

ORIGINAL RESEARCH OPEN ACCESS

# Revisiting Accessibility to Amenities: Equity Implications From Comparing Cumulative Opportunity Measure and Two-Step Floating Catchment Area Method

 Yue Chen<sup>1,2</sup>  | Shunping Jia<sup>1</sup>  | Steve O'Hern<sup>2</sup>  | Qi Xu<sup>1</sup> 
<sup>1</sup>School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China | <sup>2</sup>Institute For Transport Studies, University of Leeds, Leeds, UK

**Correspondence:** Yue Chen ([jjxm1881@leeds.ac.uk](mailto:jjxm1881@leeds.ac.uk))

**Received:** 13 June 2025 | **Revised:** 22 December 2025 | **Accepted:** 18 January 2026

## ABSTRACT

Evaluating the accessibility of amenities is fundamental to achieving equitable urban planning of cities. The cumulative opportunity measure (CO) and the two-step floating catchment area method (2SFCA) are widely used in previous studies. Although there is ongoing debate and discussion about the choice of method for measuring accessibility, the comparison between these two methods has not been thoroughly examined and differences in the spatial distribution of accessibility and the resulting equity from them have tended to be ignored. Here, we contrasted the similarities and differences in spatial accessibility in 12 different scenarios by using CO and 2SFCA, respectively. The scenarios considered the two models in two transportation modes, public transport (PT) and private car (PC), and six key urban services, company, education, healthcare, shopping, restaurant, and scenery, are thoroughly explored. Equity, between different housing price areas, was also evaluated by using the Gini coefficient and Palma ratio. The findings show that the spatial distributions of accessibility from CO are more related to the whole city structure, while the results from 2SFCA can better reflect the local characteristics and spatial heterogeneity. Regarding equity, PT accessibility is less equitable than PC under CO, but more equitable under 2SFCA. We also found that the accessibility and equity of PT are more susceptible to the chosen method compared to PC. This study can help planners understand accessibility and equity from different views and make adjustments of resources allocation in future planning.

## 1 | Introduction

Accessibility was first defined by Hansen [1] as the potential of opportunities for interaction. With the long-lasting development in concept and measurement [2, 3], accessibility has been widely applied in transportation and urban planning, which has led to a shift from mobility planning to accessibility planning [4–8]. Good accessibility facilitates access to urban services, while poor accessibility can lead to a lack of socioeconomic activities, affecting people's quality of life and even resulting in social segregation [9]. The variation in the spatial distribution of accessibility and the resulting issues of transport equity is a considerable obstacle to achieving high-quality urban development.

Transport equity is concerned with how the benefits and burdens of the transport system are distributed across individuals and places, and how such distributions relate to broader ideas of justice and fairness [10, 11]. Rather than focusing solely on whether average accessibility levels are high or low, equity analysis asks who experiences good or poor accessibility and whether observed disparities are socially acceptable. This is often framed in terms of horizontal equity, which refers to equal treatment for individuals or areas with similar needs, and vertical equity, which emphasizes prioritizing those with greater needs or fewer resources [12]. Within an accessibility-based planning paradigm, equity is often operationalized by examining the distribution of accessibility indicators across socio-economic

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *IET Intelligent Transport Systems* published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology.

groups or neighborhood types [13]. Therefore, it is essential to properly measure the distribution of accessibility, providing the basis for the allocation and adjustment of transport and urban facilities.

As reviewed by Geurs and van Wee [2], the theories and methods of accessibility vary. Among them, the cumulative opportunity model (CO), gravity-based model, and two-step floating catchment area method (2SFCA) are the most frequently used approaches to measuring accessibility. CO calculates accessibility by summing up the number of opportunities that can be reached within a travel cost threshold [14, 15]. CO is easy to operate and understand but simply consider the spatial interaction originating from Tobler's first law of geography [16] through the binary distance decay function. The gravity-based model differentiates the weights of opportunities in potential destinations by introducing the continuous distance decay function based on the travel cost. While the gravity-based model suffers from the operability problem as the decay function and parameter are difficult to select, the gravity-based model is more logical because of the careful consideration of the spatial interaction between places. Furthermore, as the other special form of the gravity-based model [17], 2SFCA represents a new wave of place-based accessibility theory as it not only considers the distance decay but also the competition between supply and demand.

The approaches above are widely applied in different accessibility studies. However, the accessibility results may change with the choice of methods [18, 19]. Therefore, this conflict calls for the discussion on the applicability and limitations of each method. The purpose of comparing accessibility measures is not to identify a universally superior method. Rather, different measures embody distinct conceptual assumptions regarding supply-demand interaction and spatial competition, which may lead to different interpretations of spatial accessibility and transport equity. From the planning perspective, it is critical to understand these differences as policy conclusions may vary substantially depending on the metric adopted.

In the broader literature, there has been substantial research comparing accessibility using various methods. For example, the most classic accessibility metrics, CO and gravity-based measures have been intensively compared [20–23]. Their results revealed that the choice of method has effects on accessibility. Moreover, studies exploring different 2SFCA methods [24] and different gravity-based measures [25] found that the catchment size and distance decay function are also important in accessibility evaluation.

However, a remaining hurdle is that most studies tend to focus on the comparison of correlations of accessibility by using different distance decay functions and related parameters [22]. While correlation analyses are useful for assessing overall consistency, they provide limited insight into how different measures shape spatial distribution patterns and equity outcomes. Thus, comparisons of the spatial distribution of accessibility and the resulting equity from different measures still need to be explored. Furthermore, the 2SFCA has not been compared with CO in various scenarios of the accessibility evaluation. The application scenarios in existing comparison studies are limited to job accessibility by public transit (PT) [26, 20, 22]. As a result, it remains unclear whether conclusions regarding spatial accessibility patterns,

modal accessibility gaps, and transport equity are robust to the choice between CO and 2SFCA, particularly in contexts involving different types of travel modes and urban services. This gap limits the interpretability and policy relevance of accessibility-based equity assessments.

To fill the gaps, this paper compared the performance of CO and 2SFCA in 12 different scenarios in Beijing. The spatial patterns of accessibility in these two models are explored and contrasted. Furthermore, equity is investigated using the Gini coefficient and the Palma ratio. As the two most important modes in urban transport [27, 28], the effects of method choice on PT and PC are contrasted, and the modal accessibility gap index is introduced to understand the differences between the two modes. Meanwhile, we compared six widely studied key urban services in existing accessibility research, including job [29, 30], education [31], healthcare [32–35], shopping [36], recreation [37], and scenery [38, 39].

The study answers two key research questions:

1. How does the spatial distribution of accessibility and the resulting equity differ between the CO and 2SFCA?
2. Which transportation modes and urban services are more susceptible to the choice of accessibility method?

The remainder of this paper is organized as follows. Section 2 reviews the accessibility measures and their comparison. Section 3 introduces the methodology and study area and data, respectively. Section 4 presents the main results. Section 5 provides the discussion and the final section makes the conclusion.

## 2 | Literature Review

### 2.1 | Accessibility Measures

Geurs and van Wee [2] identified four main types of accessibility measures, infrastructure-based, location-based, person-based, and utility-based. Infrastructure-based measures focus on the performance or service level of transportation infrastructure, which is more related to the mobility measurement. Person-based and utility-based measures provide more refined individual components, however, they are more difficult to operationalize and communicate as they require more data and parameter specification. Overall, location-based measures have become mainstream in accessibility applications [37, 40–45].

Among the location-based measures, CO [14] and gravity-based methods [46, 1, 47, 48] are the most classic and widely used measures. The biggest modeling difference between CO and gravity-based methods is the distance decay function. CO can be viewed as a special case of the gravity-based model [3]. The binary distance decay function gives CO the advantage of simplicity and interpretability, but the variability of the opportunities is not differentiated, and the selection of the threshold can notably affect the results [20]. Previous research shows that transportation agencies and policymakers favour the CO in practical applications such as when developing metropolitan or regional transportation plans [49, 50, 8]. Moreover, at the same time, more complicated

methods are proposed based on classic gravity-based models [51], such as the improved gravity model [52], 2SFCA [17], and enhanced 2SFCA [53].

The consideration of demand in accessibility modeling is more and more important [54, 55]. As the new wave in the place-based accessibility theory, 2SFCA is popular as it both considers the spatial interaction and the competition between supply and demand. Specifically, the 2SFCA first calculates the supply-to-demand ratio by dividing the capacity of the supply point by the surrounding population into the demand points within the travel distance threshold, then aggregates all the calculated supply-to-demand ratios of supply points for each demand point.

Many scholars have extended the original 2SFCA since Luo and Wang [17] applied the 2SFCA method to evaluate healthcare accessibility. The improvements can be categorized into three parts, the catchment area, the distance decay function, and the competition between supply and demand [56]. Although these three aspects are essential for more accurate accessibility modeling, the distance decay function has been paid the most attention. For instance, Luo and Qi [53] proposed the Enhanced 2SFCA (E2SFCA), which assigns fixed coefficients to several sub-areas based on distance. Moreover, continuous functions such as the inverse power function [57], exponential function [58], Gaussian function [59], and kernel density function [60] have been introduced to depict the effects of travel distance or cost between the supply point and demand point. Because of the consideration of the competition of supply and demand, 2SFCA has further applied to many other scenarios such as employment location [30], schools [61], public libraries [62] and green spaces [63, 64, 39].

## 2.2 | Method Comparison in Accessibility Evaluation

Kwan [19] compared the relationships of 30 accessibility measures including CO, gravity-based measures, and the space-time model, and found that the observed accessibility in a particular analytical context depends on the accessibility measure used. Since then, a growing body of research has focused on the comparative study of accessibility. Amongst these, two important areas were identified, first, studies focusing on accessibility variation resulting from different distance decay functions within the particular model. Second, research concentrated on the comparison between different accessibility models.

Regarding the comparison of different distance decay functions, for example, Vale and Pereira [25] measured and compared pedestrian accessibility of 20 gravity-based measures with varying distance decay functions and parameters. They found that spatial results are similar for locations with high and low accessibility, while quite different for locations with medium accessibility. Likewise, Chen and Jia [24] analyzed the statistical correlations of 24 2SFCA models with various distance decay functions in the evaluation of food store accessibility, the results indicated that the catchment size is essential for small study scales and the distance decay function is critical for large study scales.

Among the other important research areas, CO and gravity-based measures receive considerable focus. Klar et al. [21] used 12 accessibility measures including CO, gravity-based measure, and the hybrid measure to evaluate the accessibility to all potential destinations by PT before and after transit interventions. The results show that the accessibility change from CO is notably different from other measures, and CO cannot fully reflect the geographic extent of affected areas. Similarly, Kapatsila et al. [20] compared the job accessibility of PT and PC in eight metropolitan regions across Canada by using CO and gravity-based measures. The correlation coefficient between different measures reaches approximately 0.90 when the commute time threshold approximates the regional mean travel time, which supports the reliability of the CO measure. Moreover, McCahill et al. [22] tested 15 accessibility metrics that include different modes (walking, transit, and driving), destination types (job and non-work), analytical geographies (block and block group), and metric definitions (CO and gravity-based measure) across the U.S. They hold that these factors are all important in choosing the appropriate accessibility measure in practice. However, the differences in spatial distribution patterns of various metrics are still unknown.

Regarding transport equity, although equity evaluations are often conducted using methods such as the Lorenz curve and Gini coefficient in many accessibility studies [65], few studies consider equity when comparing various accessibility methods. Giannotti et al. [26] compared the transit inequity based on job accessibility in London and Sao Paulo by using the CO, gravity-based measure, and 2SFCA. The results from the Lorenz curve and Gini coefficient suggest larger inequalities in Sao Paulo than in London. However, to our knowledge, no studies have focused on the equity comparison of various transportation modes and services.

## 2.3 | Research Gaps

In conclusion, although substantial research efforts have been made on method comparison of accessibility, there are still some challenges and knowledge gaps that require further research. Most existing research mainly focuses on the overall relevance of accessibility from various measures, overlooking the comparison of the spatial distribution pattern of accessibility and the resulting equity by using different measures. Furthermore, there has yet to be a study that simultaneously concentrates on the comparison between CO and 2SFCA in various scenarios including different transportation modes and key urban services. Thus, the heterogeneity effects of the method choice on different modes and services remain unknown. In general, previous research has not explored the similarities and differences between CO and 2SFCA in various scenarios, which raises questions regarding their appropriate application. Consequently, in this study, we compare the spatial distribution of accessibility, and equity by using these two models in 12 typical scenarios including different transportation modes and urban services.

## 3 | Material and Method

The research framework is illustrated in Figure 1. First, three data sets were collected that were required for accessibility and

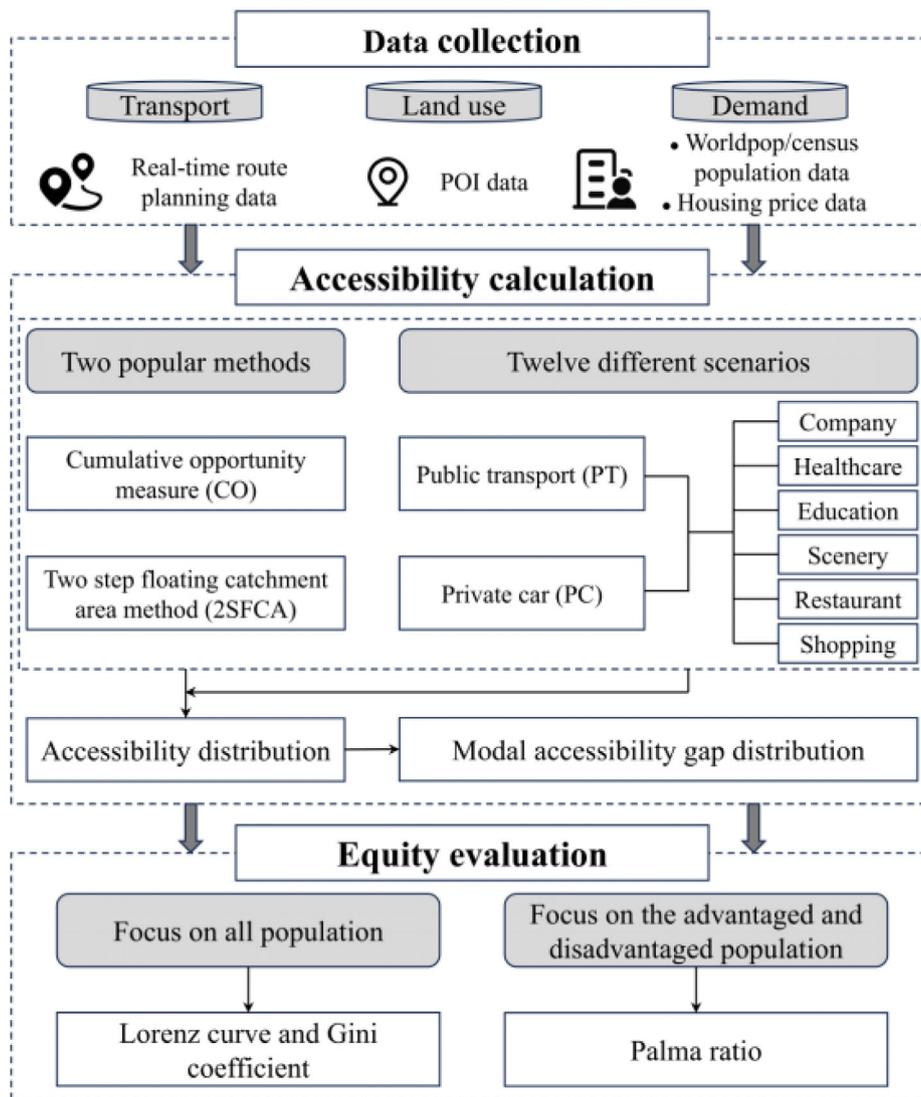


FIGURE 1 | Research framework.

equity modeling, including transport, land use, and demand data. Second, we compared the accessibility distribution from the CO and 2SFCA in 12 different scenarios, which included two transportation modes (PT and PC) and six key urban services. Then, the modal accessibility gap distribution was investigated. Finally, equity, focusing on the entire population and the subset of disadvantaged populations, was evaluated by the Gini coefficient and Palma ratio.

### 3.1 | Study Context

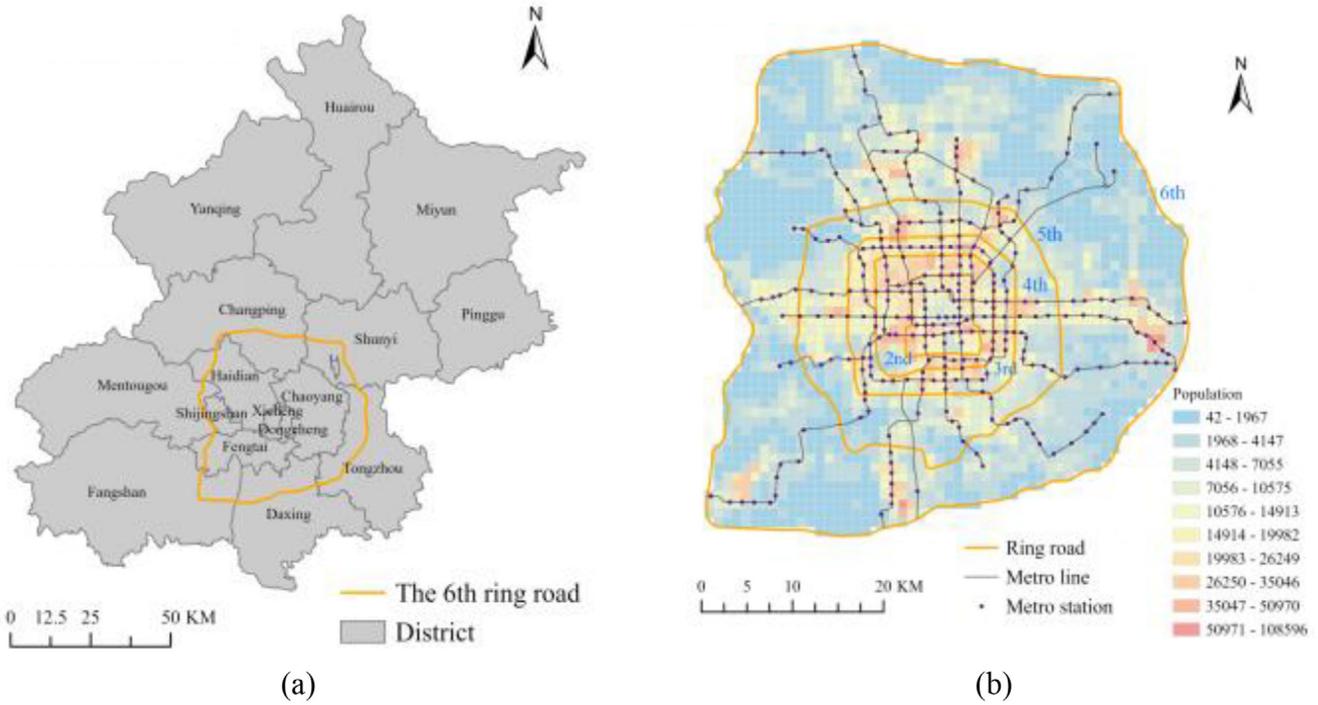
The areas within the sixth Ring Road of Beijing were selected as the study area (Figure 2). It covers about 2267 km<sup>2</sup>, including 12 districts in both central and suburban areas. Among these districts, Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan districts are considered as six central districts in Beijing while Changping, Shunyi, Tongzhou, Daxing, Fangshan, and Mentougou are viewed as suburban areas. As of 2020, there are 24 urban rail transit lines and 311 metro stations in the study area, with a total operational mileage of 727 km.

The residential population in the study area accounts for 78% of Beijing's total population [66]. Furthermore, 79% of employment in Beijing is located within the study area, with nearly half of these jobs concentrated within the fifth ring road, in clusters such as the CBD, Zhongguancun, Jinrongjie, Wangjing, and Fengtaikejiyuan. Given the high population and employment opportunities, the study area provides an excellent case study for researching accessibility and equity.

To balance the fineness of spatial scale and computational power, we chose a 1 km×1 km grid as the study unit. After excluding several peripheral grids, we ultimately defined 2,219 study units within the study area.

### 3.2 | Data Collection

We used the travel route planning API (Application Programming Interface) of Gaode Map (<https://lbs.amap.com/>) to obtain real-time route planning data during 2 weeks in May 2020. It includes the travel data of 9,847,922 OD pairs between the centroids



**FIGURE 2** | Study area: (a) the whole Beijing city, and (b) the population distribution in the areas within the sixth ring road.

**TABLE 1** | The statistics and Global Moran's *I* of different POI.

POI	Total number	Mean	Std	Global Moran's <i>I</i>
Company	95,055	42.84	80.07	0.59
Education	8,970	4.04	11.33	0.45
Healthcare	20,105	9.06	15.55	0.55
Scenery	4,547	2.05	8.16	0.45
Restaurant	78,271	35.27	65.29	0.54
Shopping	53,498	24.11	51.84	0.32

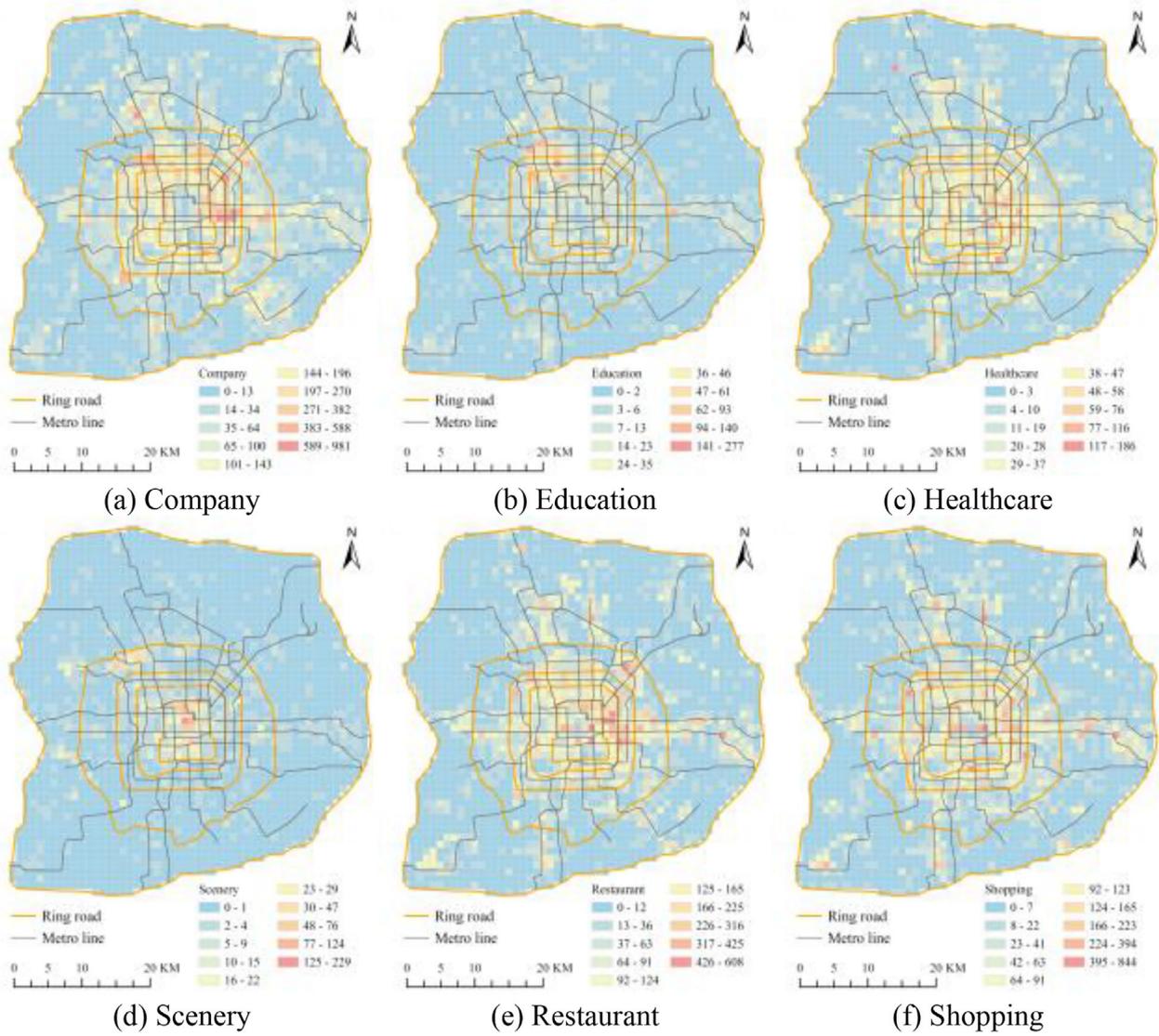
of any two grids using both PT and PC during morning peak hours. Data contains coordinates, travel distance, travel time by PC, and travel time by PT including the time of walking to the station/destination and the waiting/in-transit/transfer for PT. Moreover, the estimated travel time considers the real-time traffic congestion, which improves accuracy and helps to better conduct the comparisons between PT and PC.

We applied the POI (Point of Interest) search API of Gaode Map to obtain 260,446 POIs of six kinds of urban services within the study area, including company, education, healthcare, shopping, restaurant, and scenery. Each POI data mainly includes name, address, coordinates, and category. The spatial distribution and statistics and Global Moran's *I* of each type of POI are depicted in Figure 3 and Table 1. Company-type POIs comprise various enterprises in agriculture, industry, and services, predominantly located around CBD and the northern areas between the third and the fifth ring road. The company POI also has the highest Global Moran's *I*, indicating strong spatial autocorrelation. Education-type POIs include different levels of school, such as university,

middle school, elementary school, kindergarten, and adult education, mostly distributed in the Haidian district. Healthcare-type POIs contain various medical services such as hospital, clinic, and emergency center. Scenery-type POIs include different kinds of park, square, and tourist spot, mainly distributed in the areas within the second ring road. Shopping-type POIs consist of different shopping center, market, and store. And restaurant-type POIs feature various places providing food and beverage.

Gaode Map is one of the most widely used online map services in China. The route planning data and POI data from Gaode map have been widely applied in accessibility research [35, 67]. And it is important to note that although the data were collected during the pandemic, they are still valid for our study for several reasons. Firstly, there were no new COVID-19 cases in Beijing in May 2020, and the government downgraded the emergency response level for public health emergencies at the end of April, considering the reduced impact of the pandemic. Secondly, according to the report from Baidu Map, the road congestion index during peak hours in Beijing in May 2020 increased by 15.4% compared to the same period in 2019 [68]. It indicates that the road traffic did not decrease due to the pandemic.

Regarding the demand data, we first acquired a large-scale dataset of residential communities in Beijing from Lianjia (<https://bj.lianjia.com/>), a prominent real estate brokerage company in China. After pre-processing to eliminate errors and missing values, we compiled housing data for 7,575 residential communities, including details such as name, address, coordinates, housing price, and the number of households. Moreover, to determine the population distribution within each grid, we utilized 100m-level population data from Worldpop (<https://hub.worldpop.org/project/categories?id=3>), adjusting it using data from the seventh Population Census of China in 2020 at the Jiedao level.



**FIGURE 3** | The spatial distribution of different POI.

Finally, the population of each grid was aggregated, resulting in a total population of 15,577,525 within the study area, with an average of 7,020 per grid. As shown in Figure 2(b), the population in the study area is primarily concentrated within the fourth ring road and in areas between the fifth and sixth ring road along the metro lines.

### 3.3 | Accessibility Calculation

#### 3.3.1 | Cumulative Opportunity Measure (CO)

CO calculates the accessibility of different urban services by PT and PC using the formulas below:

$$A_i^{m,n} = \sum_j O_j^n f(t_{ij}^m) \quad (1)$$

$$f(t_{ij}^m) = \begin{cases} 1, & \text{if } t_{ij}^m \leq t_0 \\ 0, & \text{if } t_{ij}^m > t_0 \end{cases} \quad (2)$$

where  $A_i^{m,n}$  is the accessibility to the  $n^{\text{th}}$  urban service of grid  $i$  by the  $m^{\text{th}}$  mode;  $O_j^n$  is the number of the  $n^{\text{th}}$  urban service in grid  $j$  and the size and quality of different POIs is not taken into account due to the lack of information;  $f(\cdot)$  is the 0–1 function;  $t_{ij}^m$  indicates the traveling time from the centroid of grid  $i$  to the centroid of grid  $j$  by the  $m^{\text{th}}$  mode;  $t_0$  is the travel time threshold, which is set as 60 min considering that the average commuting time in Beijing is 47 min [69] and the goal of one-hour travel circle in the metropolitan proposed by the ministry of transport of China [70].

#### 3.3.2 | Two Step Floating Catchment Area Method (2SFCA)

The 2SFCA that measures the accessibility of different urban services by PT and PC at each grid can be estimated as follows:

Step 1: For each supply point  $j$ , the supply-to-demand ratio  $R_j^{m,n}$  is calculated by:

$$R_j^{m,n} = \frac{O_j^n}{\sum_i P_i \cdot g(t_{ij}^m)} \quad (3)$$

where  $P_i$  is the population of the demand location  $i$ ;  $g()$  is the distance decay function. In this paper, the standardized Gaussian function is chosen as the distance decay function due to its relatively slow decay rate near the origin (Dai, 2010; [71–73]). It can be illustrated as:

$$g(t_{ij}^m) = \begin{cases} \frac{e^{-\frac{1}{2}\left(\frac{t_{ij}^m}{t_0}\right)^2} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & \text{if } t_{ij}^m \leq t_0 \\ 0, & \text{if } t_{ij}^m > t_0 \end{cases} \quad (4)$$

Step 2: For each demand location  $i$ ,  $A_i^{m,n}$ , namely the accessibility to the  $n^{\text{th}}$  urban service of grid  $i$  by the  $m^{\text{th}}$  mode, can be aggregated as follows:

$$A_i^{m,n} = \sum_j R_j^{m,n} \cdot g(t_{ij}^m) \quad (5)$$

It is noted that we only use the standardized Gaussian distance decay function for various urban services for several reasons. First, considering the limitation of travel behaviour data for people accessing different urban services, it is hard to determine the unique distance decay function for each urban service. Second, by using the same distance decay function, we can better compare the accessibility and equity of different urban services and analyze their variations.

Furthermore, it is also important to note that the same travel time matrices are used for both the CO and 2SFCA calculations. This ensures that differences in accessibility outcomes arise from the formulation of the measures rather than from travel time estimation.

### 3.3.3 | Modal Accessibility Gap Index

We apply the classic measurement of the modal accessibility gap (MAG) proposed by [74] to explore the accessibility differences between PT and PC, which is also widely applied in subsequent research [28, 75–77]. It can be illustrated as follows:

$$MAG_i^n = \frac{A_i^{PT,n} - A_i^{PC,n}}{A_i^{PT,n} + A_i^{PC,n}} \quad (6)$$

where  $MAG_i^n$  is the MAG of  $n^{\text{th}}$  service in the grid  $i$ ;  $A_i^{PT,n}$  and  $A_i^{PC,n}$  represents the PT and PC accessibility of  $n^{\text{th}}$  service in the grid  $i$ .

There are two advantages to using this MAG index. First, the measurement has both good operability and interpretation. The index is between -1 and 1, with values above 0 indicating PT accessibility is better, and values below 0 indicating PC accessibility is better. Furthermore, by using the same measurement as other studies, we can make a comparison of MAG among different study areas.

## 3.4 | Equity Evaluation

### 3.4.1 | Lorenz Curve and Gini Coefficient

In this study, we first use the Lorenz curve to quantify equity. The Lorenz curve shows the relationship between residential areas and their corresponding cumulative accessibility. Specifically, the grids with residential communities were ranked in ascending order by the average housing price, which allows us to investigate the spatial equity of urban services in different residential areas. The resulting Gini coefficient  $G$  can be approximated using the following formula [78]:

$$G = 1 - \sum_{u=1}^U (X_u - X_{u-1})(Y_u + Y_{u-1}) \quad (7)$$

where  $X_u$  and  $Y_u$  are the cumulated percentage of the residential communities and accessibility, respectively.  $u$  is the index of the residential area,  $u = 1, 2, \dots, U$ . The value of  $U$  equals the number of study units. Correspondingly,  $X_0 = 0$ ,  $X_U = 1$ ,  $Y_0 = 0$ , and  $Y_U = 1$ . The  $G$  ranges from 0 to 1 and the higher the value means the accessibility distribution is more unequal.

Although the Lorenz curve and Gini coefficient have been widely applied in the evaluation of transport equity [65, 79–81], the Gini coefficient has the disadvantage of disproportionately highlighting the inequality experienced by individuals in the middle of the Lorenz curve, while failing to adequately capture the disparity faced by those at both ends of the distribution curve [82].

### 3.4.2 | Palma Ratio

To address this limitation, we further apply the Palma ratio to measure the equity between the grids with the highest housing price (top 10%) and the grids with the lowest housing price (bottom 40%). Specifically, the Palma ratio is calculated as follows:

$$P_m^n = \frac{\bar{A}_{i,top10\%}^{m,n}}{\bar{A}_{i,bottom40\%}^{m,n}} \quad (8)$$

where  $P_m^n$  is the Palma ratio calculated from the accessibility of the  $n^{\text{th}}$  urban service by the  $m^{\text{th}}$  mode;  $\bar{A}_{i,top10\%}^{m,n}$  and  $\bar{A}_{i,bottom40\%}^{m,n}$  is the average accessibility of the  $n^{\text{th}}$  urban service by the  $m^{\text{th}}$  mode for the grids with the highest 10% housing price and the lowest 40% housing price, respectively.

The Palma ratio does not have a defined theoretical range. Typically, a higher Palma ratio indicates more serious inequality in accessibility between different populations, while a lower Palma ratio suggests less disparity in accessibility. Specifically, a Palma ratio equal to or below 1 is commonly viewed as indicative of a low level of inequality, in accordance with the results of Liu et al. [83].

### 3.5 | Global Moran's $I$

Global Moran's  $I$  [84] is the most common indicator of global spatial autocorrelation statistics, which ranges between  $-1$  and  $1$ . The closer the value is to  $1$ , the more pronounced the spatial clustering of similar values. A value closer to  $-1$  indicates a dispersed spatial distribution, while a value near  $0$  suggests a random spatial distribution. It can be calculated by the following equation:

$$I = \frac{N}{\sum_i \sum_j W_{ij}} \frac{\sum_i \sum_j W_{ij} (X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} \quad (9)$$

where  $N$  is the total number of observations;  $X_i$  and  $X_j$  are the  $i^{\text{th}}$  and  $j^{\text{th}}$  variable values and  $\bar{X}$  is the mean of all variable values; and  $W_{ij}$  is the spatial weight between the  $i^{\text{th}}$  and  $j^{\text{th}}$  variable.

## 4 | Results

### 4.1 | Accessibility Distribution

Figures 4 and 5 show the spatial distribution of accessibility to company, healthcare, and education from CO and 2SFCA by using PT and PC, respectively (results for scenery, restaurant, and shopping services are included in Appendix A). Accessibility values are divided into five classes based on natural breaks to show the heterogeneity of different grids.

The distribution pattern of accessibility from the two measures varies substantially. The results from CO present that the accessibility by PT is extremely high within the third ring road and is much lower in the areas between the fifth and sixth ring road (see Figures 4a–c). It indicates that Beijing has a monocentric urban structure, with most resources highly concentrated in urban central areas. However, the results from 2SFCA show that the grids with high accessibility values are dispersed in both central and peripheral areas (see Figures 4d–f). Meanwhile, more local characteristics are shown under 2SFCA. For example, although the accessibility distribution from the CO presents a certain degree of corridor characteristic along the subway lines, the phenomenon is much more evident when using the 2SFCA. It indicates that the 2SFCA that considers the supply-demand competition and distance decay can better identify the key role of urban rail transit.

Furthermore, compared with CO, the accessibility distribution pattern of various urban services by 2SFCA demonstrates greater differences. When considering the company, the areas with the highest accessibility values concentrate in the western third ring road where the CBD is located, and southeastern areas in Yizhuang, an economic-technological development area in Beijing. It indicates that Yizhuang has higher job accessibility and achieves a better population-to-employment balance than other new towns. As for healthcare services, the Fangshan district and some areas in the northwest and northeast were found to have the best accessibility. When considering education accessibility, it has a relatively similar pattern to that of CO, with a strong focus on the Haidian district which is a district with many colleges and universities in Beijing. The distribution pattern of accessibility

to scenery considerably changed in 2SFCA. The central areas no longer have huge advantages.

In contrast with PT, the accessibility of PC shows two different characteristics (see Figure 5). First, regardless of the kind of service, all accessibility distributions decrease from the city center to outer areas, and the accessibility in the north and east are better than the south and west. It corresponds to the overall structure of urban resources and private transportation in Beijing. The results of 2SFCA are similar to that of CO. The unique local features presented in PT evidently no longer exist in the context of PC. This change can be attributed to the enlarged catchment areas of PC (the average number of accessible grids for PT and PC is 62 and 925, respectively), reducing the regional advantages in some peripheral areas. Therefore, it can be concluded that the accessibility distribution of PT is more sensitive to the choice of the calculating measure.

Second, in terms of accessibility values, the overall accessibility of PC is much higher than that of PT in CO. This is because PC has higher mobility and provides door-to-door travel, enabling people to easily access various opportunities. For CO, the gap between the accessibility of PT and PC is evident. For 2SFCA, although the accessibility value of many grids by PT is higher than that of PC, especially in the outer areas along the lines of PT, the overall accessibility level of PC is still higher. These findings indicate that PC has accessibility advantages in Beijing in both methods.

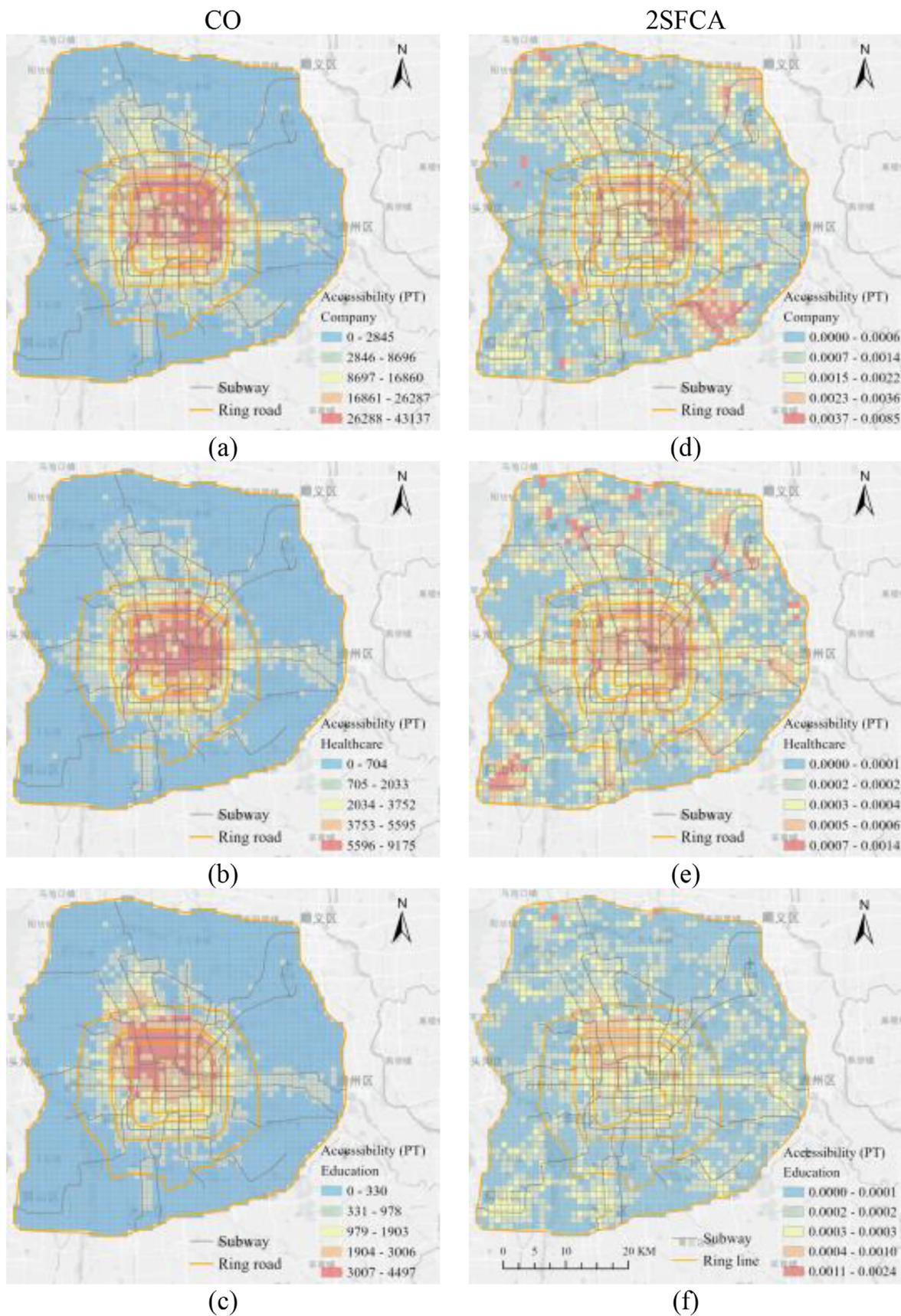
### 4.2 | MAG Distribution

To further evaluate the accessibility differences between PT and PC, MAG was calculated for each grid in Figure 6 (see the results of the other 3 urban services including scenery, restaurant, and shopping in Appendix B). The MAG values are divided into 5 classes based on natural breaks to show the heterogeneity of different grids.

For both measures the characteristics of the MAG are similar with most areas below 0, indicating that PT accessibility is lower than PC accessibility. It indicates that Beijing is still highly PC-dominated. There were also some differences between the two measures. The average MAG for CO and 2SFCA were  $-0.83$  and  $-0.3$ , respectively. The disadvantage of PT is narrowed after considering the population demand and distance decay in 2SFCA. Furthermore, the spatial distributions of MAG are distinct in the two measures. For CO, although the MAG is relatively higher in outer areas surrounding urban rail transit lines, the areas with the highest MAG are mostly located in the central areas. For 2SFCA, however, MAG is the highest and above 0 in the outer new towns along the end of the subway such as Fangshan, Yizhuang, Tongzhou, and Changping. In these areas, the accessibility of PT is higher than that of PC, reflecting the social value of TOD (transit-oriented development).

### 4.3 | Equity in Accessibility

After identifying the average housing price of 1074 grids, Figures 7 and 8 display the Lorenz curves and the Gini coefficient based on different kinds of accessibility, respectively. When considering the



**FIGURE 4** | The accessibility to company, healthcare, and education opportunities by PT (left side from CO and right side from 2SFCA).

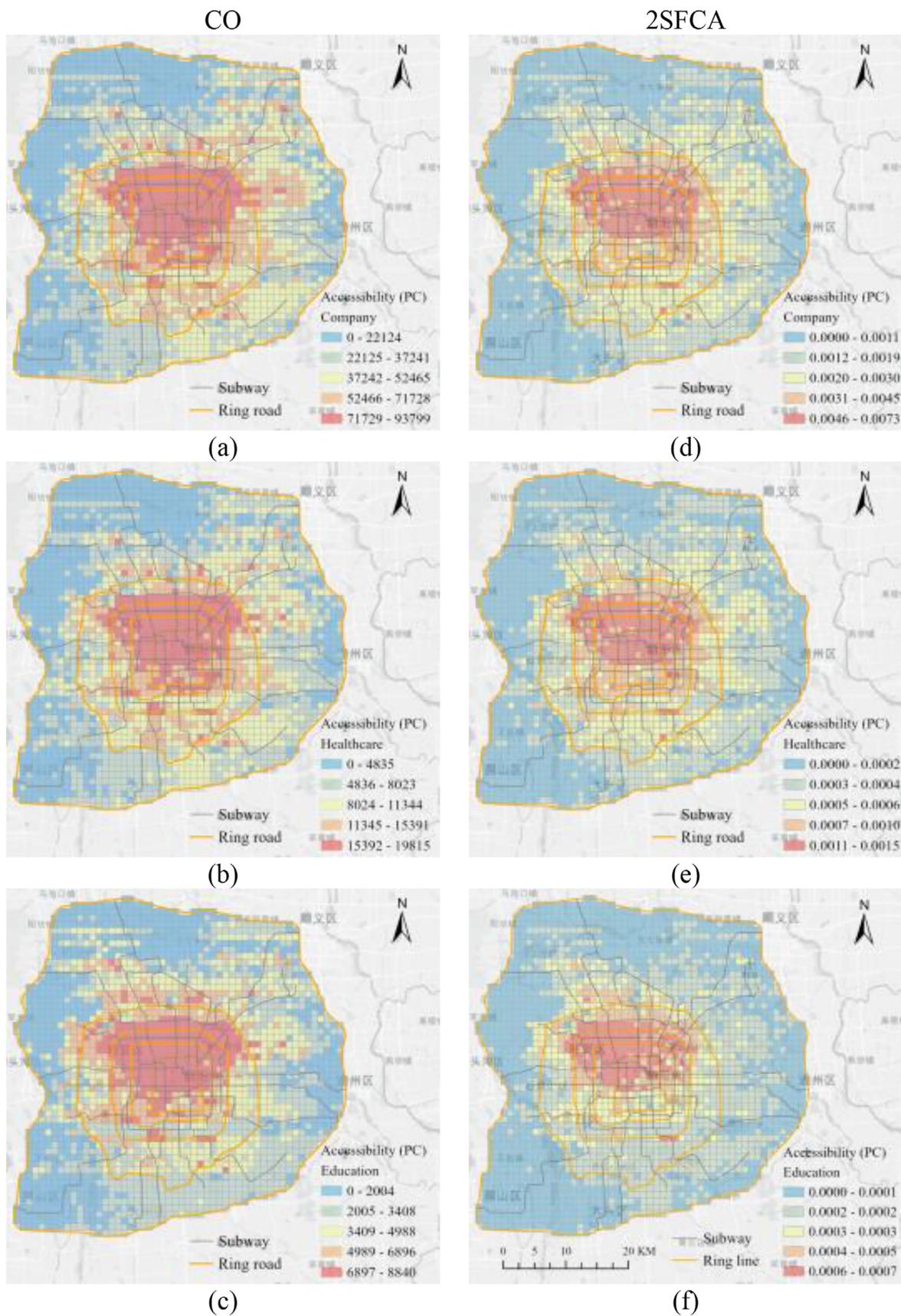
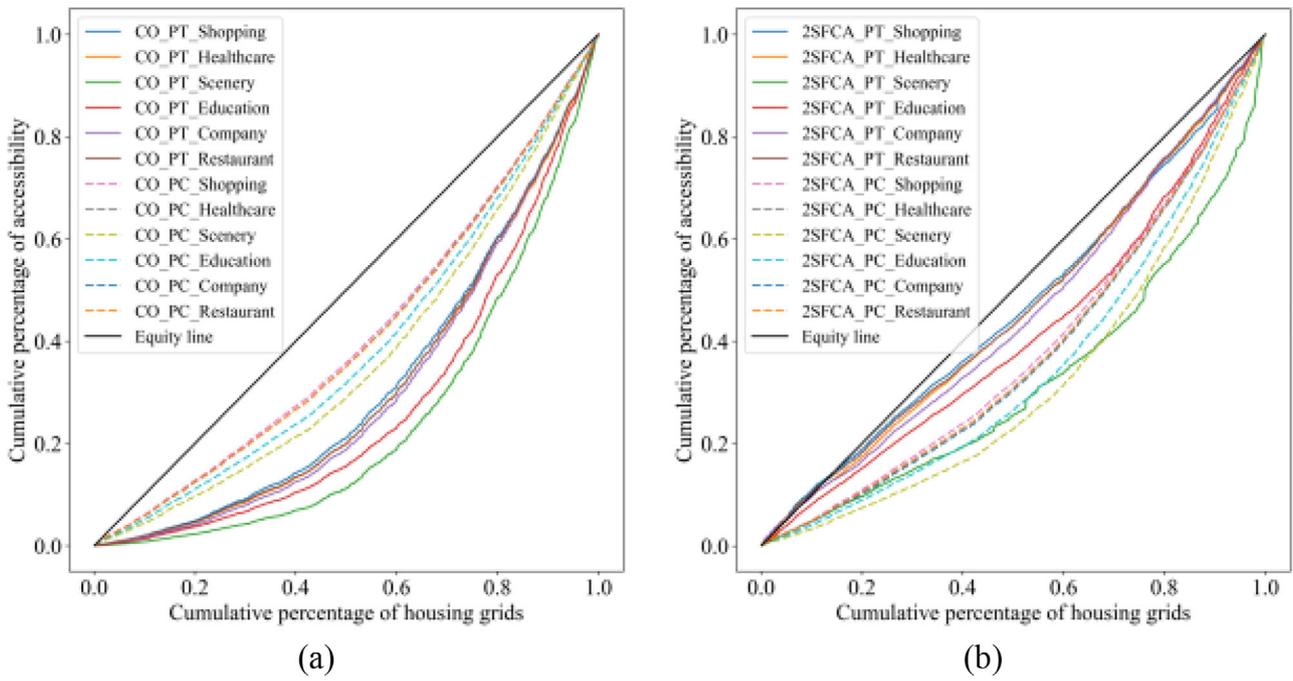


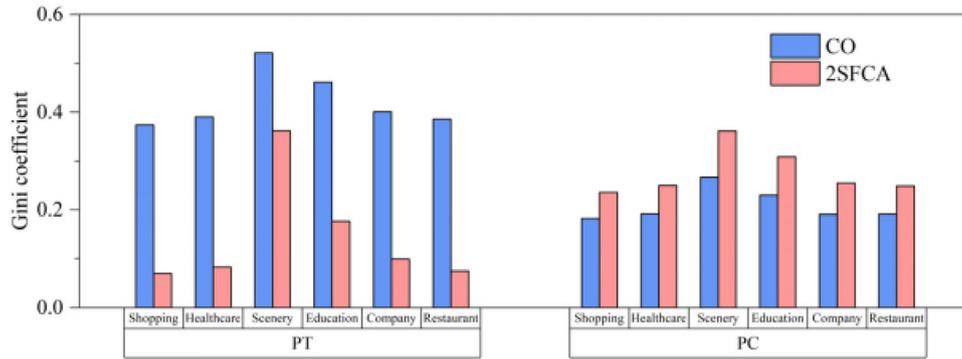
FIGURE 5 | The accessibility to company, healthcare, and education opportunities by PC (left side from CO and right side from 2SFCA).



**FIGURE 6** | Spatial distributions of modal accessibility gap of company, healthcare, and scenery opportunities (left side from CO and right side from 2SFCA).



**FIGURE 7** | Lorenz curves of various urban services by PT and PC: (a) CO and (b) 2SFCA.



**FIGURE 8** | Gini coefficient of various urban services by PT and PC.

CO, curves are divided into two groups by modes (see Figure 7a). The curves of PT are below that of PC and farther away from the equity line, indicating that the accessibility distribution is more unequal for PT. For instance, the 20% of vulnerable grids with the lowest housing price only account for less than 5% of total accessibility. This phenomenon demonstrates that the PT accessibility by CO is much lower in the outer areas where housing price is also lower. Therefore, people in these outer areas are more likely to suffer from spatial inequity, especially those transit-dependent travellers.

However, the result of 2SFCA shows an opposite trend (see Figure 7b). The curves of PT dramatically rise closer to the equity line and the curves of PC fall. Therefore, the curves of PT are higher than that of PC. For example, the Gini coefficient of PT dramatically decreases from about 0.4 to 0.1 for shopping, healthcare, company, and restaurant, while the Gini coefficient of PC slightly increases to about 0.3 (see Figure 8). It means that the accessibility distribution of PT is more equal in contrast to PC, which is different from the result of CO. This change

can be attributed to the accessibility advantage for outer areas after considering the demand distribution and distance decay in 2SFCA.

The equity in different urban services also varies. Regardless of calculating measures and transportation modes, the curves of shopping, healthcare, company, and restaurant are quite similar and close to each other, while the curves of education and scenery deviate most from the equity line. It illustrates that education and scenery are the least equitable urban services in Beijing. Consequently, more resources should be allocated to affordable housing areas to provide the basic needs of amenities such as schools and parks.

As indicated in Figure 9, the Palma ratios in all scenarios are much higher than 1, indicating that the average accessibility of the areas with the highest 10% housing price is considerably higher than that of the areas with the lowest 40% housing price. The inequity between different populations means that the accessibility of the disadvantaged needs further improvement by

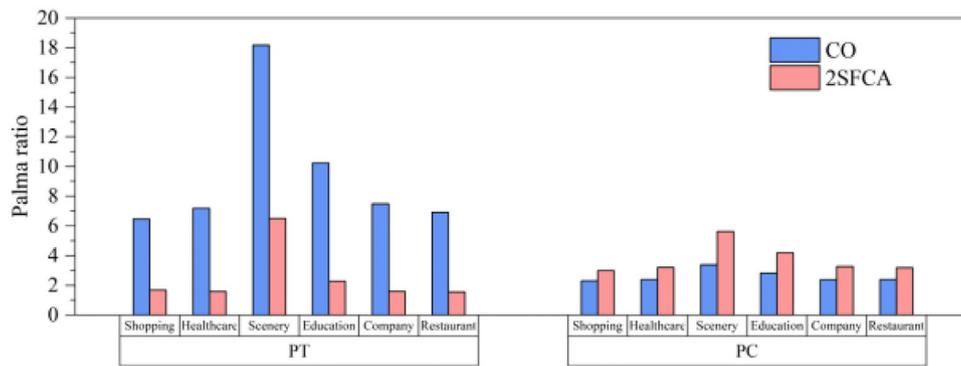


Fig. 9. The Palma ratio of various urban services by PT and PC.

FIGURE 9 | The Palma ratio of various urban services by PT and PC.

providing more transport facilities and urban services. In terms of the differences between CO and 2SFCA, the results of the Palma ratio show similar patterns to that of the Gini coefficient. First, the Palma ratios of PT are higher than that of PC when using CO while the Palma ratios of PT are slightly lower than that of PC when using 2SFCA. It also can be attributed to the local advantages of accessibility in outer areas surrounding the metro network in the results of 2SFCA.

Regarding various urban services, it also can be found that the accessibility distribution of scenery and education in different populations is the most unequal among all urban services. From CO to 2SFCA, it is noted that the Palma ratios of company, healthcare, and education service by PT change most, reaching almost 80%. These results are a result of the distributions of company, healthcare, and education being highly concentrated (their global Moran's  $I$  reach 0.59, 0.55, and 0.45, respectively) and the housing price of these gathering areas tending to be high. On the other hand, the Palma ratios of scenery, education, and company service by PC change the most, reaching 67%, 49%, and 37%, respectively. Thus, it can be concluded that the company and education service are more susceptible to the method choice when measuring the equity focusing on disadvantaged people.

From the results of the Gini coefficient and Palma ratio, it can be concluded that the distribution of PT accessibility is more unequal than PC in CO while the distribution of PC accessibility is more unequal in 2SFCA. Furthermore, the results of the two methods both show that equity can be improved by providing PT rather than PC, especially for those vulnerable areas.

## 5 | Discussions

### 5.1 | The Causes of the Differences From the Method Choice

The key differences in accessibility between CO and 2SFCA originate from the consideration of population and distance decay function in the modeling. CO calculates accessibility by directly aggregating the supply within the catchment area. This uniform treatment makes the accessibility of the place much more similar to the surrounding grids at the large scale (see in Figure 4). CO treats every opportunity within the threshold as equally

available, regardless of how many people are competing for it. This inherently favors central areas where the absolute number of amenities is high, reinforcing a monocentric view of the city.

Compared with accessibility from CO, accessibility from 2SFCA not only depends on the surrounding supply but also on the demand and is more affected by closer places than distant places in the catchment areas due to the distance decay function. Therefore, accessibility from 2SFCA has more local characteristics and spatial heterogeneity at the small scale (see in Figure 4). That is also the reason that accessibility from 2SFCA can be viewed as the average urban service that each person can obtain within the certain travel cost. In Beijing, while the city center has the most hospitals and jobs, it also has the highest population density, leading to intense competition. 2SFCA captures this congestion effect, lowering the accessibility score in the center and highlighting sub-centers (like Yizhuang and Fangshan) where the ratio of amenities to population is more favorable. As shown in Table C1 (Appendix C), the average global Moran's  $I$  of accessibility from CO is much larger than that of 2SFCA, confirming higher spatial heterogeneity in the accessibility distribution from 2SFCA. It is noted that these spatial differences and causes are lacking in existing studies that merely consider the correlation of accessibility results from various measures [24, 20], thus underlining the importance of spatial distribution in future accessibility comparability studies.

Furthermore, the results also show that PT is more susceptible to method choice than PC (see in Figures 4 and 5). The causes may come from the spatial scale of the catchment areas of different modes. The catchment areas of PT are much smaller than those of PC. The gap of catchment areas can be attributed to the mobility differences and various supply patterns of transportation networks. Thus, the accessibility by PT is more susceptible to the supply and demand of local areas. For some suburban areas, urban services concentrate along the metro lines and the potential demand in PT's catchment areas is not huge, leading to higher accessibility in these areas by using the 2SFCA. And the accessibility by PT is even higher than by PC (see in Figures 4 and 6). On the other hand, even after considering the population distribution, the accessibility by PC is still measured in large catchment areas and the potential demand is also massive at the region level. Consequently, the accessibility in these suburban areas is still low and the accessibility in central areas even

presents a more concentrated distribution (see in Figure 5). The high global Moran's  $I$  of the accessibility by PT from 2SFCA also confirms that (see in Table C1). The heterogeneity in PT and PC from various measures has not been found in previous comparability studies [26, 20, 22], which raises more consideration of the method choice in the evaluation of accessibility by PT in future research.

The differences between PT and PC then naturally result in the significant equity change. Because the affordable housing areas tend to be located in the suburban areas with good PT accessibility by using the 2SFCA. Therefore, the PT accessibility distribution is more equal compared with the results of CO (see in Figures 8 and 9). Regarding different urban services, the equity of company and education are more susceptible to the method choice. Because they are highly concentrated in several areas with high housing price and are more likely to be affected by the local supply-demand ratio, especially considering the advantaged and disadvantaged people.

Generally, it is needed to consider the effect of the method choice on the accessibility and equity evaluation by PT in future practice, especially for the company and education service. Different methods may lead to very different results. From the perspective of CO, the results more suggest the macro supply pattern at the city level, which is close to the city structure. While for the perspective of 2SFCA, the results more indicate the pattern of interactions between supply and demand at the local level, providing insights for the equitable allocation and adjustments of transport and urban resources.

## 5.2 | Limitations

There are several limitations to the present study. First, while CO can be extended through the introduction of distance decay or competition effects, such modifications often blur the conceptual boundary between CO and gravity-based or floating catchment area approaches. This study focuses on the standard forms of CO and 2SFCA to maintain conceptual clarity and comparability. Future studies could explore how modified CO compares with 2SFCA based on this study's analytical frameworks. Second, we only chose the 2SFCA with the Gaussian distance decay function and 60-min threshold for all kinds of urban services and thus ignore the heterogeneity in travel behaviour for various purposes. While the existing research shows highly similar characteristics between various kinds of 2SFCA [24], the correlations and differences in accessibility between CO and more forms of 2SFCA still need to be explored further. Third, regarding the limitation of the data from the Gaode Map, the POI data only include the quantity of different kinds of amenities, ignoring the quality and scale of various POIs. Moreover, we merely used the travel route planning data in the morning peak hour, neglecting the dynamics of accessibility that has become the research focus in recent years [32, 85]. Therefore, the accessibility of PT and PC and the resulting MAG in more periods should be considered in future studies. Forth, we did not consider other transportation modes such as cycling and multimodal travel, which is more and more important in accessibility modelling [64, 86]. In future studies, the comparisons between more modes should be included and the multimodal accessibility needs to be modeled. Finally, the results

of the method comparison from Beijing, a rapidly changing monocentric city, may be different from other research areas. Thus, more comparison research can be done in other cities to deeply understand the associations and differences between various accessibility methods.

## 6 | Conclusion

This paper contrasted the accessibility and equity in 12 different scenarios by using CO and 2SFCA, respectively. The key findings from this study show that there are considerable differences between the results of CO and 2SFCA. The spatial distributions of accessibility from CO are more related to the whole city structure, while the results from 2SFCA can better reflect the local characteristics due to the consideration of population distribution and distance decay. We also answer the second proposed question that the accessibility and equity of PT are more susceptible to the method choice than PC because of the much smaller catchment areas of PT. Regarding equity, the distribution of PC accessibility is more unequal than PT in 2SFCA, which is opposite to the result of CO. Moreover, for different urban services, the accessibility of scenery and education is distributed most unequally. Company and education are more susceptible to the method choice when measuring the equity focusing on disadvantaged people.

These findings have direct implications for environmentally friendly transport planning. The CO method suggests that PT is vastly inferior to PC across the board, which might discourage investments in transit under the assumption that the gap is too wide to bridge. However, 2SFCA reveals that in specific suburban new towns, PT accessibility already rivals or exceeds PC when competition is considered. This suggests that green transport policies should target these specific transit-oriented hubs to maximize utility. Furthermore, understanding these differences helps planners internalize the externalities of congestion; by using 2SFCA, planners can identify areas where high facility density is negated by overcrowding, prompting a need for decentralization rather than just adding more capacity to the center.

Our contributions are mainly twofold. On the one hand, this paper provides the research framework to compare the accessibility and equity of CO and 2SFCA in many typical scenarios. Based on the correlations of the accessibility results that most existing research focuses on [24, 20–22], we further include the comparison of the spatial distributions of accessibility and MAG and the equity in 12 different scenarios including two transportation modes and six key urban services. In this way, this paper broadens the research on method comparison in accessibility evaluation and sheds light on future research to compare various models from more perspectives.

On the other hand, from the perspective of accessibility planning, the key findings of this work can help planners and policymakers better understand the effect of method choice on the evaluation of accessibility and equity. The massive differences in the results of CO and 2SFCA in Beijing reveal that different accessibility metrics should be used in various application scenarios in practice, especially for PT. For example, for one new subway line, the method choice on the job accessibility evaluation may eventually affect the planning or operating issues. From the

overall perspective of CO, a new metro line in Beijing indeed can improve accessibility but may not change the monocentric structure. But from the local perspective of 2SFCA, it may considerably improve the equity along the lines and help us to plan the hub and properly allocate the urban services according to the accessibility considering the potential demand. Therefore, these spatial comparisons not only can test the robustness of accessibility and equity but also provide the complementation to know the integration of transport and land use from different views to provide insights for accessibility planning.

### Author Contributions

**Yue Chen:** conceptualization, methodology, formal analysis, funding acquisition, visualisation, writing – original draft preparation, reviewing and editing. **Shunping Jia:** supervision, funding acquisition, project administration. **Steve O'Hern:** supervision, writing – reviewing and editing. **Qi Xu:** funding acquisition, supervision, writing – reviewing and editing.

### Funding

The research work was supported by the Fundamental Research Funds for the Central Universities (2023YJIS134).

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### References

1. W. G. Hansen, "How Accessibility Shapes Land Use," *Journal of the American Institute of Planners* 25 (1959): 73–76, <https://doi.org/10.1080/01944365908978307>.
2. K. T. Geurs and B. van Wee, "Accessibility Evaluation of Land-use and Transport Strategies: Review and Research Directions," *Journal of Transport Geography* 12 (2004): 127–140, <https://doi.org/10.1016/j.jtrangeo.2003.10.005>.
3. S. L. Handy and D. A. Niemeier, "Measuring Accessibility: An Exploration of Issues and Alternatives," *Environment and Planning A: Economy and Space* 29 (1997): 1175–1194, <https://doi.org/10.1068/a291175>.
4. P. Anderson, D. Levinson, and P. Parthasarathi, "Accessibility Futures," *Transactions in GIS* 17 (2013): 683–705, <https://doi.org/10.1111/tgis.12024>.
5. B. Arslangulova and K. Galanakis, "The Accessibility of Public Electric Vehicle (EV) Charging Infrastructure: Evidence From the Cities of Nottingham and Frankfurt," *IET Intelligent Transport Systems* 18 (2024): 3058–3068, <https://doi.org/10.1049/itr2.12564>.
6. L. Hu, J. Cao, and J. Yang, "Planning for Accessibility," *Transportation Research Part D: Transport and Environment* 88 (2020): 102575, <https://doi.org/10.1016/j.trd.2020.102575>.
7. J. Levine, "A Century of Evolution of the Accessibility Concept," *Transportation Research Part D: Transport and Environment* 83 (2020): 102309, <https://doi.org/10.1016/j.trd.2020.102309>.
8. D. G. Proffitt, K. Bartholomew, R. Ewing, and H. J. Miller, "Accessibility Planning in American Metropolitan Areas: Are We There yet?," *Urban Studies* 56 (2019): 167–192, <https://doi.org/10.1177/0042098017710122>.
9. K. Kelobonye, G. McCarney, J. Xia Cecilia, M. S. H. Swapan, F. Mao, and H. Zhou, "Relative Accessibility Analysis for Key Land Uses: A Spatial Equity Perspective," *Journal of Transport Geography* 75 (2019): 82–93, <https://doi.org/10.1016/j.jtrangeo.2019.01.015>.
10. F. Bruzzone, F. Cavallaro, and S. Nocera, "The Definition of Equity in Transport," *Transportation Research Procedia* 69 (2023): 440–447, <https://doi.org/10.1016/j.trpro.2023.02.193>.
11. L. Zhu and K. Lucas, "Towards Calculated and Perceived Transport Equity: An Equity Evaluation Framework for Accessibility," *Transportation Research Part D: Transport and Environment* 146 (2025): 104908, <https://doi.org/10.1016/j.trd.2025.104908>.
12. N. Chen and C.-H. Wang, "Does Green Transportation Promote Accessibility for Equity in Medium-Size U.S. Cities?," *Transportation Research Part D: Transport and Environment* 84 (2020): 102365, <https://doi.org/10.1016/j.trd.2020.102365>.
13. O. Armantalab, J. Hawkins, and M. D. S. Hasnine, "Transportation Access Equity Analysis in Two US Cities Using Bayesian Inference-Based Logsum Compensating Variation Metrics," *Travel Behaviour and Society* 41 (2025): 101073, <https://doi.org/10.1016/j.tbs.2025.101073>.
14. D. R. Ingram, "The Concept of Accessibility: A Search for an Operational Form," *Regional Studies* 5 (1971): 101–107, <https://doi.org/10.1080/09595237100185131>.
15. C. F. Martínez, F. Hodgson, C. Mullen, and P. Timms, "Creating Inequality in Accessibility: The Relationships Between Public Transport and Social Housing Policy in Deprived Areas of Santiago de Chile," *Journal of Transport Geography* 67 (2018): 102–109, <https://doi.org/10.1016/j.jtrangeo.2017.09.006>.
16. W. R. Tobler, "A Computer Movie Simulating Urban Growth in the Detroit Region," *Economic Geography* 46 (1970): 234, <https://doi.org/10.2307/143141>.
17. W. Luo and F. Wang, "Measures of Spatial Accessibility to Health Care in a Gis Environment: Synthesis and a Case Study in the Chicago Region," *Environment and Planning B: Planning and Design* 30 (2003): 865–884, <https://doi.org/10.1068/b29120>.
18. K. T. Geurs, A. De Montis, and Reggiani, "Recent Advances and Applications in Accessibility Modelling," *Computers, Environment and Urban Systems* 49 (2015): 82–85, <https://doi.org/10.1016/j.compenvurbusys.2014.09.003>.
19. M.-P. Kwan, "Space-Time and Integral Measures of Individual Accessibility: A Comparative Analysis Using a Point-Based Framework," *Geographical Analysis* 30 (2010): 191–216, <https://doi.org/10.1111/j.1538-4632.1998.tb00396.x>.
20. B. Kapatsila, M. S. Palacios, E. Grisé, and A. El-Geneidy, "Resolving the Accessibility Dilemma: Comparing Cumulative and Gravity-Based Measures of Accessibility in Eight Canadian Cities," *Journal of Transport Geography* 107 (2023): 103530, <https://doi.org/10.1016/j.jtrangeo.2023.103530>.
21. B. Klar, J. Lee, J. A. Long, and E. Diab, "The Impacts of Accessibility Measure Choice on Public Transit Project Evaluation: A Comparative Study of Cumulative, Gravity-based, and Hybrid Approaches," *Journal of Transport Geography* 106 (2023): 103508, <https://doi.org/10.1016/j.jtrangeo.2022.103508>.
22. C. McCahill, S. Jain, and M. Brenneis, "Comparative Assessment of Accessibility Metrics Across the U.S.," *Transportation Research Part D: Transport and Environment* 83 (2020): 102328, <https://doi.org/10.1016/j.trd.2020.102328>.
23. M. Santana Palacios and A. El-geneidy, 2022. Cumulative versus gravity-based accessibility measures: Which one to use? Findings February, <https://doi.org/10.32866/001c.32444>.
24. X. Chen and P. Jia, "A Comparative Analysis of Accessibility Measures by the Two-Step Floating Catchment Area (2SFCA) Method," *International Journal of Geographical Information Science* 33 (2019): 1739–1758, <https://doi.org/10.1080/13658816.2019.1591415>.
25. D. S. Vale and M. Pereira, "The Influence of the Impedance Function on Gravity-Based Pedestrian Accessibility Measures: A Comparative

- Analysis," *Environment and Planning B: Urban Analytics and City Science* 44 (2017): 740–763, <https://doi.org/10.1177/0265813516641685>.
26. M. Giannotti, J. Barros, D. B. Tomasiello, et al., "Inequalities in Transit Accessibility: Contributions From a Comparative Study Between Global South and North Metropolitan Regions," *Cities* 109 (2021): 103016, <https://doi.org/10.1016/j.cities.2020.103016>.
27. J. Grengs, "Job Accessibility and the Modal Mismatch in Detroit," *Journal of Transport Geography* 18 (2010): 42–54, <https://doi.org/10.1016/j.jtrangeo.2009.01.012>.
28. J. Guan, K. Zhang, Q. Shen, and Y. He, "Dynamic Modal Accessibility Gap: Measurement and Application Using Travel Routes Data," *Transportation Research Part D: Transport and Environment* 81 (2020): 102272, <https://doi.org/10.1016/j.trd.2020.102272>.
29. G. Boisjoly and A. El-Geneidy, "Daily Fluctuations in Transit and Job Availability: A Comparative Assessment of Time-sensitive Accessibility Measures," *Journal of Transport Geography* 52 (2016): 73–81, <https://doi.org/10.1016/j.jtrangeo.2016.03.004>.
30. W. Xiao, Y. D. Wei, and N. Wan, "Modeling Job Accessibility Using Online Map Data: An Extended Two-Step Floating Catchment Area Method With Multiple Travel Modes," *Journal of Transport Geography* 93 (2021): 103065, <https://doi.org/10.1016/j.jtrangeo.2021.103065>.
31. B. Pizzol, M. Giannotti, and D. B. Tomasiello, "Qualifying Accessibility to Education to Investigate Spatial Equity," *Journal of Transport Geography* 96 (2021): 103199, <https://doi.org/10.1016/j.jtrangeo.2021.103199>.
32. Y. Chen, S. Jia, Q. Xu, Z. Xiao, and S. Zhang, "Measuring the Dynamic Accessibility to COVID-19 Testing Sites in the 15-min City: A Focus on Service Congestion and Mobility Difference," *Journal of Transport Geography* 111 (2023): 103670, <https://doi.org/10.1016/j.jtrangeo.2023.103670>.
33. M. Ghorbanzadeh, K. Kim, E. Erman Ozguven, and M. W. Horner, "Spatial Accessibility Assessment of COVID-19 Patients to Healthcare Facilities: A Case Study of Florida," *Travel Behaviour and Society* 24 (2021): 95–101, <https://doi.org/10.1016/j.tbs.2021.03.004>.
34. S. Gong, Y. Gao, F. Zhang, L. Mu, C. Kang, and Y. Liu, "Evaluating Healthcare Resource Inequality in Beijing, China Based on an Improved Spatial Accessibility Measurement," *Transactions in GIS* 25 (2021): 1504–1521, <https://doi.org/10.1111/tgis.12737>.
35. J. Xing and S. T. Ng, "Analyzing Spatiotemporal Accessibility Patterns to Tertiary Healthcare Services by Integrating Total Travel Cost Into an Improved E3SFCA Method in Changsha, China," *Cities* 122 (2022): 103541, <https://doi.org/10.1016/j.cities.2021.103541>.
36. J. Li and C. Kim, "Exploring Relationships of Grocery Shopping Patterns and Healthy Food Accessibility in Residential Neighborhoods and Activity Space," *Applied Geography* 116 (2020): 102169, <https://doi.org/10.1016/j.apgeog.2020.102169>.
37. L. Cheng, F. Caset, J. De Vos, B. Derudder, and F. Witlox, "Investigating Walking Accessibility to Recreational Amenities for Elderly People in Nanjing, China," *Transportation Research Part D: Transport and Environment* 76 (2019): 85–99, <https://doi.org/10.1016/j.trd.2019.09.019>.
38. W. Yang, R. Yang, and S. Zhou, "The Spatial Heterogeneity of Urban Green Space Inequity From a Perspective of the Vulnerable: A Case Study of Guangzhou, China," *Cities* 130 (2022): 103855, <https://doi.org/10.1016/j.cities.2022.103855>.
39. W. Zhang, Y. Gao, S. Li, et al., "Accessibility Measurements for Urban Parks Considering Age-Grouped Walkers' Sectorial Travel Behavior and Built Environment," *Urban Forestry & Urban Greening* 76 (2022): 127715, <https://doi.org/10.1016/j.ufug.2022.127715>.
40. E. Desjardins, C. D. Higgins, and A. Páez, "Examining Equity in Accessibility to Bike Share: A Balanced Floating Catchment Area Approach," *Transportation Research Part D: Transport and Environment* 102 (2022): 103091, <https://doi.org/10.1016/j.trd.2021.103091>.
41. A. Ermagun, F. Janatabadi, and S. Maharjan, "Inequity Analysis of Spatial Mismatch for Low-Income Socially Vulnerable Populations Across America," *Transportation Research Part D: Transport and Environment* 118 (2023): 103692, <https://doi.org/10.1016/j.trd.2023.103692>.
42. L. Hu, "Job Accessibility and Employment Outcomes: Which Income Groups Benefit the Most?," *Transportation* 44 (2017): 1421–1443, <https://doi.org/10.1007/s11116-016-9708-4>.
43. L. Hu, "Racial/Ethnic Differences in Job Accessibility Effects: Explaining Employment and Commutes in the Los Angeles Region," *Transportation Research Part D: Transport and Environment* 76 (2019): 56–71, <https://doi.org/10.1016/j.trd.2019.09.007>.
44. Q. Pan, Z. Jin, and X. Liu, "Measuring the Effects of Job Competition and Matching on Employment Accessibility," *Transportation Research Part D: Transport and Environment* 87 (2020): 102535, <https://doi.org/10.1016/j.trd.2020.102535>.
45. D. Vale, "Effective Accessibility: Using Effective Speed to Measure Accessibility by Cost," *Transportation Research Part D: Transport and Environment* 80 (2020): 102263, <https://doi.org/10.1016/j.trd.2020.102263>.
46. M. Q. Dalvi and K. M. Martin, "The Measurement of Accessibility: Some Preliminary Results," *Transportation* 5 (1976): 17–42, <https://doi.org/10.1007/BF00165245>.
47. D. Liu and M.-P. Kwan, "Measuring Spatial Mismatch and Job Access Inequity Based on Transit-Based Job Accessibility for Poor Job Seekers," *Travel Behaviour and Society* 19 (2020): 184–193, <https://doi.org/10.1016/j.tbs.2020.01.005>.
48. J. Q. Stewart, "Empirical Mathematical Rules Concerning the Distribution and Equilibrium of Population," *Geographical Review* 37 (1947): 461, <https://doi.org/10.2307/211132>.
49. G. Boisjoly and A. M. El-Geneidy, "How to Get There? A Critical Assessment of Accessibility Objectives and Indicators in Metropolitan Transportation Plans," *Transport Policy* 55 (2017): 38–50, <https://doi.org/10.1016/j.tranpol.2016.12.011>.
50. K. Hosford, J. Bearsto, and M. Winters, "Is the 15-minute city Within Reach? Evaluating Walking and Cycling Accessibility to Grocery Stores in Vancouver," *Transportation Research Interdisciplinary Perspectives* 14 (2022): 100602, <https://doi.org/10.1016/j.trip.2022.100602>.
51. A. E. Joseph and P. R. Bantock, "Measuring Potential Physical Accessibility to General Practitioners in Rural Areas: A Method and Case Study," *Social Science & Medicine* 16 (1982): 85–90, [https://doi.org/10.1016/0277-9536\(82\)90428-2](https://doi.org/10.1016/0277-9536(82)90428-2).
52. Q. Shen, "Location Characteristics of Inner-city Neighborhoods and Employment Accessibility of Low-Wage Workers," *Environment and Planning B: Planning and Design* 25 (1998): 345–365, <https://doi.org/10.1068/b250345>.
53. W. Luo and Y. Qi, "An Enhanced Two-Step Floating Catchment Area (E2SFCA) Method for Measuring Spatial Accessibility to Primary Care Physicians," *Health & Place* 15 (2009): 1100–1107, <https://doi.org/10.1016/j.healthplace.2009.06.002>.
54. K. Kelobonye, H. Zhou, G. McCarney, and J. Xia Cecilia, "Measuring the Accessibility and Spatial Equity of Urban Services Under Competition Using the Cumulative Opportunities Measure," *Journal of Transport Geography* 85 (2020): 102706, <https://doi.org/10.1016/j.jtrangeo.2020.102706>.
55. J. Luo, "Integrating the Huff Model and Floating Catchment Area Methods to Analyze Spatial Access to Healthcare Services: Analyzing Spatial Access to Healthcare Services," *Transactions in GIS* 18 (2014): 436–448, <https://doi.org/10.1111/tgis.12096>.
56. Z. Tao and Y. Cheng, "Modelling the Spatial Accessibility of the Elderly to Healthcare Services in Beijing," *China Environment and Planning B: Urban Analytics and City Science* 46 (2019): 1132–1147, <https://doi.org/10.1177/2399808318755145>.
57. N. Schuurman, M. Bérubé, and V. A. Crooks, "Measuring Potential Spatial Access to Primary Health Care Physicians Using a Modified Gravity Model," *Canadian Geographies / Géographies Canadiennes* 54 (2010): 29–45, <https://doi.org/10.1111/j.1541-0064.2009.00301.x>.

58. S. Jamtsho, R. Corner, and A. Dewan, "Spatio-Temporal Analysis of Spatial Accessibility to Primary Health Care in Bhutan," *ISPRS International Journal of Geo-Information* 4 (2015): 1584–1604, <https://doi.org/10.3390/ijgi4031584>.
59. N. Wan, F. B. Zhan, B. Zou, and E. Chow, "A Relative Spatial Access Assessment Approach for Analyzing Potential Spatial Access to Colorectal Cancer Services in Texas," *Applied Geography* 32 (2012): 291–299, <https://doi.org/10.1016/j.apgeog.2011.05.001>.
60. D. Dai and F. Wang, "Geographic Disparities in Accessibility to Food Stores in Southwest Mississippi," *Environment and Planning B: Planning and Design* 38 (2011): 659–677, <https://doi.org/10.1068/b36149>.
61. Z. Han, C. Cui, Y. Kong, Q. Li, Y. Chen, and X. Chen, "Improving Educational Equity by Maximizing Service Coverage in Rural Changyuan, China: An Evaluation-Optimization-Validation Framework Based on Spatial Accessibility to Schools," *Applied Geography* 152 (2023): 102891, <https://doi.org/10.1016/j.apgeog.2023.102891>.
62. S. Takyi, R. B. Antwi, E. Erman Ozguven, et al., "Measuring Spatial Accessibility of Public Libraries Using Floating Catchment Area Methods: A Comparative Case Study in Calhoun County," *Florida Transportation Research Interdisciplinary Perspectives* 22 (2023): 100944, <https://doi.org/10.1016/j.trip.2023.100944>.
63. Y. Ye, Y. Xiang, H. Qiu, and X. Li, "Revealing Urban Greenspace Accessibility Inequity Using the Carrying Capacity-Based 3SFCA Method and Location Big Data," *Sustainable Cities and Society* 108 (2024): 105513, <https://doi.org/10.1016/j.scs.2024.105513>.
64. M. Zhang, Z. Li, and H. Peng, "The Accessibility Analysis of Multiple Public Facilities in the Central Urban Areas Based on Multi-Transportation Modes: A Study in Chengdu," *Transactions in GIS* 27 (2023): 2213–2233, <https://doi.org/10.1111/tgis.13117>.
65. P. R. Carleton and J. D. Porter, "A Comparative Analysis of the Challenges in Measuring Transit Equity: Definitions, Interpretations, and Limitations," *Journal of Transport Geography* 72 (2018): 64–75, <https://doi.org/10.1016/j.jtrangeo.2018.08.012>.
66. Beijing Transport Institute, "2020 Beijing Transport Development Annual Report," accessed August 12, 2023, <https://www.bjtrc.org.cn/List/index/cid/7/p/1.html>.
67. L. Zhu and F. Shi, "Spatial and Social Inequalities of Job Accessibility in Kunshan City, China: Application of the Amap API and Mobile Phone Signaling Data," *Journal of Transport Geography* 104 (2022): 103451, <https://doi.org/10.1016/j.jtrangeo.2022.103451>.
68. Baidu Map, "Congestion Degree Platform for Chinese Cities," accessed May 21, 2020, <https://jiaotong.baidu.com/congestion/country/city/>.
69. Baidu Map, "2020 National Commuting Monitoring Report for Major Cities," accessed 4 December 2023, <https://huiyan.baidu.com/cms/report/2020tongqin/>.
70. Y. Li, J. Feng, and C. Jiang, "Comprehensive Evaluation and Countermeasures of 1-2-3 Travel Circles Development in China," *China Transportation Review* 42, no. 06 (2020): 1–7.
71. S. Guo, T. Pei, X. Wang, et al., "Equity of Subway Accessibility: A Perspective From Work Commute Trips," *Transportation Research Part D: Transport and Environment* 113 (2022): 103515, <https://doi.org/10.1016/j.trd.2022.103515>.
72. L. Ma, N. Luo, T. Wan, C. Hu, and M. Peng, "An Improved Healthcare Accessibility Measure Considering the Temporal Dimension and Population Demand of Different Ages," *International Journal of Environmental Research and Public Health* 15 (2018): 2421, <https://doi.org/10.3390/ijerph15112421>.
73. L. Xing, Q. Chen, Y. Liu, and H. He, "Evaluating the Accessibility and Equity of Urban Health Resources Based on Multi-Source Big Data in High-Density City," *Sustainable Cities and Society* 100 (2024): 105049, <https://doi.org/10.1016/j.scs.2023.105049>.
74. R. C. W. Kwok and A. G. O. Yeh, "The Use of Modal Accessibility Gap as an Indicator for Sustainable Transport Development," *Environment and Planning A: Economy and Space* 36 (2004): 921–936, <https://doi.org/10.1068/a3673>.
75. A. Larsson, E. Elldér, E. Vafeiadis, C. Curtis, and A. Steiner, "Exploring the Potential for Sustainable Accessibility Across Settlement Types. A Swedish Case," *Transportation Research Part D: Transport and Environment* 107 (2022): 103297, <https://doi.org/10.1016/j.trd.2022.103297>.
76. S. Maharjan, N. Tilahun, and A. Ermagun, "Spatial Equity of Modal Access Gap to Multiple Destination Types Across Chicago," *Journal of Transport Geography* 104 (2022): 103437, <https://doi.org/10.1016/j.jtrangeo.2022.103437>.
77. W. Yang, B. Y. Chen, X. Cao, T. Li, and P. Li, "The Spatial Characteristics and Influencing Factors of Modal Accessibility Gaps: A Case Study for Guangzhou," *China Journal of Transport Geography* 60 (2017): 21–32, <https://doi.org/10.1016/j.jtrangeo.2017.02.005>.
78. T. F. Welch and S. Mishra, "A Measure of Equity for Public Transit Connectivity," *Journal of Transport Geography* 33 (2013): 29–41, <https://doi.org/10.1016/j.jtrangeo.2013.09.007>.
79. G. A. Cromley, "Measuring Differential Access to Facilities Between Population Groups Using Spatial Lorenz Curves and Related Indices," *Transactions in GIS* 23 (2019): 1332–1351, <https://doi.org/10.1111/tgis.12577>.
80. J. Ding, Y. Zhang, and L. Li, "Accessibility Measure of Bus Transit Networks," *IET Intelligent Transport Systems* 12 (2018): 682–688, <https://doi.org/10.1049/iet-its.2017.0286>.
81. K. Lucas, B. Van Wee, and K. Maat, "A Method to Evaluate Equitable Accessibility: Combining Ethical Theories and Accessibility-Based Approaches," *Transportation* 43 (2016): 473–490, <https://doi.org/10.1007/s11116-015-9585-2>.
82. D. Liu, M.-P. Kwan, J. Huang, Z. Kan, Y. Song, and X. Li, "Analyzing Income-Based Inequality in Transit Nodal Accessibility," *Travel Behaviour and Society* 27 (2022): 57–64, <https://doi.org/10.1016/j.tbs.2021.11.005>.
83. D. Liu, M.-P. Kwan, and Z. Kan, "Analysis of Urban Green Space Accessibility and Distribution Inequity in the City of Chicago," *Urban Forestry & Urban Greening* 59 (2021): 127029, <https://doi.org/10.1016/j.ufug.2021.127029>.
84. L. Anselin, "Local Indicators of Spatial Association—LISA," *Geographical Analysis* 27 (1995): 93–115, <https://doi.org/10.1111/j.1538-4632.1995.tb00338.x>.
85. K. Kim and K. Kwon, "Time-Varying Spatial Accessibility of Primary Healthcare Services Based on Spatiotemporal Variations in Demand, Supply, and Traffic Conditions: A Case Study of Seoul, South Korea," *Journal of Transport & Health* 27 (2022): 101531, <https://doi.org/10.1016/j.jth.2022.101531>.
86. Y. Zhang, X. Fu, Z. Yu, and S. Luo, "How Does Multi-Modal Travel Enhance Tourist Attraction Accessibility? A Refined Two-Step Floating Catchment Area Method Using Multi-Source Data," *Transactions in GIS* 28 (2024): 278–302, <https://doi.org/10.1111/tgis.13136>.

Appendix A: Accessibility of Other Three Urban Services

Figures A1 and A2.

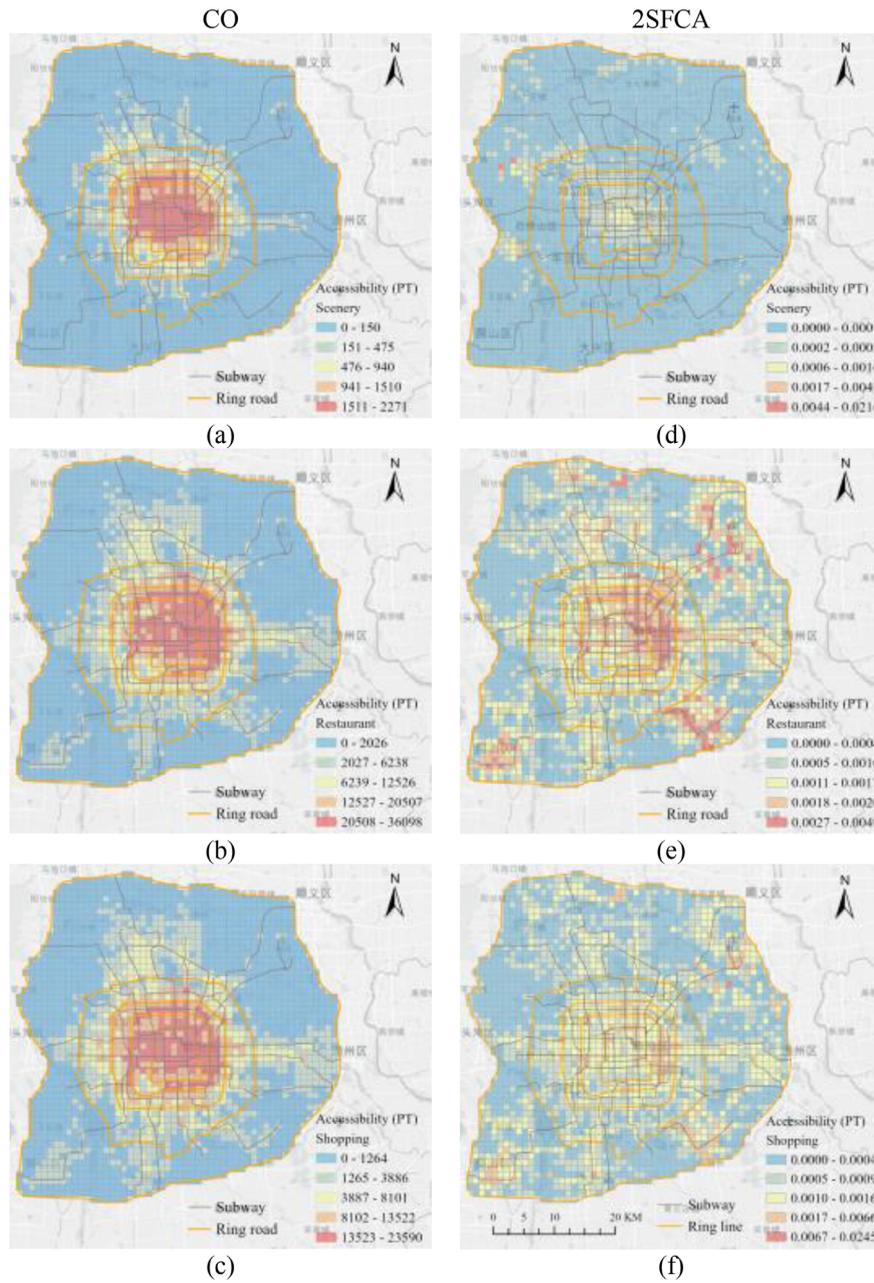


FIGURE A1 | The accessibility to scenery, restaurant, and shopping opportunities by PT (left side from CO and right side from 2SFCA).

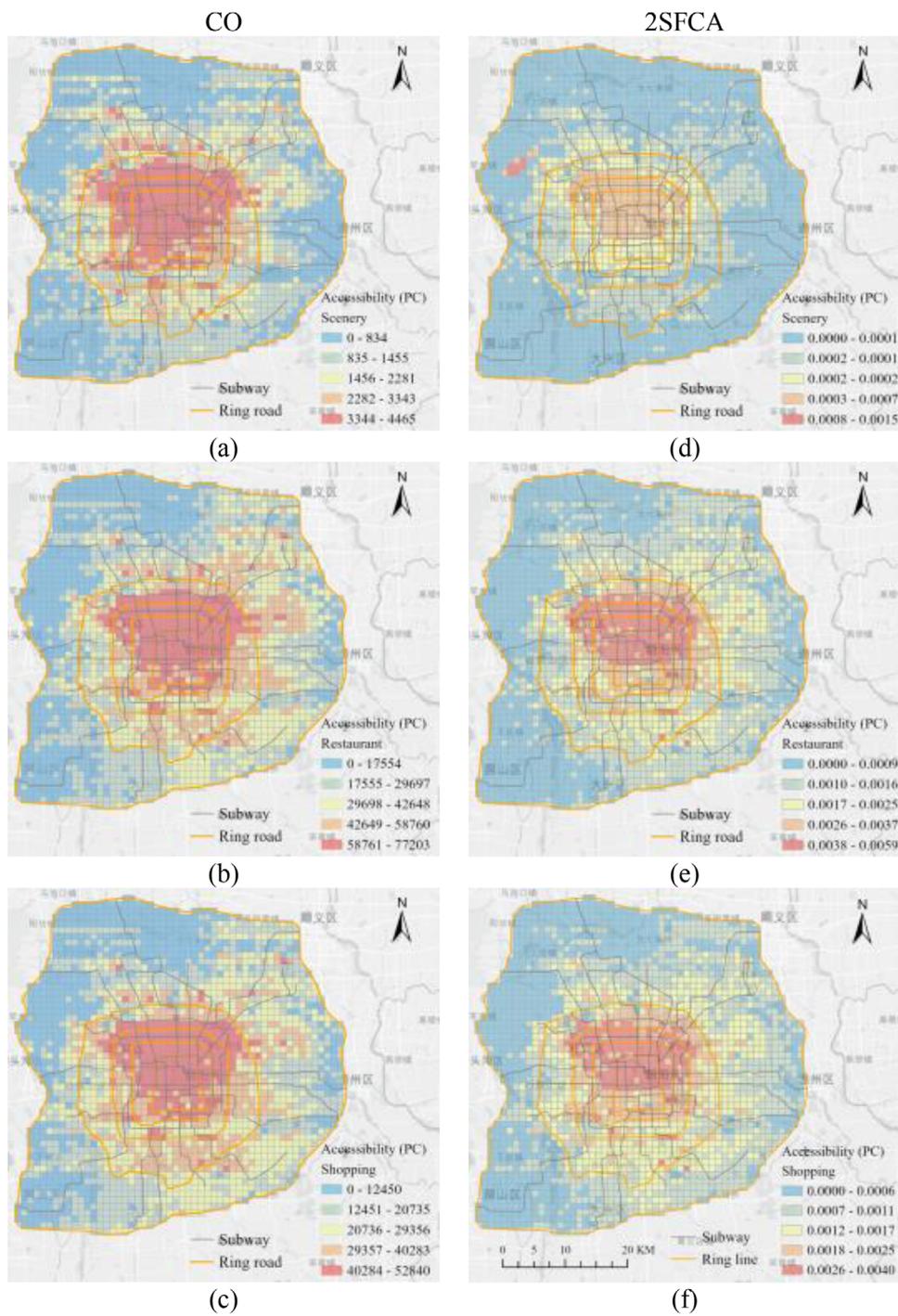


FIGURE A2 | The accessibility to scenery, restaurant, and shopping opportunities by PT (left side from CO and right side from 2SFCA).

Appendix B: MAG of Other Three Urban Services

Figure B1.

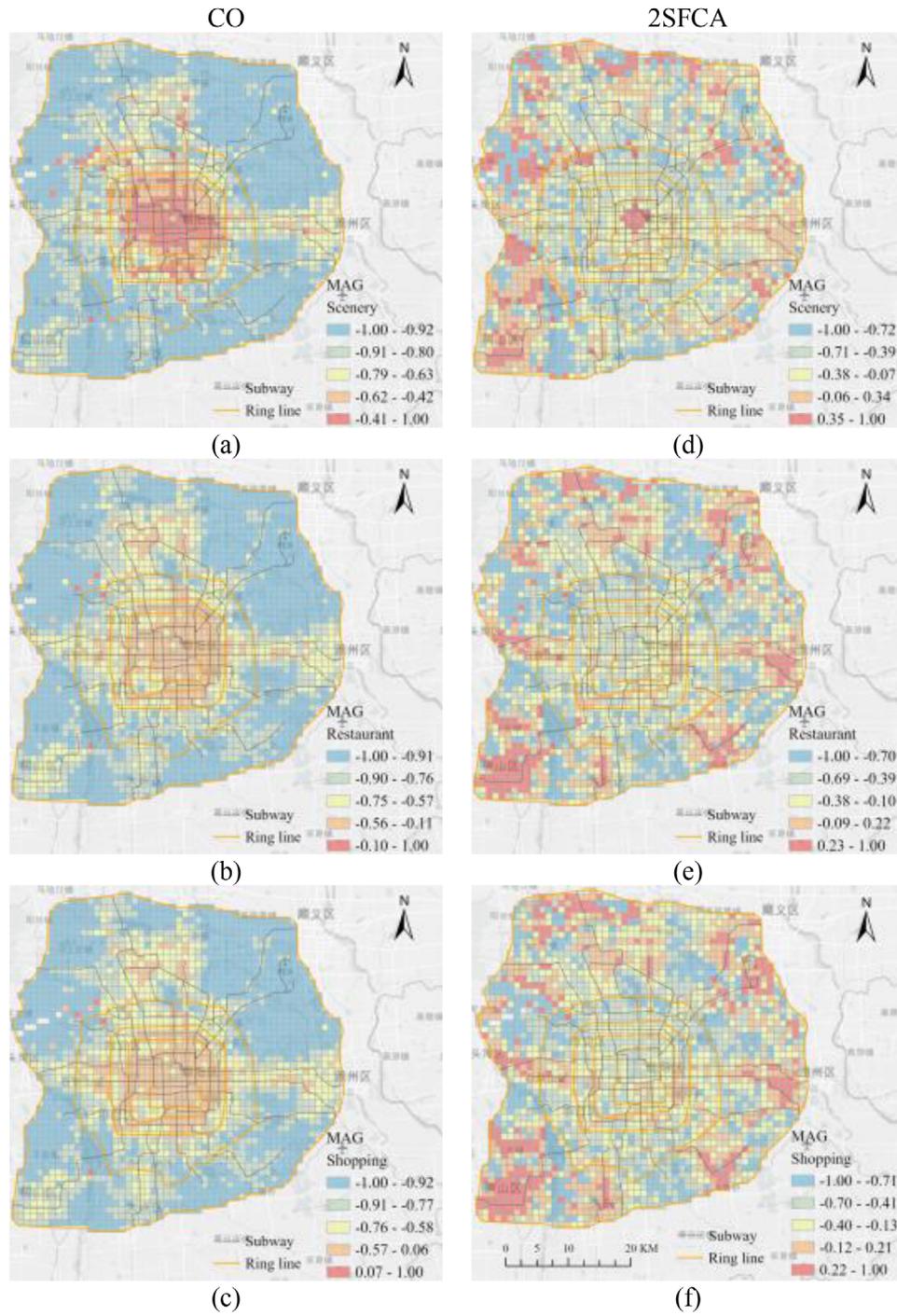


FIGURE B1 | Spatial distributions of MAG of scenery, restaurant, and shopping opportunities (left side from CO and right side from 2SFCA).

**Appendix C: The Global Moran's I of the Accessibility to Different Kinds of Urban Service**

**TABLE C1** | The global Moran's *I* of the accessibility to different kinds of urban service.

Urban service	CO		2SFCA	
	PT	PC	PT	PC
Company	0.92	0.86	0.62	0.88
Education	0.92	0.85	0.51	0.89
Healthcare	0.92	0.86	0.60	0.87
Scenery	0.94	0.86	0.10	0.73
Restaurant	0.92	0.87	0.66	0.88
Shopping	0.92	0.86	0.29	0.87