GPS-based data) (S. Jiang, Guan, He, & Yang, 2018; Laatikainen, Piiroinen, Lehtinen, & Kyttä, 2017), as well as appropriately-recorded open sources (e.g., General transit feed specification (GTFS) transit schedule data, OpenStreeMap) (Blanchard & Waddell, 2017a; Guthrie, Fan, & Das, 2017).

In the step of estimating opportunities, however, more disaggregated data would be needed if perceived opportunities are to be assessed (Cascetta et al., 2013, 2016), and obtaining such data could be difficult. In addition, the implementation of the results from an analysis of perceived opportunities requires other tools to operate regression models, which make the estimation of opportunities more difficult than simply counting the number of objective opportunities (see Cascetta et al., 2013, 2016; Kulkarni et al., 2000). *Usability as Social/Economic/Environment Indicators*

Geurs and van Wee (2004) claimed that the contour measure was not usable for economic and social impact assessment, however, some newly identified papers use this accessibility measure to investigate the benefits of transportation investments or plans (see A. El-Geneidy, Cerda, Fischler, & Luka, 2011; H. Jiang & Levinson, 2017; Manaugh, Miranda-Moreno, & El-Geneidy, 2010). Another 37 papers use this measure to assess social impacts, including the accessibility of jobs, cinemas, etc. (Blanchard & Waddell, 2017b; Cascetta et al., 2016; Guthrie et al., 2017; Munir, Hafeez, Rashid, Iqbal, & Javed, 2019).

AV adoption

A report from Securing America's Future Energy (SAFE) assesses the impact of AVs on job accessibility using the contour measure (Gains & Growth, 2018). This report assumes that the commuting time will decrease by 50% if AVs reach their full potential, or alternatively workers can travel greater distances to search for jobs with the same time budget (Montgomery, 2018). The accessibility impact of AVs is measured by the increased number of jobs that can be reached with the same commuting time under the 'full potential' scenario for AVs.

3.2.2 Potential

Previous progress (Background)

The potential accessibility measure estimates the potential of origins (zone i) to obtain opportunities in destinations (zone j), in which the potential to obtain opportunities in a destination declines when the distance between the origin and destination increases, but increases when the number of opportunities increases. The general formulation can be expressed as:

$$A_{ik} = \sum_j W_{jk} f(c_{ij}) \tag{3}$$

Where A_{ik} is the accessibility, W_{jk} is the attractive mass, *f()* is an impedance function, and c_{ij} is the transport cost traveling between *i* and *j*.

The interpretation and operation of the potential measure, though more complicated than the contour measure, are relatively easy. Some common steps for operating the potential measure are: (1) the selection of the analysis unit; and (2) the estimation of the accessibility indicators according to the measure.

The potential measure has theoretical advances over the contour measure in terms of capturing an individuals' behavioral (travel) pattern in a location, and existing shortcomings of this measure have been studied and appropriately resolved (K.T Geurs & Eck, 2001).

In the first step, the analysis unit needs to be defined which ideally should avoid an overestimation issue due to the inclusion of much more opportunities caused by the much larger size of the analysis zone. Some commonly used analysis zones include, for example, the Transport Analysis Zone (TAZ), different sizes of grids (e.g., 1km x1km grids).

In the second step, from a land use component perspective, the development of the adapted potential measures and the spatial interaction models (see Section 3.2.3 & Section 3.2.4) were appropriately overcome by ignoring competition effects in this (basic) potential measure

(K.T Geurs & Eck, 2001; Karst T. Geurs & van Wee, 2004). For the transport component, internally, the self-potential measures (the number of opportunities within origin zone *i* weighted by the average travel time or distance within that zone) were incorporated in order to solve the problem of omitting the accessibility of the local zone (Melhorado, Condeço, Demirel, Kompil, Navajas, & Christidis, 2016). In contrast, the external transport cost calculation was refined by computing the network travel time instead of the linear travel time between zones. For the individual component, other impedance functions have been generated to more accurately capture the impacts of spatial resistance on the residents' travel pattern in a study area. These functions include (see Table 2) (1) power function, (2) exponential function, (3) Box-Cox function, (4) Gaussian function, (5) Tanner function, (6) logistic function, etc. (Guy, 1983; Hansen, 1959; Shen, 1998; Willigers, Floor, & van Wee, 2007).

Improvements

Theoretical Basis

During the last two decades, theoretical improvements of potential measures were primarily based on the foundation described above, but included temporal component advancements as well.

Keeping the steps of processing in mind, in the first step, a study was conducted to test how different geographical scale of grids would impact the relationship of modeling accessibility and population changes, and it concluded that the proper scale of analysis units of accessibility for predicting population changes was 24km x 24km grids (Kotavaara, Antikainen, Marmion, & Rusanen, 2012). This result provides a good way to test the suitability of the sizes of the analysis unit.

In the second step, progress has been made in all four components - i.e., land use, transport, temporal, and individual. For the land use component, improvements mainly focus on refining the demand side of the users/travelers approach by evaluating the opportunity as the space-time sensitive utility gains based on residents' needs and satisfactions (Y. Wang et al., 2018) (see Section 3.4.2 for a more detailed discussion on space-time utility functions). Notably, this space-time sensitive utility function introduced the temporal constraints as well. The progress of competition effects will be discussed in the next two sections.

For the transport component, advances have been made in both internally (travel cost inside a zone) and externally (travel cost between zones). Internally, the self-potential transport cost was refined by: (1) a modified approach to measuring distance by accounting for the shape of the area, instead of assuming a circle-shaped region (Kotavaara, Antikainen, & Rusanen, 2011); (2) modifying the generalized transport cost by taking into account financial costs, travel time, and the reliability of travel times (Koopmans, Groot, Warffemius, Annema, & Hoogendoorn-Lanser, 2013; Niehaus, Galilea, & Hurtubia, 2016); and (3) considering both network distance and population centers for calculating internal travel time (Melhorado, Condeço et al., 2016). Externally, the improvements include: (1) calculating travel time by taking into account both road network and different speeds by road type (Franke, Vorel, & Peltan, 2017), or assigning different weights to different parts of travel time (e.g., waiting time, in-vehicle time, etc.) (Tahmasbi & Haghshenas, 2019); (2) the generalized travel time of multi-modes by incorporating door-to-door transit travel time, door-to-door free-flow automobile travel time, and highway distance between zones (Alam, 2009); and (3) the approach of measuring the generalized transport cost (Beria, Debernardi, & Ferrara, 2017; Karst T. Geurs, La Paix, & Van Weperen, 2016; Koopmans et al., 2013).

For the temporal component, Tomasiello et al. (2019) developed a multi-temporal network consisting of a private and public network. This model assesses accessibility based on changing the travel cost and impedance variables during different times-of-day.

From an individual component perspective, there were mainly two directions to further develop the impedance functions for capturing the travel patterns of residents: (1) applying statistics models that can highly correspond to the shape of residents' distribution frequencies, e.g., normal cumulative distribution model (Franke et al., 2017) and logistic cumulative distribution model (Candia, 2015; Garcia, Macário, Menezes, & Loureiro, 2018; L. M. Martínez & Viegas, 2013); and (2) using functions developed from theories (e.g., random utility theory) to capture the diversity of benefits that the different transport modes may offer the travelers who have different traveling preferences (Waddell & Nourzad, 2002; Willigers et al., 2007). The performance of different functions varies when the measurement scales differ. Theoretically, according to a detailed test of different types of the distance-decay impedance functions, for the studies within settlements or districts, the logistic and log-logistic approach should be used. For country-level studies, the exponential approach should be used, and for a European-scale study the Gaussian approach is preferred to estimate the inter-regional travel pattern of residents (Geza & Kincses, 2015; L. M. Martínez & Viegas, 2013).

Table 2: Impedance Functions Used in Potential Measures

Impedance Function *f(x)*	**Basic Form in Literature**
Power function	x^{β}
Exponential function	$e^{\beta x}$
Box-Cox function	$\begin{cases} \exp(\beta \frac{x^{\lambda}-1}{\lambda}), & \lambda \neq 0) \\ x^{\beta}, & \lambda = 0 \end{cases}$
Gaussian function	$\begin{cases} 1, & x < \gamma(\text{threshold value}) \\ ae^{\frac{-(x-b)^2}{c}}, & x \geq \gamma \end{cases}$
Tanner function	$x^{\beta_1} e^{\beta_2 x}$
Logistic function	$\frac{1}{1+e^{-\beta x}}$

Operation

The operation improvements for potential accessibility measures focus on the second step of operation in terms of datasets and implementation tools. In additional to GIS-based implementation tools (e.g., ArcGIS, TransCAD GIS), other tools (e.g., UrbanAccess, TomTom) have been adopted to generate Origin-Destination Matrices (Blanchard & Waddell, 2017b; Tomasiello et al., 2019). For the datasets, a growing number of network open source data (e.g., OpenStreetMap, GTFS, Baidu Map) and activity open data (e.g., Longitudinal Employer-Household Dynamics (LEHD) data) are now available (Blanchard & Waddell, 2017b; Franke et al., 2017; Y. Wang et al., 2018). In addition, GPS data is now used to more accurately capture travel patterns and the temporal change of accessibility (Verma, Verma, Rahul, Khurana, & Rai, 2019).

Interpretation

The interpretation of the potential model could become more complicated since, for example, the space-time utility measures are integrated into the attractiveness parameters and the utility measures are incorporated into the impedance functions.

Usability

The potential measures are also used to evaluate transportation-related impacts on the environment (e.g., the influence on global environmental change caused by market accessibility change, the costs of emissions) (Nahdalina et al., 2017; Verburg et al., 2011).

AV Adoption

Meyer et al. (2017) uses a scenario-based approach to study the possible impact of (shared) AVs on accessibility. The BPR volume-delay function (the Bureau of Public Roads, 1964) is used to link road capacity and travel time. The effects of road capacity on both internal travel demand (demand from existing groups of users) and external travel demand (demand from new groups of users, e.g. old people, disabled) are computed by multiple scenario-based simplified factors such as pricing schemes and regulations, mode shift, and the characteristics of traffic flow (e.g., assumed empty rides rate, induced travel demand by increased accessibility). The potential accessibility measure is used. Other components such as activity distribution and the impedance parameter (travel pattern) are unchanged (Meyer, Becker, Bösch, & Axhausen, 2017).

3.2.3 Adapted Potential

Previous progress (Background)

The adapted potential measures incorporate competition effects based on contour and basic potential formulations, since the ignorance of the competition effects for activities that have a competition nature (e.g., job, healthcare) can cause an inaccurate or even misleading accessibility result (Shen, 1998). Several adapted potential approaches have been summarized by Geurs and van Wee (K.T Geurs & Eck, 2001; Karst T. Geurs & van Wee, 2004) and include: (1) using the quotient of opportunities reachable from origin zone *i* (supply side) and the demand potential from the zone itself (demand side) (Knox, 1978; van Wee, Hagoort, & Annema, 2001; Weibull, 1976); and (2) dividing the opportunities of origin zone *i* by the demand potential from all other destination zones *j* (Joseph & Bantock, 1982; Shen, 1998). A newly identified paper introduces the competition effects from the providers' perspective. VanHorn and Mosurinjohn (2015) use the Huff model to change the absolute opportunity value to a visiting probability, which takes into account the competition effects among providers/facilitators (Van Horn & Mosurinjohn, 2015). As noticed, these three approaches only consider one side of the competition effect, either the origin (users/travelers) or destination side (providers/facilities).

Improvements

Theoretical Basis

During the last two decades, some attempts have been made to improve the effects of competition. Firstly, the introduction of a job diversity factor into the measure as a factor illustrating the competition on origin (the competition among employers for attracting workers) (J. Cheng & Bertolini, 2013; J. Cheng, Bertolini, & Le Clercq, 2007). Secondly, a new type of adapted potential measure has developed called the Two-Step Floating Catchment Area (2SFCA) measure. One of the extensions of the new 2SFCA measure considers competition effects on both the supply and demand side.

The creation of the 2SFCA method was an attempt to solve the shortcomings of the regional availability measure (the simple provider-to-population ratio within a certain administrative boundary, such as county, census tract, block group), which usually overestimated the demand potential, since the service coverage of, for example, healthcare facilities are generally unable to cover the whole administrative boundary (Luo & Wang, 2003). The basic measuring steps of 2SFCA are shown below:

$$R_j = \frac{S_j}{\sum_{k \in \{Dist(k,j) \leq d_0\}} P_k} \tag{4}$$

In the first step of the measurement, from the service provider/facility perspective, by centering each service provider j, catchment area is generated with a search threshold of a given travel cost d_0. The capacity of the service provider, S_j, is then divided by the sum of all the population, P_k, within the catchment area with a threshold value d_0:

$$A_i^F = \sum_{j \in \{d_{ij} \leq d_0\}} R_j = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} P_k} \tag{5}$$

This basic form of the 2SFCA measure can be regarded as the contour measure with both sides of the competition effects taken into account. Thus, it has the same disadvantages as the contour measure. As a result, this measure has been criticized as: (1) creating a dichotomy boundary to define service accessibility (individual component); (2) assuming that people are not influenced by distance impedance within the catchment area (individual component); and (3) ignoring the competition effect among service providers (land use component) (L. Ma, Luo, Wan, Hu, & Peng, 2018). The improvements and extensions on the basic 2SFCA measure solve the three disadvantages identified.

a. Refining the catchment area

The purpose of refining the catchment areas is to generate a catchment area size that more closely matches the reality of the service coverage of facilities/the search range of population for accessing the facilities, and thus, reflects a more accurate accessibility situation.

There are several ways that improvements have been made: (1) the variable catchment sizes were more accurately estimated by dynamically increasing the searching bandwidth size until both the demand and supply-to-demand ratio reach their predefined respective thresholds (Ni, Wang, Rui, Qian, & Wang, 2015); (2) the catchment area size was considered as a function of the characteristics of facility/population (e.g., the location features, the attractiveness of the facility, etc.) with multiple predefined threshold values (e.g., 15min, 30min, 45min, etc.) (Dony, Delmelle, & Delmelle, 2015; Y. Kim, Byon, & Yeo, 2018; McGrail & Humphreys, 2014); and (3) the creation of specific shapes of the catchment area due to condition limitations - i.e., better quality data - are now possible. For the latter, Pan et al. (2018) created a novel integrated catchment area by incorporating actual human travel behavior data into the assessment of a healthcare facility's accessibility (Pan et al., 2018). In contrast, Patel (2013) employed a network-based Voronoi diagram for catchment areas due to the unreliability of local socioeconomic demographic data.

b. Introducing impedance functions

The introduction of the impedance function to weight the opportunities inside the catchment areas can be expressed in a general formulation as:

$$A_i^F = \sum_{j \in \{d_{ij} \le d_0\}} R_j f(d_{ij}) = \sum_{j \in \{d_{ij} \le d_0\}} \frac{S_j f(d_{ij})}{\sum_{k \in \{d_{kj} \le d_0\}} P_k f(d_{kj})} \tag{6}$$

Where *f()* is the impedance function. In the literature, many types of impedance functions have been applied to demonstrate the distance decay effects, they mainly include: (1) a power function; (2) a Gaussian function; (3) a logistic function; (4) a Tanner function, (5) a Butterworth filter; (6) a linear function, etc. (Bauer & Groneberg, 2016; Bree, Diab, & Bell, 2019; Gao, Kihal, Meur, Souris, & Deguen, 2017; Gharani, Stewart, & Ryan, 2015; Luo & Qi, 2009; Tao, Cheng, Zheng, & Li, 2018) (Table 3)

Table 3: Impedance Functions Used in Two-step Floating Catchment Area Measures

Impedance Function	**Basic Form in Literature**
Power function	x^{β}
Gaussian function	$\begin{cases} 1, & x < \gamma (\text{threshold value}) \\ ae^{\frac{-(x-b)^2}{c}}, & x \ge \gamma \end{cases}$
Logistic function	$\frac{1}{1+e^{-\beta x}}$
Tanner function	$x^{\beta_1} e^{\beta_2 x}$
Butterworth filter	$\frac{1}{\sqrt{[1+\xi(x \div d)]}}$ where ξ is sensitive parameter, *d* is the threshold value where distance decay occur

c. Attractiveness, demand effects

Another advance based on the enhanced 2SFCA measures was the introduction of competition effects between service facilities, which, if ignored, would mean the population demand would be overestimated (Lee, Sohn, & Heo, 2018; L. Ma et al., 2018; Polo et al., 2015). To correct this issue, a selection weight for adjusting demand of people was introduced into the 2SFCA measures. The selection weight *G* can be computed by:

$$G_{ij} = \frac{T_{ij}}{\sum\limits_{k \in \{Dist(k,j) \le d_0\}} T_{ik}} \tag{7}$$

where G_{ij} represents the probability of selecting a service facility, T_{ij} and T_{ik} are the predefined weights for service site *j* and *k*, respectively. And therefore, the further refined 2SFCA measure can be expressed as:

$$A_i^F = \sum_{j \in \{d_{ij} \le d_0\}} G_{ij} R_j f(d_{ij}) = \sum_{j \in \{d_{ij} \le d_0\}} \frac{G_{ij} S_j f(d_{ij})}{\sum\limits_{k \in \{d_{kj} \le d_0\}} G_{ik} P_k f(d_{kj})} \tag{8}$$

Operation

In general, 2SFCA measures involve in four types of data: (1) data on the capability of a provider/facility; (2) population distribution data; (3) the travel cost data; and (4) the impedance parameter. The first two types of data are readily available from open data sources (e.g., the number of physicians on an official website, census data for population distribution, respectively) (L. Ma et al., 2018; McGrail & Humphreys, 2014). However, the travel cost data might not be easily available in some regions (e.g., rural areas), especially when the cost is travel time, because the travel speeds in these regions are difficult to obtain. In order to overcome this problem, low-cost GPS data are used to capture the real-time travel speed in some research (Lee et al., 2018; T. Xia et al., 2019). Moreover, since the catchment area is much smaller than a city, the travel pattern in a catchment area is likely to be different from that found at the city level.

Thus, the impedance parameter could also be obtained by using the GPS trajectory to record the service-use pattern for a catchment area and to calculate the impedance parameters.

Interpretation

The 2SFCA measures are more complex than the adapted potential measures, because these types of measures need to be interpreted from both a facility/provider and a resident/user perspective.

Usability

The 2SFCA measures can be used to assess both social (mainly healthcare facility accessibility) and economic impacts (e.g., transit performance which will influence infrastructure investments) (Langford, Fry, & Higgs, 2012; Lee et al., 2018; Xu, Ding, Zhou, & Li, 2015).

AV Adoption

The 2SFCA measures have not been used to study AV accessibility.

3.2.4 Spatial Interaction Models

The spatial interaction models refer to the models that estimate the magnitude of trip flows from origins (zone *i*) to destinations (zone *j*) with or without a weighting function. Parts of the results from the models estimations could be used as an input to calibrate location accessibility (Piovani, Arcaute, Uchoa, Wilson, & Batty, 2018; N. Xia et al., 2018), or as the accessibility indicators directly (G. Wang, Zhong, Teo, & Liu, 2015). There are mainly three types of spatial interaction models: (1) balancing factors measures; (2) place-rank model; and (3) radiation model.

Balancing Factors Measures (Gravity Model)

The balancing factors measures derive from the well-known double model proposed by Wilson (1970), and are developed based on entropy theory. The balancing factors A_i and B_j adjust the sum of flow magnitude from *i* to *j* by origin *i* (destination *j)* equal to the total number of opportunities in zone *j* - e.g., jobs (zone *i* - e.g., workers) (A.G.Wilson, 1970). These balancing factors can be interpreted as accessibility measures that account for competition effects (A.G.Wilson, 1970; Karst T. Geurs & van Wee, 2004).

$$A_i = \frac{1}{\sum_j B_j D_j f(c_{ij})} \tag{9}$$

$$B_j = \frac{1}{\sum_i A_i O_i f(c_{ij})} \tag{10}$$

With the two mutually dependent measures, the accessibility results incorporate both the competition on supplied opportunities D_j (e.g., competition among workers for jobs) and the competition on demand O_i (e.g., competition among employers for employees).

However, some limitations were identified in the balancing factors measures. Firstly, the measures typically assessed a specific mode (transport component), and secondly, not all activity participants value the same opportunity in the same way (land use component). Thus, there is a need to value the opportunities on actual demand rather on the assumed demand (A. M. El-Geneidy & Levinson, 2011). A new accessibility measure has been developed for solving these problems, called the “place-rank” model.

Place-Rank Model

The place-rank model is a new spatial interaction model that is based on the methodology of ranking web pages for a larger search engine developed by Brin and Page (1998). It was first proposed by El-Geneidy (2007, 2011) and has been applied under in an urban context to calculate the place-rank scores as accessibility indicators. The model uses only trip flow data with the assumption that the impedance function is already embedded into the flow data, and, therefore, is generic enough to incorporate all modes (A. M. El-Geneidy & Levinson, 2011; El-geneidy & Levinson, 2007). In addition, the actual values that vary participant by participant can be derived from the actual flow data to calculate the distribution of participants in a study area. The mathematical formulation is expressed as:

$$P_{i,t} = \frac{R_{i,t}}{O_i} \tag{11}$$

$$E_{ij,t} = E_{ij,0} \times P_{i,t-1} \tag{12}$$

$$R_{j,t} = \sum_{i=1}^{I} E_{ij,t} \tag{13}$$

$$R_{i,t} = R_{j,t}^{T} \tag{14}$$

$$\text{If } R_{i,t} = R_{i,t-1}, \text{ stop; Else}(Eq.(11) - (15)) \tag{15}$$

Where $P_{i,t}$ is the power of each person leaving origin i in iteration t; $R_{j,t}$ is Place Rank for zone j in iteration t, $R_{j,0} = \sum_i E_{ij,0}$; O_i is the number of people originating in area i; $O_i = \sum_j E_{ij,0}$; $E_{ij,t}$ is weighted trip table, the number of people leaving origin i to reach activity in j, $E_{ij;0}$ is the origin trip matrix; and I is the total number of zone i.

The result of the place rank $R_{i,t}$ is the number of jobs in a weighted format (A. M. El-Geneidy & Levinson, 2011) that reflect how people perceive zone i as, for example, a job center across all zones in the study area. The results can also be regarded as the redistribution of the total number of people weighted by the power of each person $P_{i,t}$ (Vega, 2012). While only flow data is used, the result of the place-rank model has been found to be a valid accessibility indicator (G. Wang et al., 2015).

Radiation Model

Another spatial interaction model is the radiation model which overcomes a series of limitations of the Gravity model for predicting more accurate trip flows (Piovani et al., 2018; Simini, González, Maritan, & Barabási, 2012) . The formulation of the model is:

$$T_{ij} = T_i \frac{P_i P_j}{(P_i + P_{ij})(P_i + P_j + P_{ij})} \tag{16}$$

where P_{ij} is the population in zones included in a radius of distance or travel time d_{ij}, and excluding those of zones P_i and P_j. These represent the opportunities between them, and T_i is the amount of commuters in *i*.

This radiation model has a high level of accuracy on a intra-country scale prediction, but not on smaller scales. Therefore, some advances were made to generate adequate outcomes at different geographical scales. Notably, this model only needs trip flow data for prediction. The results of the model prediction could be used to refine the demand potential or the trip flow data that contribute to the computing of the accessibility indicators.

Operation

Since no newly operational model or tools are identified for improving the gravity model, this section mainly focuses on the operationalization of the place-rank and radiation models.

A significant advancement of the place-rank and radiation models is the readily available data and relatively easy computation processes. For the place-rank model, only trip flow distribution data are needed, and the type of data could be flexible as long as the data bear the features of population mobility, e.g., commonly used origin-destination matrices, smart call records, etc. (Piovani et al., 2018; G. Wang et al., 2015). As for the radiation model, only population distribution data are needed, and the radiation model is easy to calculate with readily available data. In contrast, the place-rank model requires iterative calculations to obtain the final results, and so far, no tool has been created to specifically operate the place-rank model. However, the calibration of this model is relatively easy without getting involved with the impedance function.

Interpretation

Regarding the two new models, the interpretation of the radiation model is relatively complex since the model can be formulated in terms of radiation and absorption processes (Simini et al., 2012). With respect to the place-rank model, the interpretation could be complicated for a person who does not know about web page rankings. In addition, the model involves the iterative calculation process, which can further complicate its interpretation.

Usability

With respect to the improvement of usability, the place-rank model could be used for evaluating social impacts (e.g., job accessibility) (A. M. El-Geneidy & Levinson, 2011; El-geneidy & Levinson, 2007) and environmental impacts (e.g., energy performance) (Vega, 2012) . As for the radiation model, the results have been used to assess economic impacts (e.g., travel cost for reaching destinations) (Piovani et al., 2018; N. Xia et al., 2018) .

AV Adoption

The spatial interaction models have not been used to study AV accessibility.

3.3 Person-based Measures

3.3.1 Previous progress (Background)

The person-based accessibility measures were developed from the space-time or time-geographical framework proposed by Hägerstrand (1970) to study the behavior of individuals under the constraints of their physical locations and time budgets. By recognizing that individuals need to physically reach a location to participate in activities, the concept of a Space-Time Prism (STP) (see Figure 3) was introduced to model the time-geographical framework. The prism delimits the spatial boundary that people can possibly reach during the time interval for two mandatory activities (e.g., work and home), restricted by the local traffic conditions (travel speeds) (Lenntorp, 1976). The projection of the STP on a space planar is defined as the Potential Path Area (PPA), which is the area in which people can potentially participate in daily social/economic activities (Lawrence D. Burns, 1979; Miller, 1991). Accessibility, under the space-time framework, is defined as the number of specific activities within the PPA.

The person-based measure possesses a strong theoretical advance that includes almost all the relevant components of an accessibility measure. The only disadvantage is the absence of the supply potential for competition effects (Karst T. Geurs & van Wee, 2004). While this may not be a problem for the person-based measure because not all activities include competition effects, when applied to activities where competition matters (e.g., jobs, healthcare, etc.), the supply potential should be included (K.T Geurs & Eck, 2001).

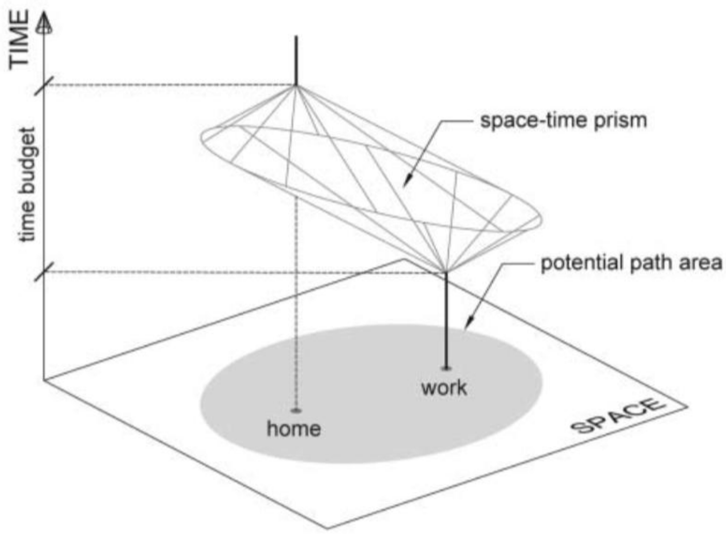

Figure 3: Space-time Concept Description & Visualization. *Source*: Farber, Neutens, Miller, and Li 2013, figure 1(B), p. 486.

Although this space-time measure has a theoretical advantage, its interpretation is not easy (Karst T. Geurs & van Wee, 2004). Form an operational perspective, it includes two main steps: (1) delimiting PPA boundaries from STPs; and (2) estimating the opportunities within the boundaries. In step one, in spite of the advances in GIS and spatial modeling, the measure's operation and modeling face many difficulties, including involving detailed individual disaggregated data that are not easily available from standard travel surveys (Thill & Horowitz, 1997), a lack of feasible operational algorithms, and the hardware required to satisfy the computational intensity (Kwan, 1998). In step two, the geo-location information of some activities could be difficult to obtain. As a result, this measure cannot be easily be translated into a useful indicator for population groups or used at a higher geographical scale to assess economic impacts (Karst T. Geurs & van Wee, 2004).

3.3.2 Improvements

Theoretical Basis

The theoretical improvement in space-time measures can be grouped using the following operation steps: (1) the refinement of the boundary of the potential path area (PPA); and (2) the more accurate estimation on opportunities.

The PPA boundaries have been refined through mainly two ways. First, transport cost measurement has been improved by incorporating network-based dynamic traffic congestion in the estimation of transport velocity (Y. Wu & Miller, 2001). This is achieved by using the time-table of public transport to assess public-transit-based PPA through the identified shortest routes, under a given limited time budget (S. Cheng, Xie, Bie, Zhang, & Zhang, 2018), and by integrating the travel time uncertainty into the space-time accessibility model for the purpose of generating the Reliable Space-Time Service Region (RSTR) (Chen et al., 2017). Second, more precise PPAs have been obtained by incorporating individual characteristics, such as the minimum activity duration to benefit from participating in the activity and consideration of a maximum acceptable length of travel time (H. M. Kim & Kwan, 2003) to improve the accuracy of the space-time prism.

The advances in estimating the opportunities were based on temporal constraints and visiting probability (demand potential). From a temporal perspective, the availability of the opportunities under temporal constraints could be seen as an implicit improvement in the supply of opportunities by temporal constraints – i.e., the availability of each identified opportunity in a specific time period. Kim and Kwan (2003) incorporates the activity duration with facility opening hours to indicate the availability of the opportunity/facility.

The visiting probability refers to the assessment of the probability of an individual to visit an opportunity available in a specified time period. The methodology for estimating visiting probability can be grouped into three categories: (1) Distance decay/kernel density estimation, that are based on the assumption that the likelihood of visiting a specific opportunity has an inverse relationship with the distances between the mobile object and opportunity locations, but has a positive relationship with the opportunity attractiveness (Chen et al., 2017; Horner & Downs, 2014; Horner & Wood, 2014). (2) Movement principles, of which the random theory (Winter & Yin, 2011) was introduced to build a mathematical framework to distinguish opportunity locations based on movement probability. Further, Song et al. (2016) applied two Markov techniques - Brownian Bridge (BB) and continuous-time semi-Markovian (SM) - to evaluate the probability of both non-vehicular and vehicular visiting probability (Y. Song, Miller, Zhou, & Proffitt, 2016). Sahebgharani et al. (2019) attempted to extend the work of Song et al. (2016) to offer an accessibility model linking attractiveness of opportunities to the transportation system by using BB and SM processes for tackling the issues of (a) the opportunity accessibility under different moments, and (b) an individual's accessibility level by spatiotemporal restriction (Sahebgharani, Haghshenas, & Mohammadi, 2019). (3) The neurofuzzy system, through which the translation between measures of metric distances and qualitative distances (e.g., "very near", "near", "normal", "far", and "very far") can be achieved based on a series of contextual and individual-based factors (e.g., time and financial resources, individual activity purposes, personal and demographic profiles, one's familiarity with the geographic area of destinations, activity preferences, etc.) (Dao & Thill, 2009). An implication from this method is that the higher the level of qualitative distance (closer to "very far") is for an opportunity, the less likely an individual would visit it.

Interpretation

With the increasing advance of the space-time accessibility measures, the interpretation of those measures is becoming harder. The new measures incorporate other disciplinary theories and concepts to further refine the measures for more realistic and usable results.

Operation

The improvement of the operationalization of person-based measures has occurred through better access to datasets and improved implementation models. As for data, three groups of datasets are necessary to use this type of measure: (1) activity diary data; (2) road network data; and (3) opportunity location data. Some other types of data (e.g., opportunity opening hours data) could also be collected based on different applications. The diary activity data are generally collected in household travel surveys by recording residents' activities, locations, and duration time. Nowadays, many of the local/region (standard) household travel surveys/studies include such activity diary data (e.g., Oregon and Southwest Washington, Utah) (Fransen, Farber, Deruyter, & De Maeyer, 2018; H.-M. Kim, 2005), which were not common two decades ago. In addition, the opportunity location data could be obtained through directly downloadable data (e.g., USDA's Food and Nutrition program SNAP retail locator mapping web service) (Horner & Wood, 2014), or extracted data from a database (Fransen et al., 2018). Regarding the implementation tools, Charleux (2015) develops a GIS toolbox specifically to compute and map person-based accessibility indicators, which is user friendly, customizable, and downloadable (see Charleux, 2015).

Usability

The usability of the measure is still constrained with regards to social impacts. However, one paper uses this measure to assess the performance of the transport system (average travel time) under a special event context through comparing the number of people who can reach a special event place under different transport system management scenarios (Ruan et al., 2016).

AV Adoption

The person-based measures have not been used to study AV accessibility.

3.4 Utility-based Measures

3.4.1 Utility-logsum Measure

Previous progress (Background)

Utility-based accessibility measures were developed from utility theory, which addresses the decision to purchase one discrete item from a set of potential choices (Greeene & Liu, 1988), to model the users' travel behavior and the benefits of variation offered by a transport system. The prime assumptions of the utility-based measure can be found in Koenig (1980). These are that: (1) people will choose the alternative that has the maximum utility to the individual; and (2) the evaluation of utility can be divided into two groups, a non-random (observed) component and a random (unobserved) component (Koenig, 1980). There were many attempts to translate the utility theory to a mathematical formulation, of which the most famous, named logsum, is based on random utility theory using a Multinomial Logit Model and Gumbel distribution. The formulation of the utility-based measure can be expressed generally as (Ben-Akiva & Lerman, 1985):

$$A_n = E(\max U_k) \tag{17}$$

$$U_k = V_k + \epsilon_k \tag{18}$$

$$A_n = \ln(\sum e^{V_k}) \tag{19}$$

Where A_n is the accessibility as benefits for individual n; U_k is the total utility of alternative k; V_k is the indirect, or observed, utility portion of the total utility of choice k; and ϵ_k is the random error.

Based on the sound micro-economic theoretical basis, the result of this measure are desirably usable as the input for assessing social and economic impacts. Previously identified theoretical disadvantages of this measure include ignoring the supply potential on competition effects and the temporal constraint (K.T Geurs & Eck, 2001; Karst T. Geurs & van Wee, 2004). Although the two shortcomings could be overcome by incorporating entropy spatial interaction model (for supply potential) (F. J. Martínez, 1995; F. J. Martínez & Araya, 2000; Miller, 1999), and space-time utility measure (temporal component) (see Section 3.4.2), respectively, the shortcomings of the entropy spatial interaction model are that it is hard to interpret and the space-time benefit measure is difficult to interpret and operate. In addition, for the logsum measure itself, the interpretation also relies on complex theories and models.

Improvements

Theoretical Basis

Chorus et al. (2011) argue that there is a discrepancy between what Logsum-measures of accessibility aim to measure (experienced-utility) and what they actually measure (decision-utility). The notion of experienced-utility refers to "the utility evaluation of a chosen alternative after the choice has been made" (Chorus & de Jong, 2011). However, the notion of decision-utility refers to "the evaluation of an alternative with the aim of making a decision" (ibid.).

Chorus et al. (2011) adopted a two-step approach to overcome the gap between these two notions by: (1) "incorporating changes in preferences between choice and experience" (ibid.); and (2) "incorporating changes in evaluation-rules between choice and experience" (ibid.). The regret-minimization theory is applied, rather than the utility-maximization theory, to evaluate the changes between the processes of choice/decision-making and experience. A new mathematical formulation was built based on the logsum method:

$$Acc = \int_{\xi}\int_{\nu}\left[\left(\sum_{j=1}^{J}(I_j^R)(\beta^R,\xi)\cdot(U_j(\beta^U,\nu))\right)\cdot f(\xi)f(\nu)\right]d\xi d\nu \tag{20}$$

$$Acc = \sum_{j=1}^{J}[P_j^R(\beta^R)\cdot(V_j(\beta^U))] + C \tag{21}$$

$$P_i^R = \frac{\exp(-R_i)}{\sum_{j=1}^{J}\exp(-R_j)} \tag{22}$$

$$R_i = \sum_{j\neq 1}\sum_{m=1}^{M}\ln(1+\exp[\beta_m\cdot(\chi_{jm}-\chi_{im})]) \tag{23}$$

where, vector β^R contains parameter estimates obtained from estimating the regret-based model on observed choices, β^U contains parameter estimates obtained from estimating the utility-based model on the same observed choices. $I^R{}_j$ is an indicator function which equals one if, given the vector of estimated parameters and conditional on the vector of random errors e, alternative j's random regret R_j is smaller than the regrets of all other alternatives in the set. R_j is the systematic regret when a decision-maker faces a set of J alternatives, each being described in terms of M attributes x_m. $V()$ is the function of the observed part in random utility U and $P^R{}_j$ is the choice probabilities of random regret (Chorus & de Jong, 2011).

Operation

The ease of operation of the logsum measure depends on the observed utility function V_k, which can be as simple as just one variable (e.g., travel time) (see Ziemke, Joubert, & Nagel, 2018), or be more complicated and include multiple sets of variable attributes involving regression modeling (see Z. (Eric) Ma, Masoud, & Idris, 2017). In the same vain, the data availability also depends on the variable(s) included in the observed utility function.

Interpretation

The interpretation of the logsum concept itself relies on the use of complex economic references to explain the accessibility measure. Converting the utility logsum measure to a monetary form can greatly help planners and policy makers understand the measure (Karst T. Geurs & van Wee, 2004). However, it may not be appropriate to translate the utility results into a monetary value under all situations.

Usability

The usability of the logsum measure covers all three types of indicators: social (Bifulco & Leone, 2014; Ziemke et al., 2018); economic (Gulhan, Ceylan, & Ceylan, 2018; C. Yang & He, 2010); and environmental impact (Peter Rickaby, 1985).

AV Adoption

Childress et al. (2015) adopted an activity-based travel model to evaluate the possible impacts of automated vehicles in Seattle, WA under four different scenarios. In addition to the seven types of system performance measures included in the model (e.g., vehicle miles traveled (VMT), trip length, speed, etc.), the travel model results were applied to assess the spatial distribution accessibility effect. The “Aggregate Logsum” measure, which is the aggregate of expectations across all locations and all modes, was used to compare the difference of utility gains between the proposed scenarios and base situation (2010 local situation as baseline) as well as between different categories of groups (e.g., low-income, high-income) under the same scenario (Childress, Nichols, Charlton, & Coe, 2015).

3.4.2 Utility-space-time

Previous progress (Background)

Based on the utility-logsum measure, the utility-space-time measure integrated the space-time constraints by defining the observed utility V_k in location k for an individual as the following space-time utility equation proposed by Burns (1979):

$$A_n = E(\max U_k) \ = \ln(\sum e^{V_k}) \tag{24}$$

$$V_k = a^{\alpha} T^{\beta} \exp(-\lambda t) \tag{25}$$

Where a is the attractiveness of opportunity location; t is the travel cost required; T is the available stay time for activity participation, $T = f(t)$; $a, t, T, \alpha, \beta, \lambda \geqslant 0$ (Lawrence D. Burns, 1979).

This utility measure demonstrates that the utility has a positive relationship with the attractiveness of activity and the available length of time for participation, but it shows a negative relationship with the travel cost required. Notably, the available stay time for participation T, is implicitly defined by the space-time prism. The accessibility measure is the utility obtained for an individual and can be calculated using either the maximum logsum format, $A_n = E(\max U)$, or the additive (sum) format, $A_n = \Sigma\ U$ (Ashiru, Polak, & Noland, 2003).

Theoretically, this measure satisfies almost all theoretical considerations except the competition effects, and thus, the result of the measure is usable for both social and economic impact evaluation. However, the introduction of the space-time measure increases the difficulty of its interpretation and operation.

Improvements

Theoretical Basis

The theoretical improvements identified from the literature review mainly focus on refining the space-time benefit equation, because the original formulation had simplified the measurement of the variables (Ashiru et al., 2003).

From a transportation perspective, the progress focus on travel time refinement. For example, the introduction of the RSTR model proposed by Chen et al. (2017) for capturing the travel time uncertainty when calculating transport cost and the available staying time (Z. Wu, Chen, & Lam, 2018); and the extension of the basic measure to encapsulate more realistic temporal constraints by modeling a more realistic transport system taking into account delay and waiting time (Ashiru et al., 2003).

Regarding the individual components, improvements included advances for (1) multi-person and (2) multi-activities through a trip-chain. For the multi-person advance, Neutens, Schwanen, Witlox, and Maeyer (2008) proposed a joint space-time benefit model with "shared or joint activities, defined as activities where at least two individuals are co-present at the same spatial-location for at least some time to pursue a common set of acts." This change further shaped the personal space-time prism and calculated the perceived benefit of individuals. For the multi-activities advance, Ashiru et al. (2003) outlined the development of a multi-trip space-time benefit measure, which assumes that an individual could participate in more than one activity between two mandatory activity space-time locations. Hsu and Hsieh (2004) formulated an individual model to evaluate accessibility benefits of participating activity(ies) through a trip chain, and further extended this model by illustrating how to maximize the benefits through location choice analysis (Hsu & Hsieh, 2004).

As for improvements on all components, Odoki, Kerali, and Santorini (2001) improved the measure by placing the measurement under the context of developing countries. The proposed measure enhanced every variable in the space-time benefit measure by incorporating income constraints on those variables.

Operation

The implementation of the utility-space-time measures introduce the complexity of the space-time measure in both operation models and disaggregated data requirements. In addition, since more parameters are introduced into the space-time benefit function (Ashiru et al., 2003; Chen et al., 2017), applying models built by programming scripts corresponding to specific needs of topic is a popular way to use and operate this measure. Although household travel survey data is a useful dataset that includes many necessary data and many open data sources are available (e.g., Jiepang website) (Wu et al., 2018), there is still a need to collect specific data through self-conducted surveys for special topics or regions where no open data available.

Interpretation

The interpretation of this new measure is becoming more and more difficult as new parameters (e.g., integrating perceived opportunity into the logsum measure) are being introduced into the space-time benefit function (Le Vine, Lee-Gosselin, Sivakumar, & Polak, 2013b).

Usability

The result of the utility-space-time measure is usable for assessing social and economic impacts, but no paper has used the measure to evaluate environmental impacts so far.

AV Adoption

The utilty-space-time measure has not been used to study AV accessibility impact.

CHAPTER 4: Discussion

This literature review reveals an overall trend in applying more advanced and comprehensive theories and/or models to evaluate accessibility - i.e., to explain people's travel behavior. The ways in which accessibility measures have been improved can be divided into two groups (see Figure 4): (1) Refining the existing measures by incorporating interdisciplinary theories/models (e.g., statistics regression models) to include missing components; and (2) Using other theories/models to create and develop new and more advanced accessibility measures. The first type of improvements result in more complicated, disaggregated, and need/satisfaction based accessibility measures (e.g., contour, potential, space-time measures). In contrast, the second type of improvements create more comprehensive measures, but with relatively lower data requirements (e.g., place-rank, radiation models). These trends could be partially explained by the need to disaggregate measures to reveal more detailed and important information (Handy & Niemeier, 1997) as well as the need to have models that satisfy relevant theoretical criteria and are relatively easy to operate and interpret (Karst T. Geurs & van Wee, 2004).

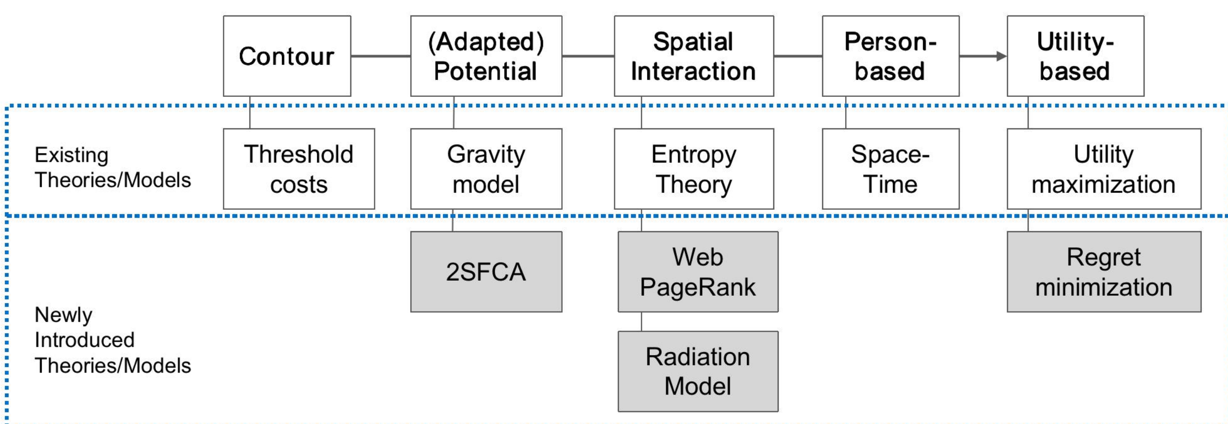

Figure 4: The Progress of Accessibility Development

From a theoretical perspective, accessibility measures are now incorporating more theoretical components, making the interpretability of the measures more difficult. However, the implementation of the majority of these accessibility measures is becoming easier, since more data can now be relatively easily obtained from open sources, and both the calculation models and computation hardware are improving. Therefore, these improved accessibility measures are becoming more usable with regards to assessing social, economic, and environmental impacts. Finally, attention has also been paid to the impacts of AV on accessibility measures.

4.1 Path for Further Research

4.1.1 Theoretical Advance

The existing practice of measuring the accessibility effects of land use and transport policy decisions/plans can be much improved by more theoretically advanced measures that can be calculated using existing data with or without the use of land use and transport models.

Firstly, there is a need for research on the two new spatial interaction models. For the place-rank model, while it uses only trip-flow data, this model satisfies most of the theoretical criteria (i.e., it embeds transport and individual components in the model). However, there are very few examples where the place-rank model has been used to evaluate land-use and transport policy/plans. The radiation model offers accurate estimations of population mobility and captures diverse processes (e.g., commuting, trade) in a wide range of time scales (e.g., hourly to yearly mobility) (Simini et al., 2012). The high quality outcome from this model has the potential to be a source for studying accessibility changes from proposed land-use and transport policy/plans, but to date there has been limited research in this area.

Second, there is also a need to have more experience with the new regret-minimization measure to evaluate accessibility changes with respect to land-use and transport policy/plans. The regret-minimization utility measure is more theoretically advanced than traditional utility-maximization measures (see Section 3.4.1). Nevertheless, limited research has been undertaken to study the usability of this accessibility measure and to evaluate its social or economic impacts on policy decision-making.

Third, although progress has been made in assessing the visiting probability of space-time measures, there is still a need to build links between household travel patterns and long-term land use changes (Karst T. Geurs & van Wee, 2004). Reconciling the space-time utility measure (that contains the person-based measure) with the location-based one (see Y. Wang et al., 2018) could shed light on this unsolved research area (Geurs and van Wee, 2004).

4.1.2 Usability as An Input for Environmental Impacts

The link between accessibility and the environment has recently gained attention due to a growing interest in sustainable development. Some advances have been made in this area (see Peter Rickaby, 1985; Vega, 2012; Nahdalina et al., 2017; Verburg et al., 2011), and the results show that accessibility measures indeed can be used as an input for environmental impacts. However, the current practice is mainly constrained to the environmental cost dimension. There is a need to have more research that expands the scope of the measures to capture other environmental dimensions besides the monetary costs.

4.1.3 Incorporation of Critical Components in Accessibility Measures

This paper has discussed the inclusion of theoretical components in accessibility measures (e.g., land use, transport, temporal, and individual components), but has not explored how to incorporate these components in the correct manner. There is a need for additional research to study the incorporation of critical components in accessibility measures. One useful approach to addressing this research need could be to use Weibull's axiomatic framework, which was developed for formulating accessibility measures (Weibull, 1976.

4.2 Accessibility in the Context of AVs

Automated vehicle transportation is expected to have a huge impact on accessibility in the coming years, given the impact of AV on all four accessibility components - land use, transport, temporal, and individual (see Section 1.2). However, due to the highly speculative future of AV adoption, quantifying accessibility under an AV future is challenging.

First, although there are a number of articles that discuss how transport cost could be affected by AVs (e.g., travel time, comfort, and financial cost) (Bellem et al., 2016; Johnson et al., 2017; Khondaker & Kattan, 2015), the extent of the travel time change is related to both road capacity and travel demand. In order to quantify the change of the travel time, changes in multiple key factors need to be quantified, such as pricing schemes, service levels, consumer preferences of AVs for mode shift, the empty rides (Meyer et al., 2017), to list just a few. Moreover, estimated changes in travel time will vary under different AV adoption scenarios and assumptions (e.g., AVs can only drive in a constrained locations, AVs can drive in all situations, or with a fleet of shared AVs usable for travelers) (ibid.). Currently, the impact of AV on some of the key factors remains unclear. Therefore, the existing practices evaluate the impact of transport cost (mainly travel time) with a simplified model to estimate expected changes.

From an individual perspective, how people's travel behavior could be impacted by AV is still a research topic that needs further exploration. Some factors (e.g., trip length, value of time) that might contribute to quantifying the impact of AVs on an individual component (e.g., impedance parameter in the accessibility measures) still remain unclear.

As for the land use component, the impacts of AVs on land use changes is a popular topic under exploration. There are some general assumptions of how land use could be affected by AVs (e.g., more compact urban land use, or sprawl in a suburban area while encouraging a more compact urban center) (Milakis et al., 2018). Nevertheless, the long-term prediction and quantification of activities distribution are very challenging at the current moment in time.

Therefore, the current practices mainly focus on studying the impact of AVs on travel time. Of the four practices identified, travel time impact was assessed by (1) scenario-based activity-based travel models (Childress et al., 2015; K. Kim et al., 2015), and (2) scenario-based estimation of the range of expected capacity impacts and the levels of additional internal and external demand generated (Meyer et al., 2017).

Accessibility impact from AV technology is still a rarely studied topic, due to the complexity of the components involved and the highly speculative future of AV adoption. However, it seems that travel time will be a key focus point for AV-related accessibility research by refining the critical aspects for more accurately measuring travel time changes.

CHAPTER 5: Conclusion

The purpose of this literature review was to: (1) review the latest developments in accessibility measures over the last two decades; and (2) identify how accessibility measures could be used to assess the impacts from automated vehicle transportation.

By undertaking an extensive literature review that builds on Geurs and van Wee (2004), a total of 495 papers were identified. These papers both enriched the research on existing accessibility measures and theoretically advanced them in relation to operation methods/models, interpretation, and usability for social, economic, and environmental impacts. Almost all of the previous types of accessibility measures have benefitted from theoretical improvements (related to the land use, transport, temporal, and individual components), and four new types of accessibility measures have been developed. With respect to the operational advance, a number of new models and tools have been created to facilitate the evaluation of accessibility. In addition, open data sources have become more available and the surge of 'big data' is also opening up new levels of access to data. With regards to interpretation, due to the overall trend toward more complicated and disaggregated measures, interpretation is growing more and more difficult. From a usability perspective, the accessibility measures have been broadened to evaluate not only social and economic impacts, but also the environmental effects of land-use and transport policies.

Interestingly, few studies focus on the impacts of AVs on accessibility. Those that were found focus on changes in the cost of transport, especially the impact of travel time, with other components (land use, temporal, individual components) being held constant. One reason for the lack of research on AVs might be that the future of AV adoption is highly speculative and the impacts of AVs on accessibility components remains unclear. Given the important role accessibility plays in transport and land use planning, more research on accessibility impacts from AV adoption is needed.

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