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Measuring temporal variation of location-based accessibility using space-time utility perspective

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ABSTRACT

Conventional location-based accessibility measures are static and cannot represent accessibility fluctuations at different times of day. To fill this gap, this study proposes location-based space-time accessibility measures to capture the temporal variation of location-based accessibility. Using the space-time utility perspective, the accessibility of a location is conceptualized as the space-time utility offered by a set of facilities accessible from the location. Individuals' facility choice behaviors among multiple alternatives are explicitly considered. A time-dependent facility attractiveness function is introduced to represent the temporal variation of individuals' needs to perform activities at a certain facility. The introduced function is formulated as two components: a time-invariant component representing individual satisfactions derived from activity participation at the facility, and a time-varying component expressing individuals' dynamic intensities to perform a certain type of activities at different times of day. To demonstrate the applicability of these proposed measures, a comprehensive case study has been carried out in Wuhan, China. The results of the case study show that the proposed measures can well capture the temporal variation of accessibility, due to the dynamics both of traffic conditions and of individuals' intensities in performing activities at different times of day. The proposed measures require moderate level of data, in terms of rich facility information; and most of these data could be extracted from social media applications.

1. Introduction

Accessibility is a core concept in transport geography, urban planning, and other related fields. It is defined as the ease with which activity locations or facilities can be reached from a particular location (or by individuals at that location) using a particular transport system (Kwan and Weber, 2008). Accessibility to various facilities (e.g., food, healthcare, park, and shopping facilities) has been intensively studied in the literature, not only for policy evaluation purposes (Páez et al., 2012; Shaw et al., 2014), but also for being an explanatory factor in many geographic phenomena analyses (e.g., social equity and justice) (Neutens et al., 2010; Lucas, 2011; van Wee and Geurs, 2011; Neutens, 2015; Giuffrida et al., 2017; Higgs et al., 2017).

The evaluation of accessibility to urban services depends on accessibility measures. In the literature, various measures have been developed and can be broadly classified into two categories: location-based (or place-based) and individual-based (or people-based) measures (Geurs and van Wee, 2004). Conventional location-based measures conceptualize accessibility largely in terms of the proximity to urban services from an individual's residential location or workplace. Common examples of location-based measures include travel distance to the nearest service location, the cumulative number of services within a specified cut-off distance, and gravity-type measures in which the attractiveness of services decreases with distance from the origin (Neutens et al., 2010). These location-based measures require small amounts of aggregated data and have been widely applied to many applications in large-scale study areas. However, a major inadequacy of such conventional location-based measures is that they are static and fail to account for the fact that accessibility levels may fluctuate at different times of day, because of the dynamic nature of human activity-travel behaviors and traffic conditions (Miller, 2007; Neutens et al., 2012a; Kwan, 2013).

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The importance of including the critical time dimension in accessibility studies has been well acknowledged in the literature by developing individual-based measures (Kwan and Weber, 2003; Miller, 2007; van Wee, 2016). Most individual-based measures are built upon the time-geographic framework (Hägerstrand, 1970), which captures the complexities of individual activity-travel behaviors under various space-time constraints. The number of reachable urban services and the cumulative activity durations at reachable urban services are two well-known individual-based measures (Kwan, 1998). A theoretically better measure is the space-time utility approach, which directly measures the individual space-time utilities of activity participation (Miller, 1999). All these individual-based measures are well suited to evaluate the accessibility of people in different social groups at different times of day (Kwan and Weber, 2008). However, such individual-based measures are difficult to generalize to large study areas (Páez et al., 2010; Horner and Downs, 2014), because it is generally very expensive to acquire a large number of samples of individual-level activity diary data in large study areas.

With the recent development of information and communication technologies (ICTs), it has become technically and economically feasible to collect and assemble huge amounts of spatiotemporal data, such as taxi trajectories, mobile phone tracking data, and social media data (Liu et al., 2015; Miller and Goodchild, 2015; de Bruijn et al., 2018; Yuan et al., 2018). These spatiotemporal Big Data enable data-driven approaches to extract information about human activity and travel behaviors and dynamic traffic conditions, thereby providing new data sources to improve conventional location-based accessibility studies (Järv et al., 2018). In the literature, considerable progress has recently been made in location-based accessibility studies by explicitly considering dynamic traffic conditions (Li et al., 2011; Tenkanen et al., 2016; Chen et al., 2017; Benenson et al., 2017; Widener et al., 2017; Yang et al., 2017; Kujala et al., 2018; Zhang et al., 2018; Moya-Gómez et al., 2018). In addition, increasing attention has been paid in the literature to improving conventional location-based accessibility measures by incorporating human mobility patterns. Páez et al. (2010) improved the conventional cumulative-opportunity measure by using distinct travel distances for people in different social groups and geographical regions. Widener et al. (2015) and Fransen et al. (2015) extended conventional location-based measures by using interaction potential metrics (Farber et al., 2013) and considering inter-zonal commuting patterns. Chen et al. (2018) improved location-based accessibility measures by using individual mobility patterns extracted from mobile phone tracking data. Järv et al. (2018) proposed a generic framework for integrating the time dimension in location-based accessibility measures, and illustrated its application in a food accessibility study by considering facilities' opening hours and temporal variation of population distributions and traffic conditions.

Along the line of data-driven geographical research (Miller and Goodchild, 2015), this study aims to incorporate the time dimension in location-based accessibility measures by explicitly considering individuals' dynamic intensities for performing activities at facilities using rich facility information. In recent years, rich facility information has become publicly available through many social media (and location-based service) applications, e.g., Foursquare, Twitter, and Google Map. For example, the Foursquare application enables users to post their location in a "check-in" to record, track, and share their life moments with friends. In the application, a user's geographical location is matched to nearby facilities such as restaurants, shopping malls, cinemas, and coffee shops. After checking into a facility, users can share their activity participation experiences through advice, photographs, and ratings of service quality. Beyond the facilities stored in the application, users are encouraged to check into new facilities, for which they earn additional rewards. These user-generated social media data provide an effective means for researchers to collect and update rich information about dynamically changing urban facilities. Such rich facility information could be a useful data source for accessibility studies because it records not only the detailed characteristics of urban facilities (e.g., facility location, type, opening hours and price), but also customers' behaviors (or experiences) in choosing and using urban facilities. However, little attention has been paid in the literature to using such rich facility information for accessibility studies.

By using rich facility information, this study proposes new location-based space-time accessibility measures to evaluate the temporal variation of location-based accessibility in large-scale study areas. The proposed accessibility measures reconciles conventional location-based accessibility measures with the space-time utility perspective (Miller, 1999; Delafontaine et al., 2012). In this study, the accessibility of a location is conceptualized as the space-time utility offered by a set of facilities that are accessible from the location. Individuals' facility choice behaviors among multiple alternatives are explicitly considered. A time-dependent facility attractiveness function is introduced to represent the temporal variation of individuals' needs to perform activities at a certain facility. The introduced function is further formulated as two components: an activity satisfaction component, and an activity intensity component. The former represents the degree of satisfaction that individuals derive from performing activities at a facility. It is time-invariant, depending on the facility's qualities. The latter represents individual intensities when participating in a particular type of activity at different times of day. It is time-varying, related to activity type and individual needs to perform this type of activity during a certain time period. Such a formulation of space-time utility reflects the observation that individuals' activity utility is related to the satisfaction of performing the activity itself and to the intensity with which the activity is performed (Axhausen and Gärling, 1992; Lam and Yin, 2001). Therefore, the proposed measures enable realistic evaluation of temporal variation of location-based accessibility at different times of day. More importantly, the proposed measures only required a moderate level of data with respect to rich facility information, and most of these data could be extracted from social media data.

2. Conventional location-based accessibility measures

This section briefly introduces conventional location-based accessibility measures to provide necessary background. Most location-based accessibility measures in the literature can be defined generically as the sum of products of an attractiveness and a distance decay function (Kwan, 1998; Páez et al., 2010):

$$A(i) = \sum_f (W_f)^\alpha K(c_{if}) \tag{1}$$

where $A(i)$ is the accessibility of individuals living at location i; W_f is the individual perception of the attractiveness of facility f; α is the sensitivity parameter with respect to facility attractiveness; and $K(\cdot)$ is a distance decay function that depends on the time (or distance) c_{if} required to travel from location i to facility f. Depending on how $K(\cdot)$ is defined, different accessibility measures can be obtained. Using a negative exponential (or power) function leads to the gravity measure (Hansen, 1959):

$$A(i) = \sum_f (W_f)^\alpha \exp(-\beta_i c_{if}) \tag{2}$$

where $\beta_i \geq 0$ is the sensitivity parameter with respect to travel time c_{if}. The larger the value of β_i, the stronger will be the distance decay effect on $A(i)$. By using a binary cutoff function $R_i(f)$, a measure of cumulative opportunities (Breheny, 1978) can be defined as follows:

$$A(i) = \sum_f (W_f)^\alpha R_i(f)$$
$$R_i(f) = \begin{cases} 1, & \text{if } c_{if} \leq \gamma_i \\ 0, & \textit{otherwise} \end{cases} \tag{3}$$

where $R_i(f) = 1$ if travel time c_{if} is less than or equal to threshold γ_i and $R_i(f) = 0$ otherwise. Smaller values of γ_i can be interpreted as lower mobility for people living in location i (i.e., a stronger distance decay