

Article

Investigating the Impact of Inter-City Patient Mobility on Local Residents' Equity in Access to High-Level Healthcare: A Case Study of Beijing

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Abstract

The equitable allocation of healthcare resources reflects social equity. Previous studies of healthcare accessibility have overlooked the impact of inter-city patient mobility on local residents' and local residents' multi-mode travel choices, distorting accessibility calculation outcomes. Taking the area within Beijing's Sixth Ring Road as an example, this study established a Multi-Mode Accessibility Model for Local Residents (MMALR) to tertiary hospitals, using the proportion of non-local patients to adjust hospital supply capacity and considering the various travel mode shares from residential communities to hospitals to calculate the number of potential patients. We compared the changes in geospatial accessibility under different travel modes and employed the Gini coefficient to evaluate the geospatial equity of accessibility for different regions when using different accessibility methods. The results indicate that the spatial distribution of healthcare accessibility via different methods is similar, and it gradually decreases along subway lines from the urban center to the periphery. We found that the equities in access to high-level healthcare for Dongcheng District, Xicheng District, the area between the Third and Fourth Ring Road, and the area between the Fourth and Fifth Ring Road, display different ranking results across different methods, revealing that an unreasonable analysis framework could mislead the placement decisions for new hospitals or the allocation of medical resources. These findings emphasize the impact of inter-city patient mobility and the diversity of travel mode choices on accessibility. Our model can assist stakeholders in more accurately evaluating the accessibility and equity of local residents in terms of tertiary hospitals, which is crucial for cities with abundant medical resources and superior conditions. Our analytical findings provide a scientific basis for the location decisions of tertiary hospitals.

Keywords: accessibility; tertiary hospitals; multiple modes of transportation; inter-city patient mobility; horizontal equity; geospatial equity; two-step floating catchment area (2SFCA)



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1. Introduction

Against the current background of accelerated social development and sustained economic growth, people's expectations regarding their living standards have increased. People's timely access to necessary medical resources and services can improve their happiness and sense of security, promoting the high-quality development of the living environment [1]. This makes it necessary for decision-makers to allocate medical resources and services in an equal and rational manner. When acquiring precise scientific information on public healthcare services, decision-makers seek to accurately identify areas with

underdeveloped medical resources and rationally allocate medical resources to improve people's health level and meet people's health needs. Relevant public healthcare policies are continually being refined, and a foundational public healthcare service system has been established [2]. However, in reality, there exist certain disparities in medical resources and services among cities of different grades [3,4]. When local residents need high-quality medical resources and services, they usually go to big cities for treatment [5]. The behavior of patients obtaining medical services across administrative or geographical boundaries is called patient mobility [6,7]. Cross-city medical treatment enables patients from cities with poor medical resources to obtain better medical services [8]. In China, high-quality medical resources and services in megacities, such as Beijing, Shanghai, Guangdong, and Shenzhen, as well as in other eastern coastal cities, are more concentrated compared to in other regions [9]. In addition, the Chinese medical policy allows medical institutions to provide services to patients nationwide without geographical restrictions, enabling patients to select their treatment locations based on their individual needs [10]. At the same time, for non-local patients, the Chinese government has been improving relevant policies to facilitate patients' smooth access to interprovincial medical resources so that high-quality medical services can be provided to people nationwide [11]. The Chinese hospital system is a three-tiered hospital structure, with medical institutions divided into tertiary, secondary, and primary levels [12]. Tertiary hospitals provide comprehensive healthcare services across regions, provinces, and cities and nationwide. Tertiary hospitals have a complete and secure medical service system, abundant medical resources, and the highest level of hospital service capacity, meaning they can meet the medical needs of most patients. Similarly, patients are more willing to go to tertiary hospitals for their medical care [13]. However, non-local patients increase the medical burden on their selected hospitals, which leads to the medical resources of local residents being used up, especially the medical resources of tertiary hospitals. Therefore, it is necessary to study the impact of inter-city patient mobility on healthcare accessibility, and it is important to allocate medical resources and services more accurately.

In evaluating the spatial allocation of various resources, accessibility is an important metric for effectively evaluating resource acquisition [14]. The calculation of medical resource accessibility should consider service capacity, the spatial distribution of the population, and travel costs [15]. Therefore, people's travel mode is one of the critical factors affecting accessibility. In practical terms, individuals utilize multiple modes to travel to medical facilities. Under different transportation modes, the distance decay effect of the accessibility of healthcare and the distance threshold also varies greatly [16]. However, numerous studies frequently focus on a single travel mode when defining how individuals travel to healthcare facilities [14,17–19]. When calculating accessibility, significant deviations can arise when using a single travel mode, so it is more precise to evaluate accessibility to medical resources under multiple travel modes [16,20,21]. Additionally, when people travel, travel distance is a primary factor affecting the selection of travel modes, which leads to variations in the population proportion across each travel mode [22–24]. Currently, few studies comprehensively account for the service scope of various travel modes and the proportion of the population using various travel modes over different travel distances when calculating the accessibility of medical resources.

The aim of this study was to establish a computational model for the accessibility of medical resources for local residents considering inter-city patient mobility under a multi-mode scenario. This model calculates the accessibility of healthcare for local residents and further examines the equity for different regions. Compared with previous research, this study mainly addresses three problems: (1) It constructed a calculation model for the multi-mode accessibility of tertiary hospitals for local residents (MMALR), considering that non-local residents utilize the service capacity of tertiary hospitals. (2) Taking Beijing as a case, this study

analyzed the spatial distribution of medical resources and service accessibility based on this model. (3) It compared the spatial variations in healthcare accessibility for local residents and the changes in the equity of medical resources and service distribution under the multi-mode scenario or the single-mode scenario (taking public transit and private cars as examples) to identify the area with poor access to healthcare. The primary contributions of this paper are as follows: First, when calculating the accessibility of healthcare, considering the occupation of medical resources and services by non-local patients, the accuracy of the service capacity of tertiary hospitals is improved. Second, this study established a novel calculation model of accessibility utilizing the multiple travel modes' shares of different travel distance intervals, filling the gap left by previous research. Third, the different equity rankings displayed by different methods reveal that an unreasonable analysis framework could mislead placement decisions regarding new hospitals or the allocation of medical resources. Finally, according to the spatial distribution of healthcare accessibility, this study identified positions lacking medical resources and services and evaluated the equity of resource allocation, which provides valuable insights for decision-makers in future planning.

The rest of this paper is structured as follows: Section 2 reviews the literature on the evaluation of inter-city patient mobility, healthcare accessibility under multiple travel modes, and the improvement process of the two-step floating catchment area (2SFCA) method. Section 3 presents the data. Section 4 introduces the calculational method. Section 5 describes the result of MMALR and then presents a comparative analysis of accessibility under multi-mode or single-mode conditions. Section 6 offers further discussion. Section 7 concludes this study.

2. Literature Review

2.1. Inter-City Patient Mobility

Inter-city patient mobility often occurs in countries with multiple administrative regions. In China, this behavior usually refers to insured individuals seeking medical treatment in cities that are inconsistent with their insured areas [25]. The analysis of the impact of inter-city patient mobility can effectively enhance regional medical service levels and facilitate the management authorities in proposing reasonable solutions to address existing problems in medical resource and service allocation [26]. In previous studies, scholars have discussed and categorized the characteristics of patient mobility in different provinces, regions, and states to define patient mobility patterns. These methods can identify regions poor healthcare in order to rationally allocate regional medical resources and services [26]. The inter-city flow of patients facilitates the equitable allocation of high-quality medical resources and services [6,27,28]. Most residents seek medical treatment in other cities to access higher-quality and more specialized healthcare for severe conditions, such as rare diseases and brain tumors [29]. Multiple studies have discussed the factors influencing these non-local patients' access to medical resources and services, such as age, social security, and inter-city transportation [28,30–32]. Cities with abundant medical resources tend to have a larger number of inter-city patients [28]. Existing studies have discussed the impact of inter-city patients on the sufficiency of local healthcare provision for local residents [33]. However, when calculating healthcare accessibility for local residents, most previous studies have overlooked or underestimated the impact of inter-city patients on the results. Non-local patients comprise a collection of individuals with various diseases who occupy medical resources and services intended for local residents [34]. Due to the insufficient consideration of inter-city patient mobility, the spatial disparity in local residents' access to medical resources and services is inaccurately reflected, which undermines the reliability of evaluating the impact of various factors on people's access to resources. Limited research has examined the impact of non-local patients on local residents in cities with high-quality medical resources and services.

2.2. Accessibility Model

Accessibility refers to the ease of reaching one location from another [35] and is mainly influenced by four factors: the transportation system, land use, time conditions, and individual characteristics [36]. In assessing the spatial allocation of various resources, accessibility is an important metric for evaluating resource acquisition [14,37]. For example, evaluating transportation systems' performance, appraising access to job opportunities and healthcare facilities, and investigating social equity and segregation are important aspects of this assessment [37–39]. Healthcare accessibility is often utilized as an evaluation metric to evaluate the ease of accessing healthcare, thereby identifying regions with healthcare shortages [40]. The healthcare accessibility explored in this study reflects the spatial access to resources for demand points. In order to achieve more accurate and realistic accessibility results, numerous scholars have built upon the concept of accessibility proposed by Hansen [41], refining the methods of evaluating accessibility. The ratio method, the shortest distance method, the potential model, the Huff model, the two-step floating catchment area method (2SFCA), the kernel density method, and the spatial expansion model are common methods to calculate accessibility [41–48]. Among these methods, the 2SFCA method is frequently applied to healthcare accessibility research [49]. The 2SFCA method determines accessibility through a two-step search of supply and demand points within the study area, considering the quantity and scale of supply and demand populations and defining a finite search threshold [50]. This approach accurately evaluates the impact of spatial and non-spatial factors on regions with healthcare shortages [51]. However, the traditional 2SFCA method employs binary division to address distance attenuation [52], overlooking the issue that increased distance reduces people's willingness in actual situations. Considering this problem, numerous scholars have extended the traditional 2SFCA method according to spatial distance. For instance, the enhanced 2SFCA (E2SFCA) method introduces a distance decay function with segmented processing; the gravity-based 2SFCA (G2SFCA) utilizes the distance decay function of the gravity model, showing a fast-then-slow rate of accessibility decay; the kernel density-based 2SFCA (KD2SFCA) incorporates a distance decay function modeled by the kernel density function, showing a slow-then-fast rate of accessibility decay; the Gaussian 2SFCA (Ga2SFCA) applies a Gaussian function as the 2SFCA distance decay function, where the accessibility decay rate shifts from slow to fast then to slow again with increasing distance or time [52]. Non-spatial factors also have an impact on accessibility. Scholars have proposed improved models such as the three-step floating catchment area (3SFCA) method, which considers the influence of resource competition and sharing on distance attenuation [53]; the hierarchical two-step floating catchment area (H2SFCA) method, which considers the impact of hierarchical differences on accessibility, such as the different service scope of hospitals at different levels or different cities [5,54]; and the enhanced three-step floating catchment area (E3SFCA) method, which incorporates the impact of travel costs into the calculation of healthcare accessibility [55]. Among these models, the attenuation speed simulated by the Ga2SFCA method is closer to actual travel patterns, and it thus is often employed as a methodology to calculate healthcare accessibility [56,57]. Therefore, this study used the Ga2SFCA method to calculate the accessibility of healthcare for local residents considering non-local patients and to analyze the changes in the healthcare accessibility for local residents.

2.3. Travel Modes

Previous researchers studying accessibility have defined the travel mode as single-mode or multi-modal [17,58]. However, considering only one travel mode does not conform to the actual travel situation, and the choice of travel modes by residents is diverse. The maximum achievable range, the resistance encountered on the road, and the travel costs

of each travel mode are different [59–61]. People select different travel modes based on road congestion conditions [62], the physical distance between the origin and the destination [63,64], socio-economic characteristics such as gender, age, level of education and level of income [62], and the characteristics of the actual road network such as road network disruptions [65] and the street network connectivity [66]. In daily life, common modes of transportation include public transit, private cars, taxis, walking, and biking [67]. When using the Ga2SFCA method to calculate accessibility, the distance decay function and the catchment service radii differ across various travel modes [63]. Travel time can better reflect the influence of various spatial and non-spatial factors such as road congestion, economic status, and age on people's access to resources [15]. Therefore, this study calculated the attenuation function of healthcare accessibility using travel time. We compiled various travel modes of people traveling to hospital in previous studies, as detailed in Table 1. Scholars have integrated multiple travel modes when calculating accessibility and calculated the attenuation function using the population proportion of each travel mode [21]. Existing research shows that the share of travel modes varies over different distances [68]. However, when existing studies discuss healthcare accessibility, they employ a uniform mode share across different travel distances for the entire population, ignoring the differences in the share of travel modes across different distance intervals. When calculating accessibility, this study considered the changes in the population proportion of each travel mode under different distance intervals.

Table 1. Summary of the healthcare accessibility calculation model.

Type	Travel Mode	Authors	Study Area	Method	Functions	Threshold	Destination
Single-mode	Public transit	Z. W [17]	Beijing, China	Ga2SFCA	Gaussian	90 min	Tertiary hospital
		P. Zhao [3]	Beijing, China	E2SFCA	Gaussian	82.9 min	All public hospitals
		D. Liu [69]	Chicago	2SFCA	Distance decay	50 min	hospital
		G. Boisjoly [70]	Canada	2SFCA	none	45 min	hospital
	private cars	T. Dai [71]	Beijing, China	2SFCA	Distance decay	30 min	County level hospitals
		L. Dong [72]	Beijing, China	Cumulative opportunity measures	none	30 min	All public hospitals
		Y. Xia [73]	Wuhan, China	Ga2SFCA	Gaussian	30 min	All hospital
		L. Ma [74]	Wuhan, China	3SFCA	Gaussian	30 min	Tertiary, secondary hospitals
		Z. L. Tao [54]	Shenzhen, China	H2SFCA	Gaussian	70 min	Tertiary hospital
						40 min	secondary hospitals
	Taxi	C. Jing [75]	Beijing, China	2SFCA	exponential function	28.4 km	Tertiary hospital
		W. Jiao [18]	Shanghai, China	Ga2SFCA	Gaussian	22.3 min	All public hospitals
		B. Y. Chen [76]	Shanghai, China	2SFCA	CDF	20 min	Tertiary, secondary hospitals
	Walking	L. Xing [77]	Guangzhou, China	Ga2SFCA	Gaussian	15 min	All hospital
	Biking	Z. L. Tao [54]	Shenzhen, China	H2SFCA	Gaussian	25 min	primary facilities

Table 1. Cont.

Type	Travel Mode	Authors	Study Area	Method	Functions	Threshold	Destination
Multi-modal	Public transit private cars	X. Ma [78]	Wuhan, China	3SFCA	Gaussian	120 min 45 min	All public hospitals
	Public transit private cars	J. Xing [55]	Changsha, China	E3SFCA	Gaussian	240 min 120 min	Tertiary hospital
	Public transit private cars	T. H. Jin [79]	Shanghai, China	G2SFCA	Gaussian	103 min 34 min	Tertiary hospital
	Public transit private cars	X. Zhou [80]	Nanjing, China	G2SFCA	Gaussian	100 km	Pediatric Clinic
	Walking					120 km	
	Biking					60 km	
						80 km	
	Public transit private cars	X. Du [81]	Shenyang, China	2SFCA	None	60 min 30 min	Tertiary hospitals
	Walking					15 min	
	Public transit private cars	J. Wu [16]	Guangzhou, China	3SFCA	Gaussian	120 min 120 min	All hospitals
	Walking					30 min	
	Biking					30 min	
	Public transit private cars	L. Mao [21]	Florida, USA	2SFCA	none	30 min	hospital

In summary, inter-city patient mobility affects healthcare accessibility for local residents. Current studies have also addressed healthcare accessibility for non-local patients. However, limited studies have discussed the impact of the competition from non-local patients for medical resources and services on healthcare accessibility for local residents. In addition, after the improvement of the original accessibility calculation methods, a variety of methods for the calculation of accessibility have been extended. Ga2SFCA is often employed as a calculation method when investigating healthcare accessibility. Although Ga2SFCA considers the impact of travel time on accessibility, different travel modes have different travel time thresholds. Moreover, the population percentages utilizing each travel mode are variable across different travel distances. Few studies have comprehensively addressed these issues. This paper proposes a calculational model considering non-local patients and multiple travel modes to measure the healthcare accessibility for local residents.

3. Study Area and Data Source

3.1. Study Area

As the capital of China, Beijing is one of the cities with the highest-quality medical resources and services nationwide, attracting a large number of non-local patients [72–74]. Therefore, it is of great significance to investigate the impact of non-local patients on local residents in Beijing. This study selected the area within Beijing's Second Ring Road and Sixth Ring Road as the research area. Administrative boundaries and POI (point of interest) data were obtained from the Amap API (<https://lbs.amap.com/> (accessed on 15 May 2024)), and road networks were obtained from Open Street Map (<https://www.openstreetmap.org/> (accessed on 15 May 2024)). The study area is shown in Figure 1. The area within the Sixth Ring Road constitutes Beijing's core urban area, including seven administrative areas: Dongcheng District, Xicheng District, Fengtai District, Daxing District, Chaoyang District, Haidian District, and Shijingshan District. In this area, there are 13,109

valid residential community data points and 82 tertiary hospitals, accounting for 84% of the total number of hospitals citywide.

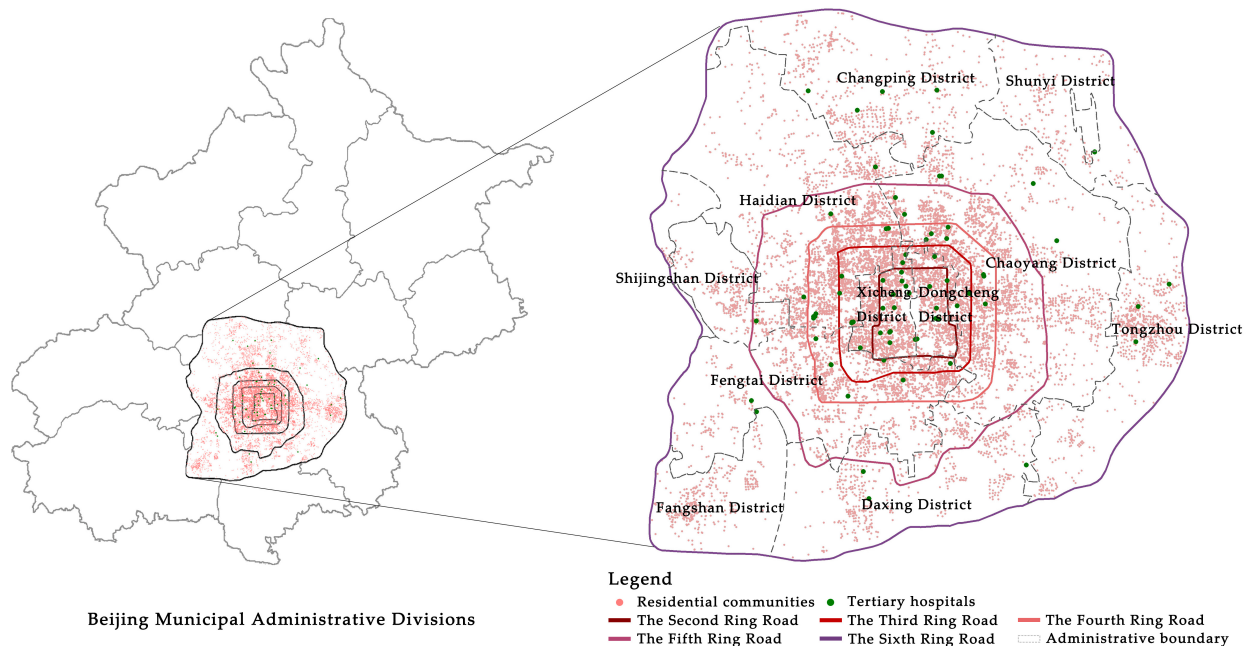


Figure 1. Study area.

3.2. Data Source

3.2.1. Hospital Data

Most scholars commonly utilize the number of hospital beds or the number of healthcare workers to measure the supply capacity of hospitals. In previous studies, we compared the healthcare accessibility of tertiary hospitals for Beijing local residents using the number of beds as the supply capacity and the number of healthcare workers as the supply capacity and found that the two accessibility outcomes had a high correlation [17]. In this study, the number of healthcare workers was used as the supply capacity of hospitals. The data on the percentage of non-local patients in Beijing's tertiary hospitals were derived from <https://mp.weixin.qq.com/s/8QO99rK-sY3xW7lRv6qpBA> (accessed on 15 May 2024).

3.2.2. Residential Community Data

The residential community's data were sourced from Anjuke platform (https://sjz.anjuke.com/?from=AJK_Web_City&from=AJK_Web_City (accessed on 15 May 2024)). This study utilized population data at the scale of residential communities. Because residential communities have local resident check-in records, the local resident data is more detailed and accurate [17].

3.2.3. Travel Cost and Travel Modes Share

This study retrieved the recommended route and travel time between origin and destination (OD) pairs for various travel modes during weekday mornings from Amap API (<https://lbs.amap.com> (accessed on 15–25 May 2024)), with the residential community centers as origins and the hospital centers as destinations. The travel modes of residents to hospitals mainly included public transit (PT), private cars (PC), taxis, walking, and biking. The share of travel modes varied across different distances. We derived the share of five travel modes from the article “Analysis of Travel Structure in Beijing from the Perspective of Big Data” (https://mp.weixin.qq.com/s/G2z-Ci_DgMNi1nhXu3Dlog (accessed on 15 May 2024)). The sorted shares of various travel modes within distinct travel distance intervals are presented in Table 2.

Table 2. The share of travel modes within distinct travel distance intervals.

Distance (m)	Travel Mode			
	PT	Private Cars	Walking and Biking	Taxi
[0, 1000]	2%	2%	96%	0%
(1000, 3000]	4%	6%	90%	0%
(3000, 5000]	30%	26%	40%	4%
(5000, 10,000]	40%	50%	5%	5%
(10,000, 15,000]	47%	45%	2%	6%
(15,000, 20,000]	50%	43%	1%	6%
(20,000, 25,000]	51%	42%	0%	7%
(25,000, 30,000]	49%	44%	0%	7%
(30,000, 35,000]	45%	47%	0%	8%
(35,000, 40,000]	42%	50%	0%	8%
(40,000, 45,000]	35%	57%	0%	8%
(45,000, 50,000]	32%	60%	0%	8%
(50,000, +∞)	22%	68%	0%	10%

4. Methodology

4.1. Research Framework

In this paper, we propose a novel accessibility computing model. In the multiple travel mode scenario, this model employs the Ga2SFCA method to calculate the accessibility of tertiary hospitals for local residents considering the competition from non-local patients. As illustrated in Figure 2, the accessibility calculation in this study was divided into two phases. In Phase 1, this study calculated the actual number of healthcare workers who can provide services for local residents based on the proportion of non-local patient in Beijing's tertiary hospitals to adjust the supply capacity. We then calculated the travel impedance between the residential communities and the hospitals based on the travel time of the five travel modes (public transit, private cars, taxis, biking, and walking) and their respective time thresholds. We used the shares of multiple travel modes across different travel distances to calculate the number of people using different travel modes in each residential community. In Phase 2, this study calculated the supply–demand ratios of each tertiary hospital using three key inputs: the adjusted number of healthcare workers, the travel impedance of various travel modes, and the number of local residents in residential communities using a specific travel mode. MMALR was calculated, and for the detailed calculation process, please refer to Equations (1)–(5) in Section 4.2. In addition, this study calculated the accessibility of tertiary hospitals for Beijing local residents traveling by private car (PCALR) and public transit (PTALR) without considering non-local patients, and then compared the spatial distribution of hospital accessibility between the single-mode and multi-mode scenarios. We calculated the Gini coefficient of administrative districts and ring road areas in Beijing to evaluate the equity of local residents' healthcare.

4.2. Calculation of MMALR

In the first step, under the multiple travel mode scenario, the number of healthcare workers in the tertiary hospital was adjusted based on the proportion of non-local patients across various tertiary hospitals. Subsequently, the residential communities' potential demand for hospitals was derived by assigning weights to residential communities using a Gaussian impedance function and the travel mode share for each distance interval (Table 2).

Compared with travel distance, travel time more accurately reflects real-world traffic conditions. According to previous studies, the time threshold of healthcare accessibility for tertiary hospitals in Beijing was 5400 s [82,83]. According to previous studies, this study defined the time threshold for reaching tertiary hospitals under different travel modes as follows: public transit, 5400 s [17]; private cars, 1800 s [81]; taxis, 1800 s [73]; biking, 1800 s [16]; and walking, 900 s [81].

All residential communities were searched within the time threshold (t_0) for each hospital location j . The adjusted supply-to-demand (healthcare workers-to-local patients) ratio in the catchment area was calculated using Equation (2):

$$S'_j = (1 - P_j)S_j \quad (1)$$

$$R_j = \frac{S'_j}{\sum_m \sum_{k \in \{t_{kj}^m \leq t_0^m\}} W_{kj}^m P_k \beta_{kj}^m} \quad (2)$$

$$\sum_m \beta_{kj}^m = 100\% \quad (3)$$

where S'_j is the supply capacity (number of healthcare workers) of tertiary hospitals j ; S_j is the uncorrected supply capacity of tertiary hospitals; P_j is the proportion of non-local patients in tertiary hospital j ; R_j is the adjusted supply-to-demand ratio of tertiary hospital j ; P_k is the total population in residential community k ; t_{kj}^m is the travel time from residential community k to tertiary hospital j under travel mode m ; t_0^m is the time threshold of the travel mode m ; β_{kj}^m is the share of travel mode m under the travel distance from residential community k to hospital j ; and W_{kj}^m is the distance decay function calculated by the Gaussian equation from residential community k to hospital j under travel mode m , as shown in Equation (4):

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

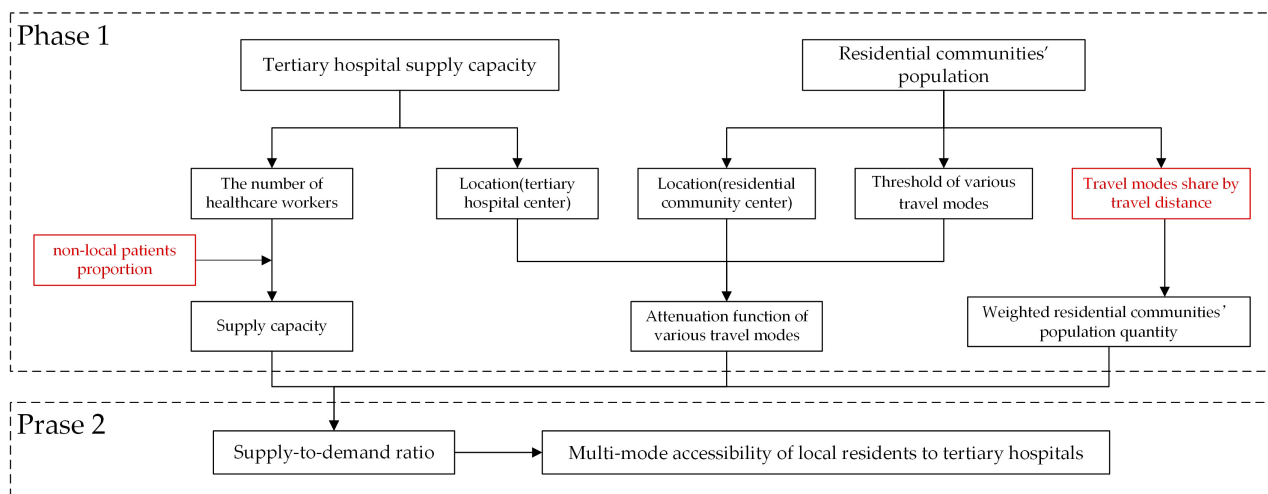


Figure 2. Calculation flowchart of MMALR.

In the second step, all hospital locations were searched within the time threshold t_0^m for each residential community l across the travel mode m . Subsequently, the supply-to-demand ratios R_j of all hospitals in the range were weighed using Gaussian functions and summed to calculate the MMALR, as shown in Equation (5):

$$A_i = \sum_m \sum_{l \in (t_{li}^m \leq t_0^m)} W_{li}^m R_l \beta_{li}^m \quad (5)$$

where A_i is the MMALR of the residential community i , with the unit being the number of healthcare workers per 1000 people; t_{li}^m is the travel time from residential community i to tertiary hospital l under travel mode m ; and W_{li}^m is the distance decay function calculated by the Gaussian equation from residential community i to hospital l under travel mode m .

Figure 3 demonstrates the healthcare accessibility calculation process using a case of 3 tertiary hospitals and 9 residential communities.

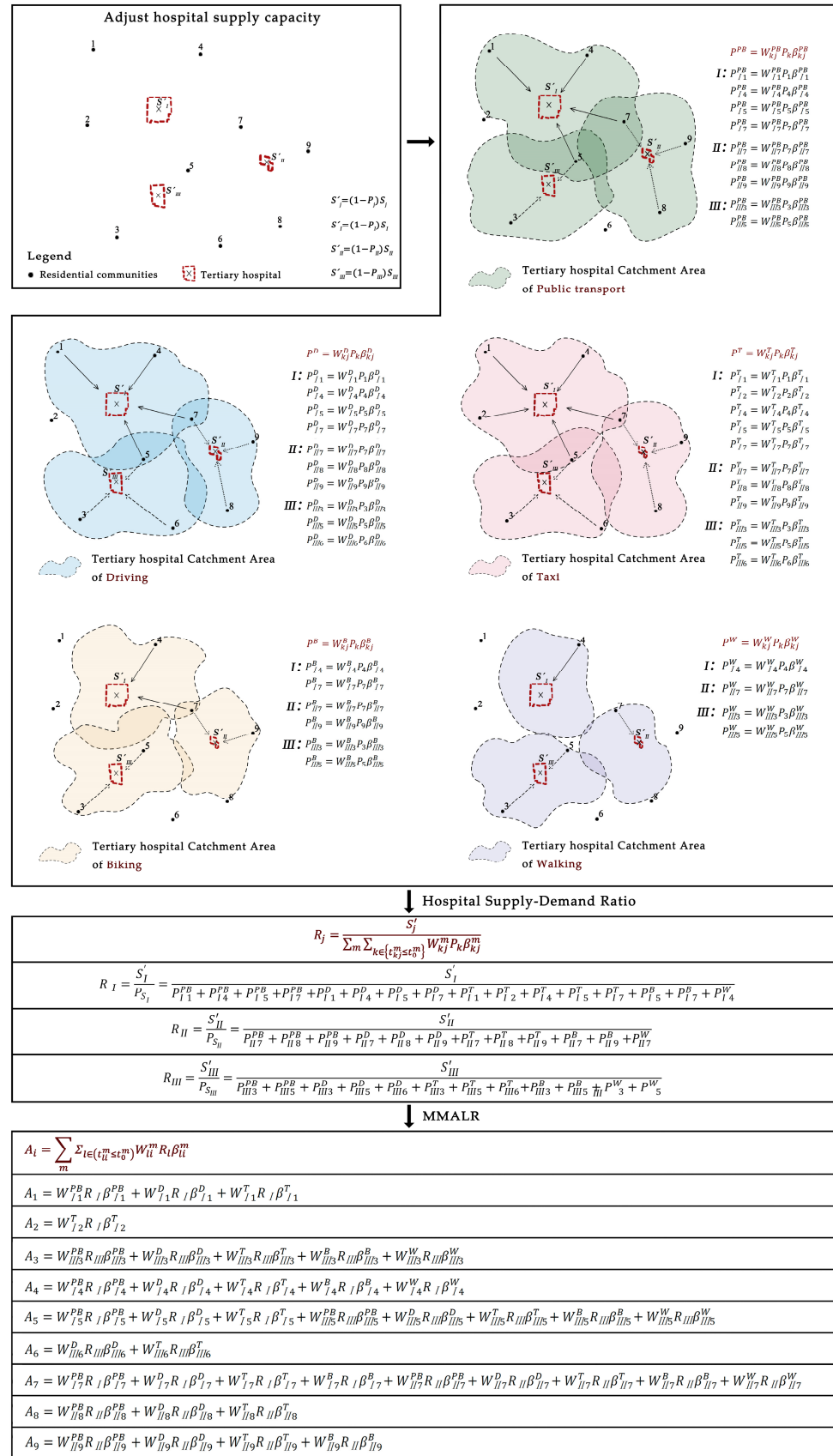


Figure 3. Sketch map and calculation process of MMALR.

4.3. Gini Coefficient

Equity includes horizontal equity and vertical equity. Horizontal equity focuses on regional disparities in access to services, while vertical equity focuses on identifying disparities among different population groups [79,84]. This research focused on comparing the equity in access to tertiary hospitals according to different administrative districts and different zones between ring roads, namely horizontal equity. The Gini coefficient is often employed to evaluate horizontal equity [76,85,86]. The Gini coefficient can accurately quantifies regional inequality [87]. The value range of the Gini coefficient is (0,1) and lower Gini values indicate more equitable spatial distribution of resources. In this study, the Gini coefficient was employed to evaluate the equity across each administrative district and zones between ring roads, and the calculation formula is as follows:

$$G = 1 - \sum_{i=0}^{n-1} p_{i+1} - p_i \left(S_{i+1}^A + S_i^A \right) \quad (6)$$

where G is the Gini coefficient of the accessibility of tertiary hospitals adjusted for the number of healthcare workers; P_i is the proportion of the total number of residential communities from 1 to i to the total number of all residential communities; P_{i+1} is the proportion of the total number of residential communities from 1 to $i + 1$ to the total number of all residential communities; S_i^A is the proportion of the cumulative accessibility value in 1~ i residential communities to the total accessibility calculated; and S_{i+1}^A is the proportion of the cumulative accessibility value in 1~ $i + 1$ residential communities to the total accessibility.

5. Results

5.1. MMALR Results

Figure 4 illustrates the accessibility distribution of tertiary hospitals in Beijing under the accessibility calculation model proposed in this paper. This study calculated the accessibility considering inter-city patient mobility under the combination of the public transit, private car, taxi, biking, and walking modes. In order to more clearly show the outcomes of MMALR, the accessibility values are divided into five grades using the quantile method: the values in the first 20% are defined as being at the lowest level, those at 20% to 40% are defined as moderately low values, those at 40% to 60% are defined as medium-level values, those at 60% to 80% are defined as being at a moderately high level, and the final 20% are defined as being at the highest level. It is evident that disparities exist in spatial accessibility in the study area. Overall, across the multi-mode scenario, the accessibility decreases from the urban core to the periphery. Specifically, the MMALR within the Third Ring Road is optimal, and the highest and higher levels of accessibility are concentrated in this area. Accessibility gradually decreases with the increase in spatial distance from the city center. The accessibility between the Fifth Ring Road and the Sixth Ring Road is generally low, and the lowest and lower levels of accessibility are concentrated in this area. Further analysis reveals that in the area between the Fifth Ring Road and the Sixth Ring Road, the accessibility of tertiary hospitals in the eastern, western, northern, and southern regions is higher than that in other locations. High accessibility is distributed in most of the residential communities within the Fourth Ring Road and those on both sides of the metro lines outside the Fourth Ring Road. Therefore, the local residents located closer to the city center generally experience greater access to tertiary hospitals and can more easily obtain healthcare resources. In addition, the time impedance of residential communities along subway lines is low, and the healthcare accessibility for residential communities along subway lines is relatively higher than for other areas. However, due to the distance from

hospitals and limited subway line coverage, the healthcare accessibility in marginal areas is low.

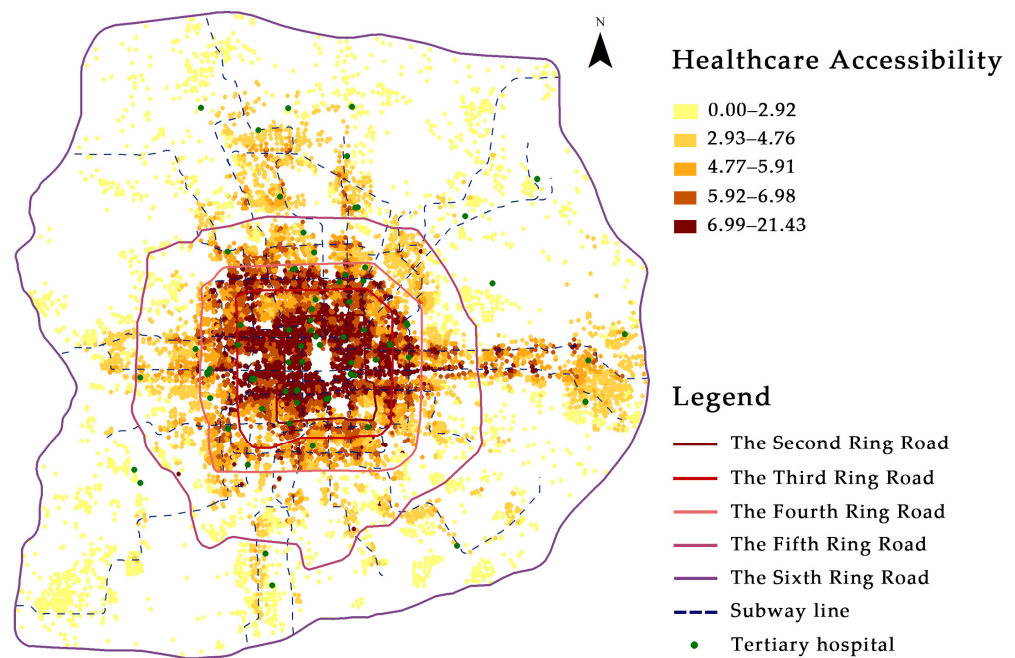


Figure 4. MMALR distribution.

5.2. MMALR vs. PTALR or PCALR

It is worth noting that, in previous accessibility studies using a single mode to analyze the accessibility of high-grade hospitals (see Table 1), public transit and private cars were commonly used as the travel mode. This study compares MMALR with PTALR and PCALR to explore the accessibility changes for the public transit mode and the private car mode. As illustrated in Table 3, comparing the values of Q1 (20% quantile), Q2 (40% quantile), Q3 (the median), Q4 (60% quantile), and Q5 (80% quantile), we find that the outcomes for the multi-mode scenario and the public transit mode are similar. However, the five quantile values of multi-mode accessibility are slightly higher than those derived from public transit. Meanwhile, the accessibility outcome for the private car mode is significantly different from those for the other two modes. The Q1 (20% quantile), Q2 (40% quantile), and Q3 (median) values for private car accessibility are all lower than those for the multi-mode scenario and public transit. However, the Q4 (60% quantile) and Q5 (80% quantile) values for private car accessibility are higher than the corresponding values for the multi-mode scenario and public transit. The large disparity between the highest and lowest accessibility values indicates that the accessibility distribution of private cars is very discrete. The PCALR method tends to underestimate the accessibility of residential communities with low accessibility levels and overestimate the accessibility of residential communities with high accessibility levels. The reason why the multi-mode accessibility is slightly higher than that of public transit may be that local residents have additional options to access tertiary hospitals, and the time threshold t_0 for private cars is greater than those for other modes. The supply-to-demand ratio of tertiary hospitals for private cars decreases more slowly than that for public transit according to travel time, which can increase healthcare accessibility for residential communities. Another reason for this is that residents with private cars can easily access all tertiary hospitals within the time threshold, offering them flexibility and more choices. However, as not all residents have private cars, using private cars to calculate accessibility produces overestimations.

Table 3. Statistics for hospital accessibility under multi-mode and single-mode scenarios.

Travel Mode	Q1	Q2	Q3	Q4	Q5
Multi-mode	2.92	4.76	5.38	5.91	6.98
Public transit	2.63	4.42	4.98	5.51	6.63
Private cars	1.95	3.66	4.91	6.27	10.03

Notes: Q1, Q2, Q3, Q4, and Q5 represent the 20% quantile, the 40% quantile, the median, the 60% quantile and the 80% quantile, respectively.

Figure 5 illustrates the PTMLA distribution results and Figure 6 illustrates the PCMLA distribution results for Beijing. It is evident that there are discrepancies in the outcomes when comparing the three modes. Overall, all three modes show a decreasing trend from the urban center to the periphery. MMALR and PTALR have a similar spatial distribution of accessibility. The highest-accessibility areas are mainly distributed within the Fourth Ring Road. Areas with accessibility above the median are distributed along the subway line from the urban center to the periphery, while the lowest-accessibility areas are concentrated between the Fourth Ring Road and Sixth Ring Road in areas that are not adjacent to subway lines. Within the Fourth Ring Road, the accessibility of the eastern region is higher than that of other areas when considering the public transit mode, whereas the accessibility of the western region is higher than that of other areas when considering the multi-mode scenario. Comparing the two modes, more regions have a higher accessibility value outside the Fourth Ring Road when considering the public transit mode. This phenomenon may be attributed to these local residents living near bus stops, which can reduce the travel time to tertiary hospitals and subway stations. The eastern areas within Beijing's Fourth Ring Road have a greater density of bus stops and areas within the Sixth Ring Road have public transit lines, meaning that these areas have higher accessibility in the public transit mode. In the private car mode, Figure 6 shows that the accessibility of the northeast area within the Sixth Ring Road is higher than that of the southwest area, and the highest-accessibility area displays a clustered distribution pattern, while the lowest-accessibility area in the eastern area within the Fourth Ring Road also displays a clustered distribution. The reasons for these phenomena are various. On the one hand, they are related to the distribution of tertiary hospitals in Beijing. The number of tertiary hospitals in Beijing gradually decreases from the urban core within the Inner Ring Road to the surrounding suburbs, which makes it easier for local residents living within the Inner Ring Road to access healthcare. In addition, the lower number of tertiary hospitals in the suburbs forces local residents to enter the Inner Ring Road to access healthcare. However, the distance between suburbs and the Inner Ring Road correlates with longer travel times, thereby reducing overall accessibility.

In order to more clearly study the accessibility changes displayed by tertiary hospitals under different modes, we calculated the variation rates for each residential community under multi-mode and single-mode conditions, subsequently comparing the accessibility changes in different areas. This method addresses previous research limitations. The formula is as follows:

$$\Delta A_i^{PT} = \frac{A_i^{PT} - A_i}{A_i} \times 100\% \quad (7)$$

$$\Delta A_i^{PC} = \frac{A_i^{PC} - A_i}{A_i} \times 100\% \quad (8)$$

where A_i^{PT} is the PTALR of the residential community i ; A_i^{PC} is the PCALR of the residential community i ; ΔA_i^{PT} is the percentage change in the PTALR of tertiary hospitals; and ΔA_i^{PC} is the percentage change in the PCALR of tertiary hospitals.

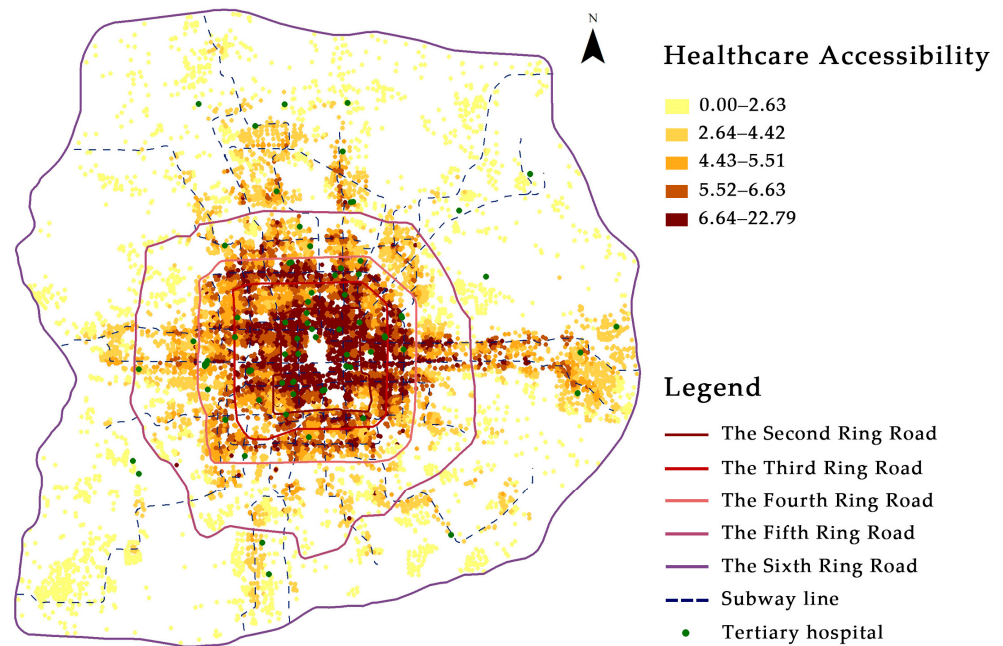


Figure 5. PTMLA distribution.

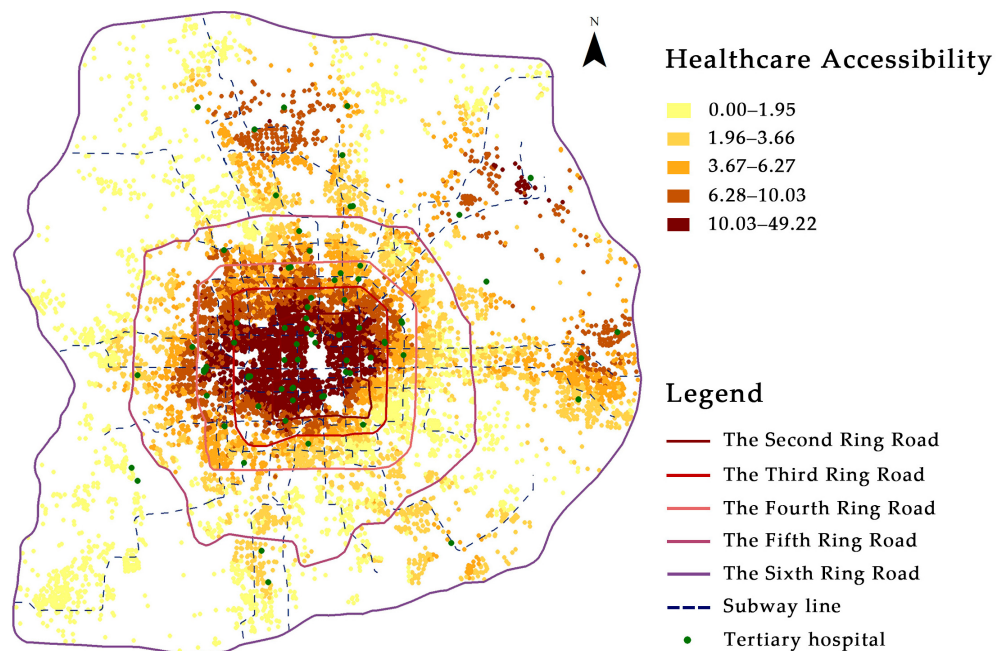


Figure 6. PCMLA distribution.

Figure 7 illustrates the percentage change in the PTMLA relative to MMALR. For the public transit mode, the accessibility of most areas is underestimated. However, over-estimation occurs in the southeast area within the Fifth Ring Road and in the northern, eastern, and southwestern corners between the Fifth Ring Road and the Sixth Ring Road, showing changes in the accessibility for public transit in a blocky distribution. It can be concluded that public transit exhibits relatively small accessibility deviation overall. Public transit provides extensive service coverage and serves more residential communities. These phenomena may be associated with people's travel habits. Public transit stops in Beijing are evenly distributed and abundant. Especially when the travel distance exceeds 10,000 m, a significant proportion of the population preferentially reach tertiary hospitals via public

transit (see Table 2), so the deviation is relatively small. However, the overall underestimation may be attributed to several factors, including the poor service quality of public transit, the low travel speeds, and the increased travel time costs caused by excessive bus transfers. When the travel time exceeds the bus time threshold, the potential accessibility from residential communities to tertiary hospitals drops to zero. This analytical approach that only uses the public transit mode may underestimate the potential accessibility.

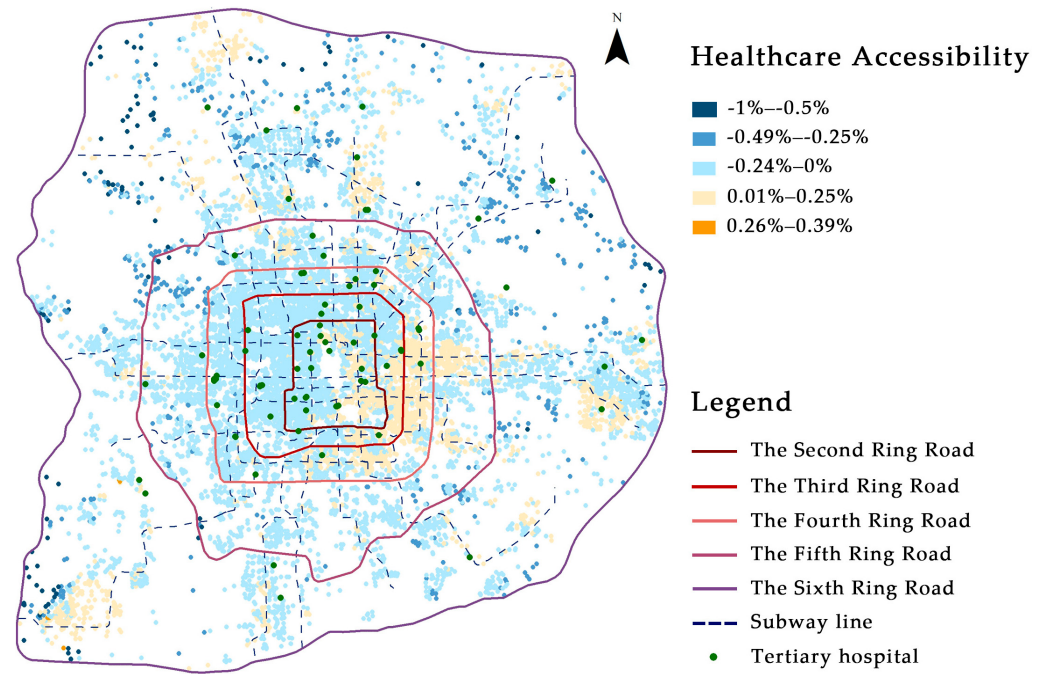


Figure 7. Percentage change in PTMLA relative to MMALR.

Figure 8 illustrates the percentage change in PCMLA relative to MMALR. For the private car mode, the accessibility of most areas within the Fifth Ring Road is overestimated, particularly the central area within the Second Ring Road, but the accessibility of certain residential communities located in the southeastern area between the Third Ring Road and the Fifth Ring Road is underestimated. Between the Fifth Ring Road and the Sixth Ring Road, there are four residential agglomeration areas where accessibility is seriously overestimated. The accessibility of these residential communities under the multi-mode scenario is low. The primary factor affecting this situation is the distance between these residential communities and tertiary hospitals, which leads to lengthy bus routes and high time consumption. When private cars are used to calculate accessibility, the assumption is that all local residents can drive to tertiary hospitals, which overestimates potential accessibility. It is impractical for all local residents to reach the hospital by car.

5.3. Multi-Mode vs. Single-Mode Equity Analysis

We calculated the Gini coefficient to evaluate equity in tertiary hospital accessibility across six administrative districts and regions within the Sixth Ring Road, thereby assisting decision-makers in allocating healthcare resources. The Gini coefficient values for each administrative district are presented in Table 4. There are 12 administrative districts within Beijing's Sixth Ring Road. This paper focuses on six districts: Dongcheng, Fengtai, Chaoyang, Haidian, Shijingshan, and Xicheng. In general, residents exhibit optimal accessibility equity in tertiary hospitals under the multi-mode scenario, while the equity is worse under the private car mode. This indicates that solely considering private car use as a mode of travel will cause significant estimation bias, thus affecting decision-making.

Notably, the Gini coefficient for Xicheng District is the lowest for all three modes, while the Gini coefficients for Chaoyang are all higher across all three modes in comparative analysis. Table 4 presents the Gini coefficients of Chaoyang, Haidian, and Fengtai Districts under multi-mode conditions, with values of 0.260, 0.234 and 0.197, respectively. This significant variability in the accessibility of tertiary hospitals across residential communities within these three administrative districts indicates that local residents experience the challenge of uneven healthcare distribution in these areas. In addition, based on the weighted average accessibility presented in Table 5, there are significant disparities in accessibility within the six administrative regions. Xicheng District has the highest level of accessibility, contrasting with Shijingshan District, which has the lowest level of accessibility. This indicates that Xicheng's local residents can more easily obtain medical resources, whereas Shijingshan's local residents find it more difficult to access essential healthcare services.

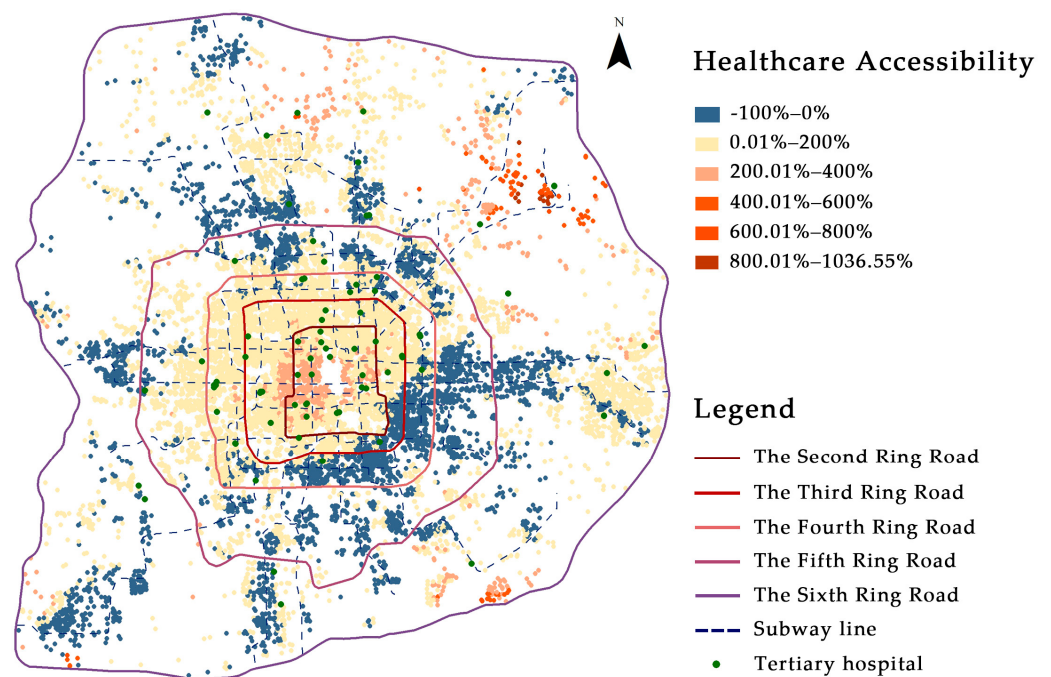


Figure 8. Percentage change in PCMLA relative to MMALR.

Table 4. Accessibility equity and ranks for six administrative districts using different methods.

Administrative District	Multi-Mode	Rank	Private Car	Rank	Public Transit	Rank
Dongcheng District	0.179	2	0.351	3	0.165	1
Fengtai District	0.197	4	0.384	4	0.207	4
Chaoyang District	0.260	6	0.498	6	0.267	6
Haidian District	0.234	5	0.414	5	0.214	5
Shijingshan district	0.182	3	0.225	2	0.205	3
Xicheng District	0.157	1	0.215	1	0.189	2

Table 5. Weighted average accessibility and ranks for six administrative districts using different methods.

Administrative District	Multi-Mode	Rank	Private Car	Rank	Public Transit	Rank
Dongcheng District	6.992	2	9.944	2	6.951	1
Fengtai District	4.865	5	3.937	4	4.589	4
Chaoyang District	5.022	4	3.449	5	4.963	3
Haidian District	5.423	3	6.185	3	4.854	5
Shijingshan district	3.426	6	2.596	6	3.220	6
Xicheng District	7.328	1	14.464	1	6.591	2

The Gini coefficient outcomes for different ring road regions are presented in Table 6. Consistent with administrative district findings, residents exhibit optimal accessibility equity with regard to tertiary hospitals under multi-mode conditions, whereas the equity in the private car mode demonstrates the lowest levels. This further confirms the low accuracy of accessibility in the private car mode. Specifically, the MMALR Gini coefficient of the areas within the Fifth Ring Road remains below 0.2, indicating an equitable distribution of medical resources in this area. Conversely, the MMALR Gini coefficient of the area between the Fifth Ring Road and the Sixth Ring Road is as high as 0.334, which indicates an imbalance in local residents' healthcare access within this area. Further analysis of Table 7 reveals that residential communities located within the Second Ring Road have the highest accessibility, whereas those situated between the Fifth Ring Road and Sixth Ring Road have the lowest accessibility. Accessibility decreases progressively from the Second Ring Road to the Sixth Ring Road. This spatial pattern reveals a healthcare accessibility decay correlating with distance from Beijing's urban core. In summary, policy-makers need to focus on areas with low accessibility and spatial inequality in the distribution of MMALR when allocating health resources.

Table 6. Accessibility equity and ranks for ring road regions using different methods.

Ring Region	Multi-Mode	Rank	Private Car	Rank	Public Transit	Rank
Within Second Ring Road	0.146	1	0.215	1	0.150	2
Between Second Ring Road and Third Ring Road	0.184	3	0.376	2	0.155	3
Between Third Ring Road and Fourth Ring Road	0.152	2	0.405	4	0.127	1
Between Fourth Ring Road and Fifth Ring Road	0.195	4	0.392	3	0.199	4
Between Fifth Ring Road and Sixth Ring Road	0.334	5	0.463	5	0.345	5

Table 7. Weighted average accessibility and ranks for ring road regions using different methods.

Ring Region	Multi-Mode	Rank	Private Car	Rank	Public Transit	Rank
Within Second Ring Road	7.362	1	13.726	1	7.030	1
Between Second Ring Road and Third Ring Road	6.564	2	8.551	2	6.119	2
Between Third Ring Road and Fourth Ring Road	6.074	3	4.999	3	5.803	3
Between Fourth Ring Road and Fifth Ring Road	4.226	4	3.041	4	3.999	4
Between Fifth Ring Road and Sixth Ring Road	2.755	5	2.924	5	2.571	5

6. Discussion

The reasonable and balanced distribution of high-quality medical resources improves the equity in healthcare access. This study developed a computational model for Multi-Mode Accessibility for Local Residents (MMALR) to tertiary hospitals. Compared with previous studies, this study further refined the supply capacity of healthcare workers, considering that non-local residents utilize the service capacity of tertiary hospitals. Furthermore, it examined the impact of the composition of the travel mode share between hospitals and residential communities on accessibility across different distance intervals, incorporating public transit, private cars, taxis, biking, and walking as residents' daily travel mode choices. The travel distance was divided into ten intervals, with varying proportions

of the population for each travel mode found in different distance intervals. This study built upon previous research by addressing limitations in the utilization of travel modes. Prior studies uniformly adopted the same travel mode share in the research scope, without considering the travel mode diversification relative to the varying origin–destination distances [58,81,84]. While some studies have examined multi-modal accessibility, these studies calculate accessibility separately for a certain travel mode, focusing on comparing the accessibility analysis outcomes of different travel modes [79,80,88].

Taking the area within the Sixth Ring Road of Beijing as an example, this study explored the spatial distribution of the MMALR. Furthermore, this study compared and analyzed the spatial differences for the MMALR, PTALR, and PCALR. On this basis, the Gini coefficient was employed to discuss and analyze the equity of access to healthcare for local residents in the different administrative districts and ring road regions. The service accessibility and equity evaluation framework of tertiary hospitals proposed in this paper highlights the impact of non-local patients and multiple travel modes on accessibility. This provides a novel perspective for other studies on urban healthcare accessibility and the accessibility of other social resources. As far as we know, no relevant studies have systematically examined the impact of inter-city patient mobility on the potential accessibility for local residents. Currently, research mainly discusses the influence of medical mobility between cities on the medical accessibility of residents in each city [5,27,32]. For countries that permit cross-regional medical treatment, metropolises with abundant medical resources should incorporate the proportion of non-local patients into evaluations of local residents' healthcare accessibility. This approach accurately quantifies the potential healthcare accessibility for local residents with regard to medical facilities.

We have presented several novel insights based on the outcomes calculated in this paper. Firstly, the accessibility distribution of tertiary hospitals within the Sixth Ring Road of Beijing displays a single-center structure, which gradually decreases from the Inner Ring Road to the Outer Ring Road along the subway line. However, higher accessibility is observed in the eastern and northern parts of the areas between the Fifth Ring Road and Sixth Ring Road. This indicates that residential communities near urban centers are more likely to have access to healthcare and are less affected by non-local patients. These findings further indicate that the distribution of medical resources in Beijing's urban core and the eastern and northern areas between the Fifth Ring Road and Sixth Ring Road more effectively addresses local residents' healthcare needs compared to other areas. Secondly, through comparative analysis of the spatial distribution differences between multi-mode and single-mode scenarios, this paper reveals that the overall accessibility using the private car mode is overestimated, while the accessibility using public transit is underestimated. The area within the Third Ring Road and the northeast areas between the Fifth Ring Road and Sixth Ring Road are the locations where accessibility is prone to variation. This indicates that considering only a single mode would result in a large deviation in accessibility outcomes, which will lead to inaccurate conclusions. The multi-mode scenario eliminates some extreme deviations observed in the single-mode scenarios, and the outcomes are more closely aligned with actual conditions. Finally, this paper compares the Gini coefficient of the different ring road regions and six administrative districts within the Sixth Ring Road of Beijing. The Gini coefficient of accessibility under multi-mode and single-mode conditions is the lowest within the Second Ring Road and in Xicheng District of Beijing, indicating the more equitable spatial distribution of healthcare resources. Conversely, the Gini coefficient is highest within the area between the Fifth Ring Road and the Sixth Ring Road and in Chaoyang District, indicating relatively poorer access to healthcare resources. In order to improve the accessibility and equity of different areas, it is essential to pay attention to the location optimization of medical facilities in

areas with low accessibility and poor equity. On the other hand, improving the service level of public transit, enhancing the speed of bus travel, and reducing the transfer time are crucial measures in increasing healthcare accessibility. The establishment of dedicated public transit medical channels could be considered. However, the combined effect of these measures requires more comprehensive evaluation.

The analysis and results of this study provide greater benefits to stakeholders. First of all, this study can assist government managers in re-evaluating and attaching importance to the assessment methods of accessibility from the perspective of enhancing equity. Adding medical resources can enhance the equity of healthcare accessibility [89]. However, different models may misjudge the accessibility and the equity across administrative regions or different areas. The case analysis presented in this paper proves that different accessibility analysis frameworks generate distinct equity rankings across the different administrative regions and ring road regions of Beijing. For example, Beijing's Shijingshan District may be overrated compared to Fengtai District in accessibility equity, while Dongcheng District may be mistakenly regarded as having better accessibility equity than Xicheng District. Existing studies compare the accessibility equity of different regions without considering the possibility that the distinct accessibility calculation frameworks may yield divergent comparative outcomes [5,34,90,91]. This discrepancy could lead to deviations in policy formulation and decision-making. The accessibility analysis framework of medical facilities that we have proposed holds significant reference value for other cities with abundant and high-quality medical resources. It is suggested that these cities consider re-evaluating the accessibility of medical facilities for local residents. The number of inter-city patients will change with the quality of medical facilities in different cities and the distribution of local residents will change due to factors such as urban development. Therefore, the systematic analysis framework of accessibility should be subject to a dynamic adjustment process. Government managers can refer to the analytical framework proposed in this study to establish a more systematic and scientifically dynamic accessibility analysis process and further investigate the impact of inter-city patient mobility on local residents' healthcare accessibility and regional equity. If a nationwide monitoring platform for inter-city patient mobility among cities is established, an analysis framework for the accessibility of healthcare for local residents in all cities can be constructed on this basis. The analysis results can present the differences in accessibility and equity among various cities. This is of great reference value for formulating policies and measures conducive to narrowing the accessibility gaps between cities. Secondly, this study can assist urban planners and transportation planners in conducting thorough evaluations during the optimization of medical facility siting, thereby enhancing the geospatial equity of healthcare accessibility. The case of Beijing shows that the accessibility level gradually decreases from the Inner Ring Road to the Outer Ring Road along the subway line. In urban planning, new medical facilities should not generally be located in areas that already have high accessibility and high equity, such as the areas within the Second Ring Road and Xicheng District. For areas with low accessibility and equity, such as Chaoyang District and Haidian District, transportation planning policies or measures that are conducive to improving travel conditions and reducing travel time should be developed, especially for locations far from rail transit stations and with relatively low accessibility. Future transportation planning should focus on enhancing the coverage of rail transit in these areas. In addition, medical institution management departments and urban planners often face a common planning problem: under the condition that the distribution of local residents and the transportation network remain unchanged, they need to establish how they should make decisions on the location selection of new hospitals and adjust the distribution of public service resources to minimize the disparity in accessibility for each residential community to obtain medical

services. These decision-makers can refer to the framework proposed in this study and combine it with the model of the maximal accessibility equality problem (MAEP) to adjust the distribution of medical resource supply and optimize hospital location decisions. Wang Fahui [92] proposed the concept of the MAEP, and developed a MAEP solution model. This study focuses on the issues of local residents' healthcare accessibility and equity in access to high-level healthcare. The issues of medical resources allocation and hospital location selection need to be further explored in future. Finally, in order to improve the accessibility of medical resources for both local and non-local residents, patients with non-acute and critical conditions (such as common diseases and chronic diseases) should attend local hospitals for treatment and avoid blindly flocking to tertiary hospitals in big cities, thereby reducing the impact of patient mobility on the accessibility of healthcare for local residents.

On the basis of previous research, this paper proposes a novel accessibility calculation model that enhances the alignment of the accessibility outcomes with the actual situation. However, certain limitations remain: (1) This study determined the proportion of non-local patients in 82 tertiary hospitals within the Sixth Ring Road of Beijing according to the known proportion of non-local patients, the average proportion of non-local patients across all hospitals, and the ranking of tertiary hospitals and other objective factors. We hope to use multi-source empirical data in future studies, which will further improve the accuracy and reliability of the ratios of patients in different hospitals while building upon the existing research. (2) When considering people's choices of medical treatment, it is essential to comprehensively consider the influence of subjective and objective factors on hospital selection. Disease needs, hospital reputation, economic conditions, and other factors may lead individuals to display specific preferences for hospital choices. Therefore, future studies should further develop an accessibility calculation method that integrates the preferences of non-local patients and local residents regarding hospitals. (3) The healthcare accessibility in this study is closely related to the urban form shaped by urban ring roads. As a physical isolation facility, urban ring roads may affect healthcare accessibility in residential communities. Future research can analyze the correlation between urban ring roads and healthcare accessibility and deconstruct their net effect as transportation infrastructure. (4) Future studies should take the temporal dimension into account. The proportion of non-local patients at different times (different months, workdays, and holidays) of the year may differ, which could potentially affect the accessibility outcomes. (5) This study assumed that the composition of travel modes' share remains consistent within certain travel distance intervals. In reality, residents in different urban areas may have varying share compositions even if they have identical travel distances to a hospital. This offers a potential research direction worthy of consideration in future research.

7. Conclusions

This study considers the impact of the proportion of non-local patients on the supply capacity of tertiary hospitals and adjusts for the number of healthcare workers. Due to the different travel distances between hospitals and residential communities, the composition of travel mode shares varies. We propose a model for the MMALR integrating the shares and the attenuation functions of the multi-mode scenario. Taking the area within Beijing's Sixth Ring Road as a case study, this paper demonstrates the concrete implementation process and findings of the proposed method. The outcomes under the multi-mode scenario indicate the following: (1) the accessibility of administrative districts ranked from highest to lowest is as follows: Xicheng District, Dongcheng District, Haidian District, Chaoyang District, Fengtai District and Shijingshan District; (2) the accessibility equity rankings in descending order are as follows: Xicheng District, Shijingshan District, Dongcheng District, Fengtai District, Haidian District and Chaoyang District, with Shijingshan District and

Dongcheng District having identical rankings. The accessibility under the multi-mode scenario is compared with those for the private car mode and the public transit mode. The PTALR underestimates the accessibility for most residential communities, while the PCALR underestimates the accessibility of residential communities with a low MMALR and overestimates the accessibility of residential communities with a high MMALR. This study found that the accessibility equity of Dongcheng District, Fengtai District, Chaoyang District, Haidian District, and the regions within the Second Ring Road and the Fifth Ring Road have large deviations in the calculation results under the three different travel modes. It is important to note that the calculation models across distinct travel modes yield varying assessment results regarding accessibility in different urban areas, which may lead to erroneous decision-making. The accessibility analysis model and framework developed in this study could more realistically evaluate the accessibility and equity of access to tertiary hospitals for local residents, which is crucial for cities with abundant medical resources and superior conditions. We conducted discussions with the respective stakeholders. Other cities can refer to the analytical framework we have proposed here to explore the issues of local residents' healthcare accessibility and equity in access to high-level healthcare. It should be noted that the proportion of non-local patients in tertiary hospitals varies in each city and the proportional composition of travel modes also differs among cities. Therefore, each city needs to adjust these input parameters when calculating accessibility. The research methods and results presented in this study provide a reference for constructing a national analysis framework on healthcare accessibility for local residents, which incorporates the composition ratio of each travel mode in different cities and the proportion of non-local patients in various hospitals. Our framework emphasizes the impact of inter-city patient mobility on equity in access to high-level healthcare, especially for cities with abundant medical resources and superior conditions. The analytical results provide some references for different stakeholders.

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