Hindawi
Journal of Advanced Transportation
Volume 2022, Article ID 9380884, 13 pages
https://doi.org/10.1155/2022/9380884

Research Article

Reliability of Accessibility: An Interpreted Approach to Understanding Time-Varying Transit Accessibility

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Received 4 March 2022; Revised 3 May 2022; Accepted 28 May 2022; Published 16 June 2022

Academic Editor: Zhixiang Fang

Variable traffic conditions cause travel time uncertainty and further lead to time-varying accessibility. Most current studies do not fully consider fluctuations in accessibility and use complicated methods that likely overestimate the level of accessibility and hinder the application of accessibility measures. To address this issue, we utilized large-scale open-source data and proposed an interpretation of the reliability of accessibility concept that incorporates reliability, travel time uncertainty, and a cumulative opportunity measure. We examined the reliability of accessibility to Shenzhen, a major city in China, focusing on transit accessibility and job opportunities. The results demonstrate that the reliability of accessibility displays a bimodal distribution along urban railway lines and can be used to calculate the impact of urban railways in terms of punctuality. The new approach illustrates time-varying characteristics in the form of probabilities and provides further guidance on accessibility for governments.

1. Introduction

As a key variable used to evaluate the relationship between land use development and transportation system investment, accessibility is a useful tool in transportation planning and urban planning practice. Public transit accessibility has become a preferred indicator among government agencies and researchers, as many people rely on public transit for commuting and other purposes (e.g., transportation to schools, shops, and hospitals) [1, 2]. In addition, public transit accessibility is also an important indicator of infrastructure investment [3].

Land use and transportation systems are two important components of transit accessibility [4]. Previous studies on job opportunities include the land use component because accessibility to jobs is increasingly sought in transportation and land-use planning [5]. Most transit accessibility studies use travel time to characterize transportation components. The two equivalence relations mean that transit accessibility is sensitive to travel time and job opportunities. Job opportunity changes take long periods to manifest and are difficult to investigate. Meanwhile, uncertain traffic conditions and different transit departure frequencies at different times of the day lead to travel time uncertainty [6]. In other words, public transit accessibility faces time variations [7].

A constant travel time, such as the average or peak hour travel time, was used in most previous studies to measure accessibility, which assumed that the travel time is fixed [8]. However, commuting often occurs during off-peak hours, as flexible working hours have become normal today. The drawback of constant travel time measurements is that they might overestimate the level of accessibility and reduce the credibility of the accessibility analysis [9]. This overestimation may cause commuters to underestimate their travel time; thus, they may not reach their destinations on time. This optimism regarding accessibility may also lead to the infrastructure needs of regions with a lower level of accessibility being ignored [10]. Therefore, measuring time-varying transit accessibility is vital for public transit planning.

Early studies on accessibility noticed that travel time uncertainty can influence the time dimension of accessibility [11]. However, exploring the influence of travel time uncertainty requires massive amounts of data, which is a major obstacle for time-varying accessibility studies [12, 13]. More recently, the mass adoption of smartphones and the use of multisource data, such as global positioning system (GPS) and general transit feed specification (GTFS) data, as well as application programming interfaces (APIs), have yielded high temporal resolution travel data. Thus, the statistical analysis of time-varying accessibility over extended periods is possible [14].

Although measuring time-varying transit accessibility is possible, this does not mean that it is easy to implement. The question of how accessibility researchers can access the increasing amount of spatial-temporal transit data still exists [15]. Specifically, transit GPS data are generated by bus companies and are not open-source, and GTFS data cannot be collected in some countries because Google's services do not cover the whole world [16]. Almost all companies that provide API services limit the amount of data users can access each day. Therefore, there are few studies on time-varying accessibility [17], especially on a large scale. Transit lines typically cross several districts in a city and impact many residents along the lines.

Travel time reliability is used in the time-varying accessibility research to describe the impact of travel time variations on traveling and is closely connected to accessibility [18]. The classic travel time reliability concept involves the probability that a traveler will realize an origin-destination (OD) pair in a specific amount of time [19]. Travel time reliability is often characterized by probabilistic indicators in time-varying accessibility studies. The probabilistic indicators extend the travel time to the travel time budget by a normal distribution and a given confidence level [20, 21]. However, these probabilistic measures are complex and do not directly reflect the variation in accessibility. The concept of travel time reliability inspired us to develop the reliability of accessibility, which means the probability that a required level of accessibility can be reached in a specific amount of time.

Some scholars have surveyed planners and managers and found that accessibility is still largely marginalized in practice [22, 23], as accessibility tools are not user-friendly and theoretically sound measures require complex calculations and are difficult to explain to the public [24]. The complexity of accessibility measures will be more complicated when the time-varying component is added, and a complicated method to describe the time-varying component is used, which may slow the progress toward determining the time-varying accessibility in practice. Therefore, we argue that a simple and user-friendly measure to describe the time-variance is needed.

As discussed above, this study aims to summarize the time-varying transit accessibility on a large scale and incorporate travel time reliability into accessibility measures using a direct and simple approach. Hence, we collected mass route plan data from web-based APIs within Shenzhen's metropolitan areas. Then, we compared the accessibility in every period and the threshold to calculate the reliability of accessibility. Finally, we investigated the results to show the scope of the impact of urban railways in terms of punctuality and to verify the validity of this approach.

The layout of this paper is as follows: Section 2 starts with a brief background based on the extant accessibility literature, including time-varying accessibility and potential data sources. Section 3 introduces the study areas and data collection. Section 4 describes in detail the accessibility and reliability of accessibility measures. Section 5 analyzes the reliability of accessibility results based on the case of Shenzhen. Section 6 discusses the results. Section 7 concludes the paper.

2. Literature Review

2.1. Concept of Time-Varying Accessibility. There is no unified definition and measure of accessibility, as researchers in different fields focus on different components [25]. Hansen proposed the classic definition of accessibility as the "potential of opportunities for interaction" [26]. Geurs et al. [12] further proposed that it be defined as "the ease with which any land use activity can be reached from a location using a particular transportation system" based on Hansen. We also use Geurs' definition in this paper, which is the most widely accepted [27]. To our knowledge, few papers clearly define time-varying accessibility or dynamic accessibility. Previous studies of dynamic accessibility developed their measures based on travel times between the same OD at different times, land use in different periods, or both. Hence, we argue that time-varying accessibility means that accessibility may be different during an arbitrary time because of travel time uncertainty.

2.2. Time-Varying Accessibility Measures. Time-varying accessibility measures are similar to traditional accessibility measures, and the largest difference is how the time-varying element is represented. This section will first review the accessibility measures and then the ways of characterizing the changes.

In general, accessibility measures can be divided into location-based and people-based measures [28]. People-based accessibility measures originate from the space-time geography field and can satisfy almost all theoretical criteria [29] since they include more elements and are more theoretically sound [30]. However, compared to place-based measures, people-based measures require more detailed datasets and are more difficult to calculate [20], which is the most significant challenge to using accessibility metrics in practice [24]. Therefore, urban planners and governments prefer to use location-based measures [31], which are convenient and can assess the space-time separation between important locations and potential locations with many activities from an aggregate perspective.

Location-based measures are typically used measurement types and can be further divided into the following three types [32]: distance, cumulative opportunities, and potential accessibility. In most cases, distance measures calculate the distance between two points and do not include the land use component, which is more likely a mobility metric than an accessibility metric, despite being the simplest metric type [33]. A potential accessibility measure is the famous gravity model, which adds decay functions based on cumulative opportunities [28]. The gravity model has an apparent shortcoming in terms of interpretability. Cumulative opportunity measures account for the number of opportunities reached from a specific location [31]. These are the measures most commonly used by policy-makers and metropolitan planning organizations [32], as they are simple to generate, interpret, and communicate [23]. On the other hand, cumulative opportunity measures also have shortcomings in terms of treating opportunities of a specific threshold equally and not considering cost differences between different areas [34].

In summary, every accessibility measure has its advantages and disadvantages. We hold the view that a cumulative opportunity measure is more suitable in this paper because it is closest to our aim to summarize the time-varying transit accessibility in a simple and understandable way.

2.2.1. Time-Varying Elements in the Accessibility Measure. As discussed above, the methods for representing the time-varying elements are important in time-varying accessibility studies. Among the time-varying studies, there are three common methods.

In the first method, the time-varying elements are always represented by directly showing the accessibility results for different periods. Guan et al. [35] used cumulative measures and compared the transit and taxi accessibility gap in many time periods. Moya-Gómez et al. [36] analyzed the changes in the average accessibility every 15 mins according to given scenarios by potential accessibility measures. Boisjoly and El-Geneidy [5] also used cumulative measures to investigate job accessibility in different periods in one day. These methods directly display the time-varying accessibility and provide extensive information to accessibility users, which may be difficult for urban planners and governments with limited time to employ.

Regarding the second method, the statistical indicators of travel time reliability are used to further develop the travel time. A common statistical indicator is the four fundamental arithmetic operations among travel times. Bimpou and Ferguson [37] used the ratio of travel time variation, the difference between the upper and the lower limit of travel time, and the particular upper observed travel time to represent the travel time reliability. Yan et al. [17] used maximum and minimum travel times to standardize the observed travel time with the same OD pair. These statistical indicators extend the classic concept but do not directly reflect the probability, which may mean that accessibility users must spend time attempting to understand the results.

Regarding the third method, probabilistic indicators of travel time reliability are popular in time-varying accessibility studies. Chen et al. [20, 30, 38] used the given confidence of the probability of arriving on time and the travel time distribution to obtain the travel time budget. Zhang et al. [21] and Lee and Miller [39] developed the reliability-based (effective) travel time cost by using the average travel time and the standard deviation of the travel time under the given on-time arrival probability. Their methods to develop time-varying accessibility measures are complex and do not directly reflect the variation in accessibility although these probabilistic measures are theoretically sound.

As discussed in the introduction, complex and incomprehensible methods may hinder the application of accessibility measures. Important information may be masked by the massive results. In this study, we use the origin reliability concept to reflect the time-varying elements in accessibility to provide direct and easily interpretable time-varying accessibility measures to planners and governments.

2.3. Potential Data Sources of Travel Time. The travel time data source is fundamental in time-varying accessibility and impacts how the time-varying element is shaped. There are three types of potential data sources in time-varying accessibility research, that is, APIs, GPS, and GTFS [36]. Every data source has special advantages and limitations.

The obvious advantages of GPS data are its recording of the real travel time, and it has highest temporal resolution, which makes calculating the travel time distribution possible. Every GPS item is generated in less than one minute. Studies that used GPS data often use probabilistic indicators to display the time-varying element and time-spatial prism to develop accessibility measures. For example, Chen et al. [38] used GPS data generated approximately every 40 seconds on average over a day and introduced the reliable space-time region to place-based accessibility. Arbex and Cunha [40] estimated the travel time variability in a congested public transport network with smart card and GPS data collected over a year to improve accessibility calculations. Zhang et al. [21] used bus GPS data in which every item was recorded every 20 seconds to develop a time-varying transit accessibility approach to calculate realistic transit service levels. They all use the 95th percentile of travel time as a threshold or a parameter to extend the travel time budget. However, the GPS dataset is also the most difficult to access, as it is not open-source. Taking the Chinese situation as an example, GPS data, especially transit GPS data, are generated by bus companies. It is almost impossible for research institutions to obtain data from bus companies if the bus companies are not willing to cooperate with them.

GTFS is an open-source, standard format used to describe transit features such as schedules, routes, and prices [41], which can also be regarded as a transit timetable. Most time-varying accessibility studies have used GTFS data [39, 42, 43], as GTFS data are more readily available than GPS data. The studies that used GTFS data calculated travel time at any time from software such as ArcGis and OpenTripplanner. They can also obtain high temporal resolution data in this way. Thus, there is no limitation on shaping the time-varying element in these studies. However, they preferred to represent time-varying elements in accessibility by showing the results for different periods [44–47]. Fayyaz et al. [48] displayed public transportation accessibility at hourly intervals between 4 am and 9 pm. Owen and Lenvinson [47] showed time-continuous transit accessibility over the period from 7 to 9 am. The shortcomings of GTFS data are as follows: first, there is an assumption that all vehicles in the transit system arrive and depart strictly according to the timetable. In other words, the transit travel time is idealistic. Second, Google's services do not cover the whole world, and researchers in some countries are unable to obtain GTFS data.

API data are based on web services provided by navigation companies such as TomTom, Google, Gaode, and Baidu. These companies record historical location data from mobile phones and obtain transit timetables from governments and transportation companies. They use these data to further predict the travel time between any two points at a specific time with an advanced algorithm [49]. In fact, API data seem to be a combination of GTFS and GPS data. However, API datasets are used less in time-varying accessibility studies than the other two types of datasets [50] because of a lack of precision in both time and space, and almost all navigation companies limit the amount of data each user can obtain from the web service. These limited studies have little preference for displaying the time-varying element, and their study areas are usually small. Bimpou and Ferguson used probabilistic indicators of travel time reliability to investigate the time-varying accessibility between a hospital and 89 postcode sectors [37]. Guan et al. showed the dynamic accessibility gap between private and transit travel modes on a community scale [35]. Yan et al. [17] discussed the peak and off-peak period accessibility among 26 freeway entrances and exits and 17 travel hotspots.

For research purposes, more detailed and realistic data are better. However, researchers are also concerned with data availability. Unfortunately, it is difficult for us to obtain GTFS data from Google because Google does not operate in China, and GPS data from local transportation companies is also difficult to obtain. Therefore, we adopted an API dataset in this study. To overcome the limitation of the small study area when using the API dataset, we spent four months collecting the data from Gaode's Map.

3. Study Area and Data

Shenzhen is one of the most dynamic cities in China, and it has been a policy and institutional innovation pioneer in various fields. Shenzhen has an area of 1998 km^2, and its population was 17.6 million in 2020. It consists of 10 administrative districts, and these districts can be divided into three types, as shown in Figure 1. The Nanshan, Futian, Luohu, and Yantian districts are densely populated preliminary special economic areas with a large industry presence. The Baoan, Longhua, and Longgang districts are new city areas with fewer job opportunities, and they became special economic zones in 2010. The Pingshan, Dapeng, and Guangming districts are suburban areas that are not as developed as the other districts.

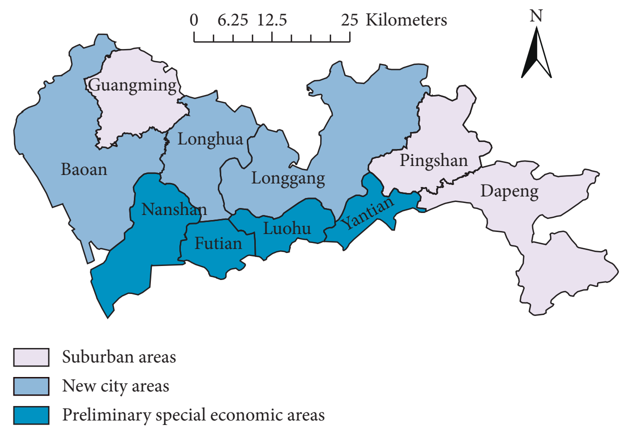

Figure 1: Administrative districts in Shenzhen.

The study area was divided into a 1200 m × 1000 m grid of 1854 blocks. We divided the area according to equal intervals of latitude and longitude, which led to the difference in length and width. We posted requests to the Gaode Map API to collect the following two datasets: a traffic dataset and a point of interest (POI) dataset. Every item in the traffic dataset includes the latitudes and longitudes of the origins and destinations, distance, financial cost, and travel time, which Gaode's service has calculated. The travel time between every two grids also contained the waiting time, walking time in all conditions, in-vehicle time, and transfer time if there were transfers. The origins and destinations were at the centers of the grids. The travel data, consisting of 37,635,840 items, were collected between 7 : 00 am and 10 : 00 pm at 60 min intervals on a weekday (2019/12/16). In this paper, we also focus on job opportunities. Chinese employer-household survey data are confidential, and almost all Chinese cases use POIs to represent opportunities in accessibility measures [35, 51]. Thus, we also used a work-related POI dataset to represent job opportunities. The POI dataset contained only industrial parks, business office buildings, well-known enterprises, companies, and factories, which are highly relevant to jobs, based on the classification of the Gaode Map API. There were 122,260 POIs, and each POI data point was aggregated into the grid based on its latitude and longitude.

In 2019, 977 bus lines and eight urban railway lines in the southwestern part of the city were operating. As shown in Figure 2, most urban railway lines are concentrated in preliminary special economic areas. A small number of urban railway lines are located in new city areas. Social resources tend to be distributed in central areas as well. The POIs in Shenzhen are clustered in the preliminary special economic areas and new city areas, especially along urban railway lines. In the new city areas, the northern part of the Baoan district and most parts of the Longhua district maintain high POI density values. In contrast, the Dapeng and Yantian districts provide fewer jobs.

In addition to travel and POI data, we also collected transit and population data. The transit data are from the

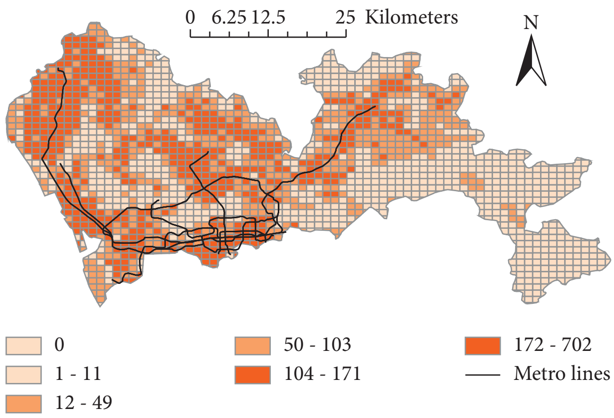

Figure 2: Job POI density in Shenzhen.

Shenzhen government. The population grid data were collected by WorldPopPopulationCounts [52].

4. Measuring the Reliability of Accessibility

Most studies have investigated accessibility based on location-based measures utilizing a constant travel time, ignoring other travel elements, such as the financial cost. Such measures may overestimate the level of accessibility. Ford et al. [53] used the value of time (VOT) to solve this problem and integrated the financial cost into the travel time. Cui and Levinson [54] further proposed the full cost accessibility framework by combining the internal and external cost components of travel time, safety, emissions, and money. As financial costs affect travelers' decisions and impede accessibility measures, we hold that accessibility studies should consider both the travel time and the financial cost.

The generalized travel cost, consisting of the travel time and travel cost, is used to describe the transportation system component of accessibility. $C_{ij}(k)$ represents the generalized travel cost from the center of grid i to the center of grid j at the k^{th} hour, and it is expressed as follows:

$$C_{ij}(k) = T_{ij}(k) + \frac{F_{ij}}{w}, \tag{1}$$

where $T_{ij}(k)$ is the travel time from the center of grid i to the center of grid j at the k^{th} hour; in the same way, F_{ij} is the financial travel cost, such as public transportation fares. The travel time and financial travel cost units are min and yuan (¥), respectively. The financial travel cost is constant since the public transportation fare in Shenzhen depends only on the distance or the number of stations between the origin and destination. w is the VOT, expressed by the average hourly wage. Travelers' VOT in Shenzhen is ¥0.53 per min, according to the Statistical Communiqué of Shenzhen on 2019 National Economic and Social Development [55].

As indicated previously, cumulative opportunity measures have many advantages. For example, they directly reflect the coupling of the transportation system and land use. However, they are sensitive to threshold changes. The threshold represents governments' goals for urban development, and it can be used to assess a city's present status. It is easy to compare results under different thresholds because obtaining different results requires little computing time. This measure can help governments adjust their expectations and serve as a reference for future planning and urban development directions. For instance, if governments want to develop a life circle within 60 min, they can use this measure and set the threshold to 60 min. In this way, the areas that do not meet the conditions can be easily found. In addition, extreme results can help governments adjust their expectations when their goals are inappropriate.

There are also some debates on cumulative opportunity measures. Stępniak et al. [56] pointed out that cumulative opportunity measures are sensitive to time resolution and may not be suitable for time-varying accessibility, but the gravity model is not sensitive. However, Boisjoly and El-Geneidy [5] point out that cumulative opportunity measures and the gravity model behave similarly in terms of time-varying accessibility. As discussed in Section 2, a simple measure is more useful for implementation.

Based on a cumulative opportunity measure and the POI dataset, the accessibility of grid i was computed as follows:

$$\begin{gathered} A_i(k) = \sum_{j}^{N} O_j f_A\left(C_{ij}(k)\right), \\ f_A\left(C_{ij}^k\right) = \begin{cases} 1 & \text{if } C_{ij}^k \le C_0 \\ 0 & \text{if } C_{ij}^k > C_0 \end{cases}, \end{gathered} \tag{2}$$

where O_j is the number of POIs in grid j; C_0 is the threshold of the generalized travel cost; $f_A(C_{ij})$ is also a binary function; $f_A(C_{ij}(k)) = 1$ indicates that the opportunities in grid j can be accessed with generalized travel cost C_0; and $f_A(C_{ij}(k)) = 0$ otherwise. The average travel time during the rush hours of different districts was investigated. Research has shown that transit riders spend 40–63 mins on their trips [57]. Thus, C_0 was set to 45 min, 60 min, and 75 min. We converted the financial cost into equivalent time through the VOT. Although C_0 and $C_{ij}(k)$ include the travel time and financial cost, by analyzing the traffic dataset, we found that the financial cost accounts for 9.34% of the generalized travel cost. Thus, the generalized travel cost can reflect 90.66% of the commute time.

R_A represents the reliability of accessibility. $R_{A,i}$ is the value of R_A in grid i and expresses the probability that passengers have access to a given number of job opportunities at any time with a particular generalized travel cost threshold. $R_{A,i}$ ranges from 0 to 1. When the value of $R_{A,i}$ is closer to 1, the accessibility of grid i is more reliable. $R_{A,i}$ is calculated as follows:

$$\begin{gathered} R_{A,i} = \frac{\sum_k f_R\left(A_i(k)\right)}{K}, \\ f_R\left(A_i(k)\right) = \begin{cases} 1 & \text{if } A_i(k) \le N_{\text{job}} \\ 0 & \text{if } A_i(k) > N_{\text{job}} \end{cases}, \end{gathered} \tag{3}$$

where $A_i(k)$ is the accessibility of grid i at the k^{th} hour. K is 15, representing the number of periods from 7 : 00 am to 10 :

00 pm with a one-hour interval. The N_{job} threshold is the number of jobs, and the reasons for setting these values are discussed in Section 5.1.

5. Results

5.1. Accessibility in Shenzhen. In this section, we investigate accessibility under the threshold $C_0 = 45$ min. The value of accessibility was averaged from 7:00 am to 10:00 pm. The generalized travel cost C_{ij} was taken as the average of all data. As shown in Figure 3, there is a hierarchy of spatial patterns of accessibility in Shenzhen. The preliminary special economic areas have the best accessibility level due to the high urban railway density and POI density. Ninety-six percent of the grids with accessibility levels above 1% are located within 1.5 km of the urban railway lines. From a city-wide perspective, the accessibility levels in 83% of the grids are less than 1%, and the accessibility levels in 0.3% of the grids are more than 5%. Other grids with accessibility levels between 1% and 5% also show significant spatial patterns.

As discussed above, the accessibility in most grids is below 1% and rarely exceeds 5% when C_0 is set to the lowest value in this paper (45 min). If the generalized travel cost threshold is raised, both the accessibility and the reliability of accessibility rise. There will be more grids with accessibility levels over 1% and 5%, and the hierarchy of the spatial patterns of accessibility may become more apparent.

According to the accessibility results, this study sets N_{job} to 1% (1226) and 5% (6130) to keep the thresholds within a reasonable range and to observe the changes in extreme values. Considering different combinations of N_{job} and C_0, there are six cases in total. These settings also allow the reliability of accessibility to vary significantly under different thresholds, highlighting the grids that are more sensitive to changes in the transportation system and land use. This plan enables us to find sensitive grids whose accessibility issues may be masked in static accessibility analyses. Policymakers can also compare results with various N_{job} and C_0 values to confirm that the thresholds are suitable in different cases.

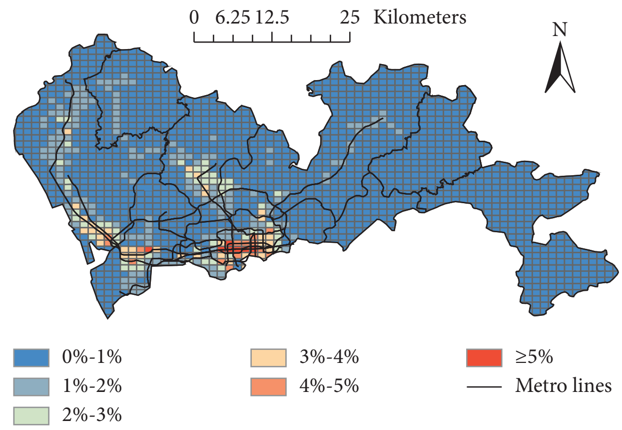

FIGURE 3: Job accessibility under the threshold $C_0 = 45$ min. The legend labels indicate the percentage of POIs that transit riders can reach from the grid with 45 min of the generalized travel cost.

5.2. Analysis of the Reliability of Accessibility. Different combinations of N_{job} and C_0 result in significant changes in R_A. The reliability of accessibility values under different combinations is shown in Figure 4. Overall, the reliability of accessibility displays a bimodal distribution (Figure 5). The areas with high reliability of accessibility values occur along urban railway lines. These areas successively expand outward along urban railway lines and areas with high POI density. Moreover, the expansion phenomenon is more evident when the value of N_{job} is lower.

When $N_{job} = 1\%$ and C_0 increases from 45 min to 60 min, the average value of R_A for the whole study area increases from 0.1551 to 0.4362 (see further details in Appendix I, Table S1), which indicates that transit users in Shenzhen can reliably access 1% of job opportunities with 2.81 times the ease under a generalized travel cost of 60 min compared to 45 min. The areas with increased reliability of accessibility expand outward along urban railway lines. As C_0 further rises to 75 min, the average value of R_A reaches 0.6174, and expansion appears in the POI-intensive areas. In 56% of the grids, R_A exceeds 0.9, suggesting that more than half of the regions have a stable coupling between the transportation system and land use. However, the reliability of accessibility is low when areas are far from urban railway lines. In most other regions where no urban railway line exists, R_A is 0. This result shows that many areas have accessibility fluctuation issues. This phenomenon also demonstrates that urban railway lines are more punctual than buses.

When $N_{job} = 5\%$ and C_0 increases from 45 min to 60 min, the average value of R_A in the whole city increases from 0.0057 to 0.3249. As C_0 increases from 60 min to 75 min, the average value of R_A in the whole city increases from 0.3249 to 0.6174. In contrast to $N_{job} = 1\%$, the expansion along urban railway lines is not apparent and does not extend to POI-intensive areas without urban railway lines. The results show that urban railway lines can attract social resources to aggregate. Nevertheless, the aggregation is limited in degree and scope.

Interestingly, regardless of N_{job}, R_A sharply decreases as C_0 increases. This phenomenon stems from the commuting behavior of people in Shenzhen. Most commute times are below 75 minutes, and the average commute time is below 60 minutes.

The results of changes in C_0 show that transit riders can obtain at least 1.4 times the reliability of accessibility by paying an extra generalized travel cost of 15 min. In other words, the ability of transit riders to stably reach job opportunities can be increased at least 1.4 times if the government improves the reliability of the public transportation system, so that transit riders can spend a generalized travel cost of 60 min to reach the areas that they could reach in 75 min before. In summary, improving the public transportation system may contribute to savings in social resources and promote urban development, and it also satisfies the need for reliable planning, as sustainability has been the goal of urban planning in China.

In contrast to the increase in C_0, when N_{job} increases, R_A decreases along urban railway lines. As N_{job} increases from 1% to 5%, the average R_A in the city drops by 47%–96%, and

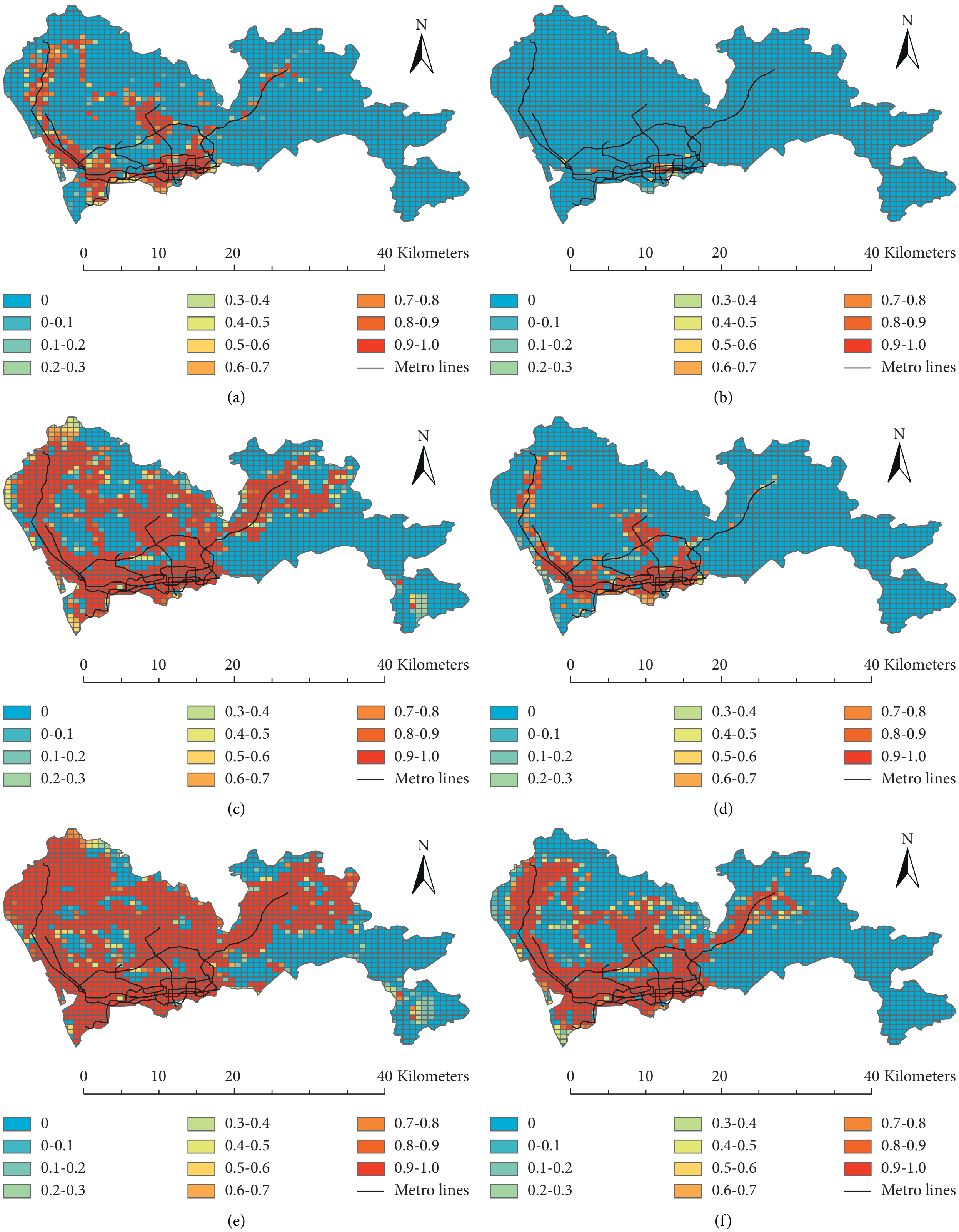

Figure 4: Reliability of accessibility.

the larger C_0 is, the more R_A decreases. If N_{job} decreases from 5% to 1%, the average R_A in the city increases by 0.9 times. The results illustrate that if four times the job opportunities could be further clustered within the areas along urban railway lines, then transit riders' ability to stably reach job opportunities could be increased by at least 1.9 times. In other words, an intensive land use policy can also be helpful in accessibility to some degree.

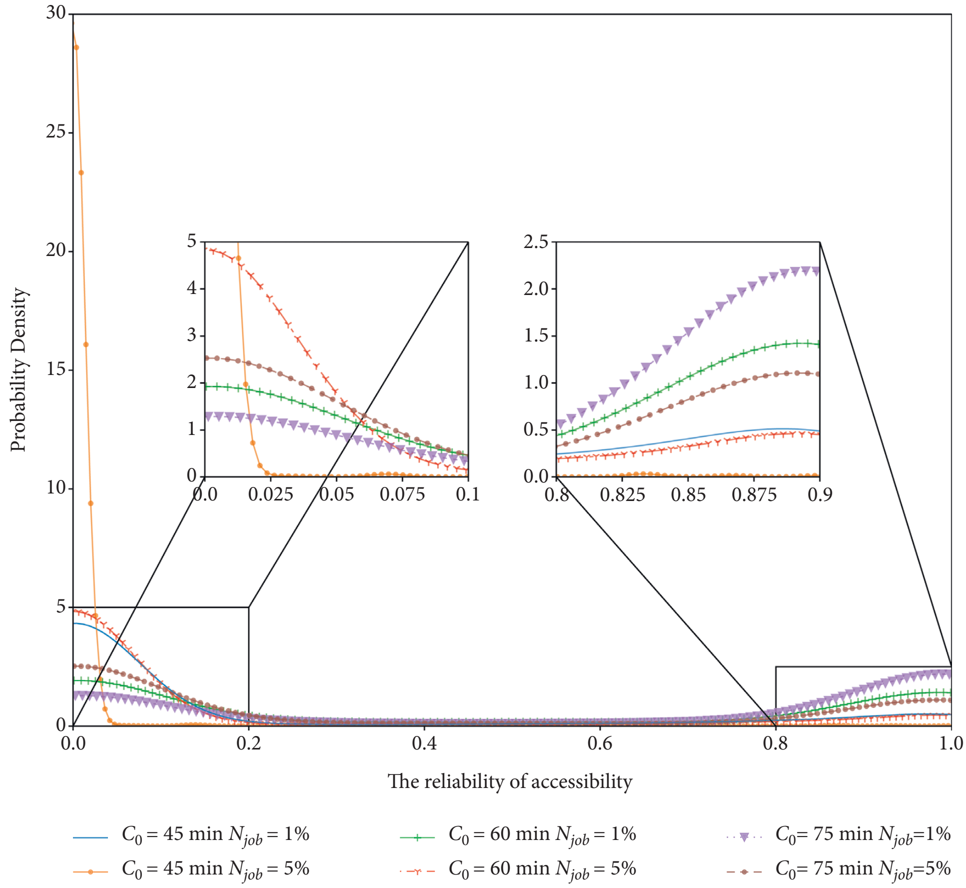

Figure 5: Probability density curves of the reliability of accessibility.

In summary, a 4% decrease in N_{job} (from 5% decrease to 1%) has a more significant impact on the reliability of accessibility than a 15 min increase in C_0. Take the comparison among the three cases ($C_0 = 60$, $N_{\text{job}} = 1\%$; $C_0 = 60$, $N_{\text{job}} = 5\%$; $C_0 = 70$, $N_{\text{job}} = 5\%$) as the example. The average R_A in the whole city is 0.1292 when $C_0 = 60$ min and $N_{\text{job}} = 5\%$. As N_{job} decreases from 5% to 1%, and C_0 remains at 60 min, the mean value of R_A increases by 0.307. However, when N_{job} remains at 5% and C_0 increases from 60 min to 75 min, the mean value of R_A increases by 0.1959. The results demonstrate that intensive land use and the provision of a reliable public transportation system are effective methods of increasing the reliability of accessibility. In this case, the former method is more effective than the latter.

From the perspective of spatial characteristics, the reliability of accessibility in Shenzhen exhibits spatial heterogeneity. Notably, R_A is close to 1 in the grids within a specific range of urban railway lines. However, beyond that range, R_A sharply falls to 0. The range expands as C_0 increases. This result shows a distinct boundary between high values (red grids) of R_A and low values (blue grids), and the boundary is not far from urban railway lines. Both the ranges and boundaries are different at different thresholds and places. We also test the impact of different thresholds on the results. All the results show obvious boundaries, and the spatial patterns of reliability of accessibility are similar to each other. We did not display other results with different thresholds because of space limitations.

We also analyzed the probability density distribution to determine the degree of separation of R_A. Figure 5 shows that the reliability of accessibility displays a bimodal distribution. The higher the value of C_0 is, the more apparent the bimodal distribution is. When $C_0 = 45$ min and $N_{\text{job}} = 5\%$, the highest probability density is 29.329, which means that R_A in most grids is close to 0. When $C_0 = 75$ min and $N_{\text{job}} = 1\%$, most values of R_A are close to 1. The above results demonstrate that a consistently high degree of integration jointly developed by land use and the transportation system is possible in limited areas with significant accessibility fluctuations in many areas. Areas with acceptable accessibility and located not very far away from urban railways may have serious resource allocation issues.

5.3. The Scope of Impact of Urban Railways in Terms of Punctuality. As discussed above, there is a distinct boundary between the high value of R_A and the low value. The distance between the distinct boundary and urban railway lines represents the scope of the impact of urban rail transport in terms of punctuality. To explore the features of the boundary, such as the distance of and social resources within the boundary, we used the slope tool in ArcgisPro 2.8 to analyze the spatial distribution of the reliability of accessibility (Figure 1). The theory of the slope tool is the calculating rate of change of the surface in the horizontal (dz/dx) and vertical (dz/dy) directions from the center cell to each adjacent cell. For method details regarding the slope tool, refer to the ArcGIS Tool Reference [58].

In Figure 6, the red and yellow lines reveal red lines. We also used the Laplace Operator, which is widely used for silhouette recognition in an image, to find the precise distance (Figure S1). As shown in Figure 4, the colors of the grids with high reliability of accessibility are quite different from those of the ones with low reliability of accessibility. The distance from the urban railway to the boundary can be found by extracting the outline of the area filled with red and orange grids. Therefore, the Laplace operator is a suitable indicator to find the distance.

Table 1 shows that the distance ranges from 274 to 4970 meters. However, 75 min is longer than the commute times of most residents in Shenzhen. Setting C_0 as 75 min and N_{job} as 5% may lead to excessive R_A values. In this case, the boundary approaches the boundaries of the city of Shenzhen. For most people, such a long commuting distance is unacceptable. Therefore, we do not analyze the situation where $C_0 = 75$ min in this section, and we hold the view that a reasonable distance range is 3452 meters, and the distance increases as C_0 increases and N_{job} decreases.

This result indicates that, for those who use transit to commute, the urban railway system is very punctual for distances of 274 m to 3452 m in most cases. Different distances correspond to various planning goals, and the results help policymakers identify the areas where intensive land use should be promoted. For instance, if governments in Shenzhen would like to keep most commute times stable at 45 minutes, workplaces must be as close as possible to the 1242 m perimeter of an urban railway line.

The high aggregation of social resources around areas influenced by urban railways directly leads to the formation of a distinct boundary. As shown in Table 2, the percentage of social resources in the region is 2.78–3.44 times the percentage of the region area. Whereas the region accounts for a minimum percentage of area, the density of social resources is highest when $C_0 = 45$ min and $N_{\text{job}} = 1\%$. The high aggregation of social resources around rail transit lines enables commuters who use urban railways to reach many destinations easily. Other areas have insufficient social resources and are not directly influenced by the urban railway. Consequently, the reliability of accessibility shows a pronounced demarcation phenomenon on both sides of the boundary. The results demonstrated that the transit system with an urban railway has a strong effect on the coupling of the transportation system and land use in the region close to the urban railway. Meanwhile, the effect sharply weakens outside of the region.

In addition to the aggregation of social resources, public transit conditions also lead to accessibility fluctuations. We analyze the reliability of generalized travel costs in Appendix II.

6. Discussion

6.1. Main Contribution. As the main contribution of this paper, the concept of the reliability of accessibility is introduced to summarize time-varying accessibility in an understandable and direct way, and a link between the research on location-based measures and reliability is established. The reliability of accessibility reflects the characteristics of time-varying accessibility and reveals the probability that accessibility reaches the expected levels. We hold the view that the largest difference between the reliability of accessibility and other classic measures is that the reliability of accessibility works directly on time-varying accessibility itself but not the changing travel time.

Our initial goal was to propose the "the reliability of accessibility" concept to illustrate the time-varying accessibility by using the idea of probability. As our research progressed, we obtained interesting findings regarding the reliability of accessibility, including the bimodal spatial distribution and the distinct boundary between the high values and low values of R_A.

Concretely, the spatial distribution of the reliability of accessibility is different from that of accessibility. The changes in accessibility near distinct boundaries are minor, but the changes in the reliability of accessibility are significant. The grids beyond the boundary may have good levels but not the best accessibility levels because of the significant fluctuations, which shows that accessibility issues are masked in static accessibility analyses and may also be severe in urban areas with reasonable levels of accessibility. These results show that the impacts of travel time uncertainty on accessibility may be significant in both urban and suburban areas.

The distance between boundaries and urban railway lines illustrates the influence of the urban railway in terms of punctuality. Previous studies of urban railway impact areas show that transit catchment areas range from 300 to 1500 meters. In our case, the average commute time is close to 45 minutes. The distance between boundaries and urban railway lines ranges from 247 m to 1274 m when C_0 is 45 min. These ranges are consistent with each other.

6.2. Potential Applications. The reliability of accessibility reflects the probability that transit riders reach a certain number of opportunities by using a particular transportation system. As a probabilistic indicator, the variable summarizes complex accessibility patterns for different periods and represents the overall conditions concisely and visually, which can help city managers quickly identify accessibility issues and confirm whether the accessibility reaches the required level.

The reliability of accessibility can clarify the scope of the impact of urban railways in terms of punctuality, which can help governments pursue high-intensity development along rail lines and identify both accessible and less accessible areas. These areas may present integration problems that could be jointly addressed through land use and transportation. Urban

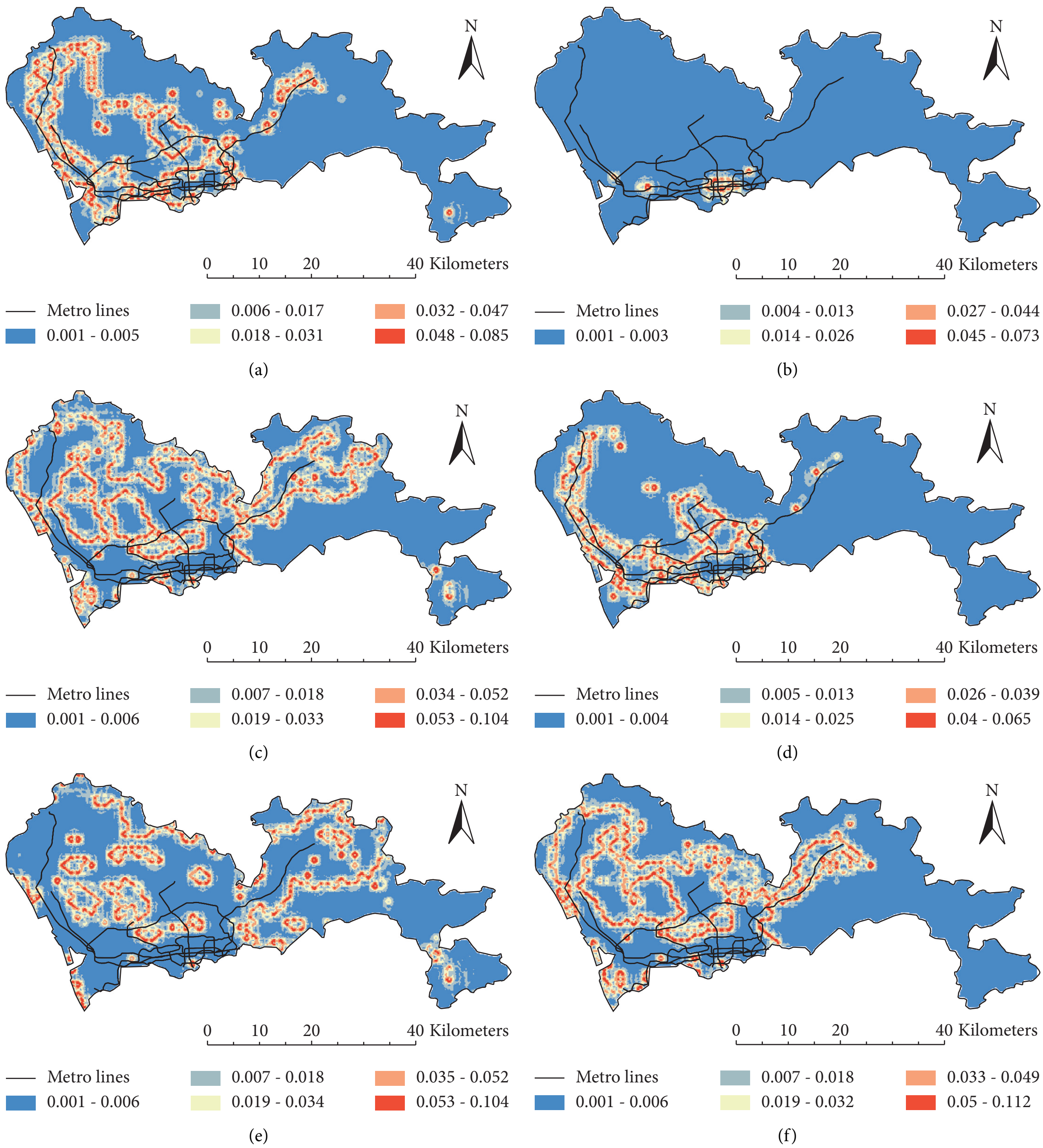

FIGURE 6: Slope of the reliability of accessibility.

TABLE 1: Median distance between the boundary and urban railway lines.

	$C_0 = 45$ min		$C_0 = 60$ min	
	$N_{job} = 1\%$	$N_{job} = 5\%$	$N_{job} = 1\%$	$N_{job} = 5\%$
Median distance (meters)	1283	274	3452	925

planning departments and governments may ignore these areas when applying accessibility measures.

Moreover, governments can use different reliability of accessibility thresholds to illustrate the specific effects of different development strategies. Specifically, expanding stable commuting areas by 15 min degrees (for instance, transit riders can pay a generalized travel cost of 60 min to reach areas that they could reach in 75 min before the public transportation system is improved) and aggregating four times the number of job opportunities could increase transit

Table 2: Social resources within the region between the boundary and urban railways.

		$C_0 = 45$ min		$C_0 = 60$ min	
		$N_{job} = 1\%$	$N_{job} = 5\%$	$N_{job} = 1\%$	$N_{job} = 5\%$
Bus lines	Number (km)	26,913	2,439	47,508	24,743
	Percentage (%)	44.66	4.05	78.84	41.06
Bus stops	Number	35,638	2,756	59,547	31,639
	Percentage (%)	51.70	4.00	86.38	45.90
Population	Number	7,065,248	366,945	12,163,253	6,423,502
	Percentage (%)	47.67	2.48	82.06	43.34
POI	Number	56,151	3,727	103,446	46,614
	Percentage (%)	45.93	3.05	84.61	38.13
Region	Area (ha)	32,381	1,397	87,180	28,102
	Percentage (%)	16.69	0.72	44.93	14.48

Percentages denote the proportion of social resources within the region of the total resources in Shenzhen.

users' reliability of accessibility levels by at least 1.4 and 1.9 times, respectively. Aggregating job opportunities involves transit-oriented development (TOD). One principle of TOD is density, which means high-density development within walking distance of a transit station.

Therefore, we argue that introducing the concept of the reliability of accessibility in accessibility research can be helpful for reliable urban planning and can improve the efficiency of social resource allocation.

6.3. Limitations. Although the current study is among the first to test the time-varying characteristic, it has several limitations. First, this study collected only public transportation data covering one day with a one-hour temporal resolution because of API rules. APIs charge based on the number of requests sent even though they are open source. Every 10 thousand data points cost 30 yuan, according to the Gaode quotation. The one-hour intervals of the travel time data cause the reliability of accessibility to seem like a fraction but not a probability indicator. However, this limitation does not mask the principle of the reliability of accessibility that reflects the probability of accessibility reaching the desired level.

Second, the current method does not consider the population element in the accessibility measurement and uses the same weight in every grid, which might improve the level of accessibility from developed to undeveloped places. The reality is that there are some areas in which no people live and that have no job opportunities, such as some mountainous regions in the northern part of Shenzhen. Thus, different grids need different thresholds.

Finally, this study used the constant accessibility threshold, resulting in reliability being an absolute value rather than a relative value. This limitation also leads to an extreme value for the reliability of accessibility. However, the accessibility of the center city is significantly better than that of the urban fringe. Fluctuations do not cause an order of magnitude change in accessibility, even though there are fluctuations in accessibility. Therefore, using a constant threshold may not accurately reflect the fluctuations in accessibility in some regions.

These issues are important for areas of future research. As the specific situation found in one major city may not fully address the above two issues, the reliability of accessibility is worthy of further exploration.

7. Conclusion

This paper presents the concept of the reliability of accessibility to summarize fluctuations in time-varying accessibility directly caused by travel time uncertainty in an easy-to-understand manner. The reliability of accessibility means the probability of whether the accessibility can reach a required level in a specific amount of time. Furthermore, this paper analyzes the spatial characteristics of the reliability of accessibility using open-source datasets for Shenzhen and presents interesting findings regarding the reliability of accessibility that can help governments better understand time variations.

First, the reliability of accessibility shows a bimodal distribution in areas along urban railway lines. In other words, there is a distinct boundary between areas with high and low reliability of accessibility values, indicating that the fluctuations in accessibility may be severe in areas with a reasonable level of accessibility. Governments should focus on these areas. Second, we observed the effects of government policies on improving public transport and intensive land use by comparing different thresholds. Finally, this paper shows that the scope of impact of urban railways in terms of punctuality may range from 274 meters to 3542 meters based on the reliability of accessibility values.

As a direct and user-friendly tool for understanding time-varying transit accessibility, the reliability of accessibility provides a new approach to present the time-varying element in accessibility. This indicator can also help urban planners and managers quickly determine whether time-varying transit accessibility is meeting their expectations and make corresponding urban planning decisions. Moreover, governments can evaluate the performance of transit systems in terms of punctuality with the reliability of accessibility. The results can also show that the level of accessibility is unstable in many areas away from urban railways, and governments should also focus on areas with acceptable levels of accessibility.

In future studies, we will investigate the robustness of the thresholds and consider the different population weights to calculate accessibility. Moreover, we will focus on the time-varying accessibility during peak hours with high temporal resolution and long-term data to make the indicator more realistic. Other accessibility measures, such as the two-step floating catchment area, will improve this concept. We also plan to explore the correlation between accessibility and the intensity of the land use mixture in the future.

Data Availability

The POI dataset and travel dataset used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

This study was supported by the projects of the National Natural Science Foundation of China (nos. 71621001 and 71971021).

Supplementary Materials

Appendix I. Table S1: Analysis of the spatial results of the reliability of accessibility. Figure S1: Results of the Laplace operator analysis. Appendix II. Table S2: Analysis of the spatial results of the reliability of the generalized travel cost. Figure S2: Reliability of the generalized travel cost. Figure S3: Cumulative distribution of the reliability of the generalized travel cost. (*Supplementary Materials*)

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