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Isochrone-Based Accessibility Analysis of Pre-Hospital Emergency Medical Facilities: A Case Study of Central Districts of Beijing

Yuan Zhao and **Ying Zhou** *

School of Architecture, Southeast University, Nanjing 210096, China; yuanz@seu.edu.cn
* Correspondence: zhouying@seu.edu.cn

Abstract: Pre-hospital emergency medical service (PHEMS) is critical for the treatment outcomes of life-threatening injuries and time-sensitive illnesses. Response time, influenced by traffic conditions and the site planning of pre-hospital emergency medical facilities (PHEMFs), is the main indicator for evaluating PHEMS. In 2020, the Beijing government released the "Special Plan for Spatial Layout of Pre-hospital Emergency Medical Facilities in Beijing (2020–2022)". This paper evaluates the functional efficiency and spatial equity of this plan within Beijing's central six districts using isochrone measures to assess the accessibility of the planned PHEMFs. The isochrone coverages of the area and population were calculated, and the temporal-spatial characteristics of isochrones were concluded. The analysis revealed that while the current planning meets several objectives, challenges in service availability and equity persist. Although 10-min isochrone coverage was high, 8-min coverage was insufficient, particularly during peak hours. This highlights gaps in service accessibility that necessitate additional emergency stations in underserved areas. The current planning approach leads to significant overlap at administrative boundaries, causing service oversupply and increased costs, which calls for a city-wide planning perspective that breaks administrative boundaries to optimize resource allocation. Traffic conditions significantly impact service coverage, with congestion reducing coverage in central areas and better coverage near traffic hubs. Future planning should strategically place stations based on traffic patterns and population distribution to enhance emergency medical service accessibility and equity in urban areas.

Keywords: emergency medical service; pre-hospital emergency medical facility; isochrone; accessibility analysis

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1. Introduction

As an integral part of the healthcare system, pre-hospital emergency medical service (PHEMS) is the first level of healthcare response for out-of-hospital medical emergencies. It refers to a system that organizes all aspects of medical care provided to patients in pre- or out-of-hospital environments [1,2]. It is critical to the treatment outcomes of life-threatening injuries and time-sensitive illnesses, which may lead to premature mortality and serious disability. Additionally, PHEMS serves as a fundamental public resource for managing common medical conditions and is essential for effective disaster response and mass casualty management [3,4]. In particular, the administrative control policies during the COVID-19 pandemic restricted citizens' free access to emergency departments, leading to greater reliance on urban EMS under emergency conditions.

In urban settings, pre-hospital care typically starts with an emergency call to a dispatch center. Trained personnel assess the need for emergency care, and ambulances are then dispatched to provide services like triage and treatment as well as transport the patients to the proper medical facility [5]. The time between the moment an emergency call is made and the equipped ambulance's arrival at the scene is defined as the response time (RT), which is a primary metric for evaluating PHEMS performance and is crucial for the success of pre-hospital care [6]. RT is divided into three components: call time (the interval from receiving the emergency call to raising the alert), gathering time (from sending the alert to dispatching the medical team), and road time (from ambulance dispatch to arrival at the scene) [7]. Among these, road time accounts for the largest percentage and has the biggest influence on patient outcomes [8]. This is affected by both the traffic conditions and the site planning of PHEMS facilities. Reasonable site planning of EMS facilities is essential to guarantee an efficient and equitable pre-hospital emergency system, as time is crucial when dealing with a patient in an emergency.

The World Health Organization recommends that emergency medical services ambulance response time to a medical emergency is within 8 min for at least 90% of calls [6,9,10]. Nonetheless, RT differs not only between nations and regions globally but also between rural, suburban, and urban sectors all within the same region [11,12]. For instance, the median of statewide RT in Texas, US, was 7 min in 2021 [13], and the RT in Japan was 7.5 min in 2016 [6]. The average RT for life-threatening calls was 10.5 min in 2023 [14], and the RT in Greece was 28.9 min in 2016 [6]. In China, regional disparities are pronounced, with urban–suburban RT differences remaining substantial even within a single city [11]. In Beijing, the capital city of China, the RT was still 16.41 min in 2020 [11], which is far behind the 8-min standard. To address this issue, the Chinese government released new guidelines for PHEMS in 2020 [15]. Specific measures were proposed, including service area, ambulance number, and maximum dispatch time. Each municipal government still has the right to set its specified response time requirement.

To enhance PHEMS, the Beijing government released the "Special Plan for Spatial Layout of Pre-hospital Emergency Medical Facilities in Beijing (2020–2022)" (Special Plan for short) in 2020 [16]. The planning objective for this Special Plan was to achieve an average RT of less than 12 min. The plan proposed 465 pre-hospital emergency medical facility sites across the city, including 278 new sites and 187 existing sites. The planning method was based on the administrative divisions, taking Jiedao (the minimum administrative unit in urban areas of China) as the basic planning unit, establishing at least one emergency station within each Jiedao. This planning method is widely applied in Chinese urban planning, and it has the advantage of easy evaluation and assessment of the government at all levels. However, there are still several issues that need further discussion. Can this planning approach achieve the planning objectives? Is the planning outcome adequate and equitable to the population? Does a situation where emergency services are unavailable or oversupplied occur? How do traffic conditions affect planning outcomes, and how can the uncertainty caused by traffic be avoided in future planning?

To discuss the questions mentioned above, this paper takes the six central districts of Beijing as the study area and applies the isochrone measure to evaluate the accessibility of the planned pre-hospital emergency medical facilities (PHEMFs) in the Special Plan. Accessibility is a critical indicator of the functional efficiency and spatial equity of urban services; it measures the ease of reaching spatially distributed opportunities [17]. Various measures, including gravity models, cumulative opportunity measures, two-step floating-catchment area (2SFCA), and kernel density estimation (KDE), have been developed to assess urban service accessibility [17,18]. These measures are widely applied in the field of transport geography and urban planning to help urban planners and policymakers evaluate the performance of transportation and land-use systems in urban areas [19,20]. However, the measure selection still needs discussion based on the complexity and realism of the practical problem. One often-used technique for measuring accessibility without designating a destination is the isochrone approach, sometimes known as the cumulative opportunities measure within the isochrone. The isochrone defines reachable locations from a fixed starting point within the given cut-off time by a specified mode of transport. Given that response time is critical for emergency medical systems, assessing PHEMF accessibility through isochrones with stringent time thresholds provides valuable insights into functional efficiency and spatial equity. This paper aims to evaluate the functional efficiency and spatial equity of the pre-hospital emergency medical facilities (PHEMF) planning in the six central districts of Beijing by applying the isochrone measure to assess accessibility, analyze the isochrone coverage results, examine the temporal–spatial characteristics, and discuss the traffic sensitivity and equality assessment of the study area.

The remainder of this paper is structured as follows. Section 2 reviews the existing literature. Section 3 introduces the methodology and data used in this paper, including basic information about the study area, the data collection and processing methods, and the analysis method used in this study. Section 4 analyzes the results obtained by applying the methods introduced in Section 3. Section 5 discusses and concludes the accessibility assessment results from both the demand side and the supply side and proposes future planning suggestions based on the analysis results. Section 6 concludes the study.

2. Literature Review

Accessibility is a deep-seated and widely used concept in the field of transport geography and urban planning, emphasized by numerous studies for its importance in the healthcare domain [18,21,22]. Archiving adequate and equitable accessibility has become a critical objective of policy making, urban planning, and public health planning. Accessibility was also applied to various urban services, such as job opportunities [23–25], urban parks [26,27], food outlets [28,29], and so on. Despite its wide-ranging applications, the literature suggests that accessibility consists of three major components: transportation component, human activity component, and land use component [18].

Determining each component is the first step in calculating accessibility. The transportation component deals with the ease of traveling; it refers to the specific transportation network within the study area, such as the subway network or the urban road network. The human activity component focuses on the preferences of service consumers, including service facility choice preferences and transportation options preferences [18]. Both the transportation network and consumer transportation choice determine travel time. The land use component refers to the spatial distribution of service facilities, determining the traveling destination of service consumers.

This study evaluated the service accessibility of the planned PHEMFs in the Special Plan. The planned PHEMF site locations were used as the facility spatial distribution, and the driving mode in the urban road network was applied to calculate the travel time. As usual, the nearest ambulance was dispatched to the patient's location and chose the fastest route; thus, the facility preference of patients was neglected in emergency conditions.

Various formulations for measuring accessibility have been proposed in the literature and can be divided into two categories based on the calculation outcomes. One group of metrics has a result with absolute units, such as distance and travel time to the nearest service facility, population-to-provider ratios, and cumulative opportunity measure (COM). COM assesses accessibility by counting the number of opportunities reachable within a specified travel time or distance from a given location. A simple form of COM is:

$$A_i = \sum_j f E_j \quad (1)$$

where A_i is the total opportunities available of location i, E_j is the number of opportunities in location j, f is 1 for locations within a given threshold, and 0 otherwise [20]. It has the advantage of being simple in calculation, direct in interpretation, and comparable across regions, but the trade-off is low accuracy and realism [20,30].

To address these limitations, another group of methods, such as gravity models, the two-step floating catchment area (2SFCA) method, and kernel density estimation (KDE), were proposed to obtain a more accurate evaluation of accessibility through more complex computations [18]. The results are expressed in relative terms by normalizing the values over a particular range [31], and their interpretation is limited to comparisons with other outcomes. These methods are commonly used to evaluate urban service equity [19,20,32], uncover social disparities [33], and assess the unequal allocation of resources [34]. For example, 2SFCA calculates the supply-to-population ratio within a defined catchment area for each facility, considering travel time or distance. It then sums these ratios for each population point, accounting for accessible facilities within their catchment areas [18]. While 2SFCA offers a comprehensive and context-sensitive analysis, it requires more detailed data and computational effort, and its results are expressed in relative terms, which may be less intuitive than COM.

Choosing the appropriate measure depends on the practical problem and requires balancing between accuracy and simplicity. Most healthcare accessibility research focuses on primary care [35], hospital care [32,36,37], and EMS [38,39]. Methods relative units, such as 2SFCA, are more appropriate for equity discussion for primary care and hospital care because the research is focused on the physical separation and resource competition that result in uneven service distribution. For emergency care, response time is the critical metric, represented in absolute units (minutes). Since response time is paramount, service coverage is defined by the total area or population within the cut-off travel time, making the cumulative opportunity measure with response time constraints (isochrone) suitable for this study.

Recently, several platforms, such as Mapbox [40], iso4app [41], and TravelTime [42], have introduced online isochrone services that are convenient to acquire, fast in calculation, and accurate in results. However, these services have limitations. Most APIs do not account for departure times, which hinders their ability to conduct temporal analyses—studies that examine variations in accessibility at different times of the day. Additionally, some APIs have region restrictions, which results in poor service rates and accuracy for mainland Chinese cities. To address these issues and construct an accurate isochrone that reflects temporal variations, this study employs a methodology that connects sample points based on equal travel times from a starting location at various times throughout the day. By integrating these temporal characteristics, we ensure that the isochrones accurately represent how accessibility changes during peak hours, midnight hours, and normal hours of the day, providing a more reliable analysis of accessibility patterns.

The sample points are specific locations within the study area where accessibility is measured. They help in assessing the spatial accessibility of the PHEMFs by providing a reference for evaluating how far the ambulance can reach within the required time under different traffic conditions. Three techniques are often used to choose sample points: using administrative divisions' centroids [43], the centroid of grid-based raster [28,37], and radial rays. The third approach draws rays that split the circumference into equiangular slices radially spread from the origin and take identical steps along the ray as the sample points. The latter two methods are most frequently used to obtain travel data through open map APIs. Although smaller spatial units can yield more accurate findings by offering higher spatial analysis precision, they also cause a large increase in API request time, which slows down the computation speed. The radial-ray-based approach can significantly reduce the quantity of API requests while maintaining sample density. In this study, parameters were chosen to balance calculation efficiency and accuracy with a radial angle of 10 degrees and a step size of 100 m.

When calculating the equity of accessibility, both the supply and demand sides must be considered. In the healthcare system, supply-side accessibility and service coverage can be evaluated using PHEMF isochrones. On the demand side, competition exists among the patients, i.e., the medical service resources are limited. More competitors reduce the available opportunities that the patient can reach in the real world than in the ideal situation, especially in special cases like mass casualty incidents (MCIs). The actual accessibility of an opportunity depends not only on it being reachable but also on the number of other competitors that can reach it [20,44]. Therefore, it is necessary to consider competition when calculating the demand-side accessibility of emergency services. Researchers have advocated the importance of considering the competition in accessibility measures and have also pointed out that accessibility should be related to changes in demand [20,25,45,46]. Nevertheless, with the improvement in calculation accuracy, the accessibility measures that account for the competition tend to be complex in calculation and difficult to interpret.

Researchers have also noted that because the COM only accounts for a single cut-off trip cost and ignores spatial distribution variance, it has the drawback of failing to take opportunity competition into account [30]. Kelobonye (2020) introduced a competition component to COM to improve its accuracy and showed its applicability and improvement in order to increase the measure's accuracy while maintaining its simplicity and broad application [20]. This study applies the cumulative opportunity measure, considering competition from the demand side, to assess the equity of emergency service accessibility.

3. Methods and Data Description

3.1. Data Description

The datasets utilized in this paper included the pre-hospital emergency medical facilities (PHEMF) data, population data, and travel time data within the study area. The sources and processing methods for these datasets are outlined below.

3.1.1. Study Area

Beijing, the capital of China, is one of the most populous metropolitan cities, with a population of 21.88 million and an area of 16.41 thousand square kilometers as of 2022 [47]. As shown in Figure 1, this study focused on the six core districts of Beijing: Dongcheng, Xicheng, Chaoyang, Haidian, Fengtai, and Shijingshan. These districts are considered the central urban regions of the city.

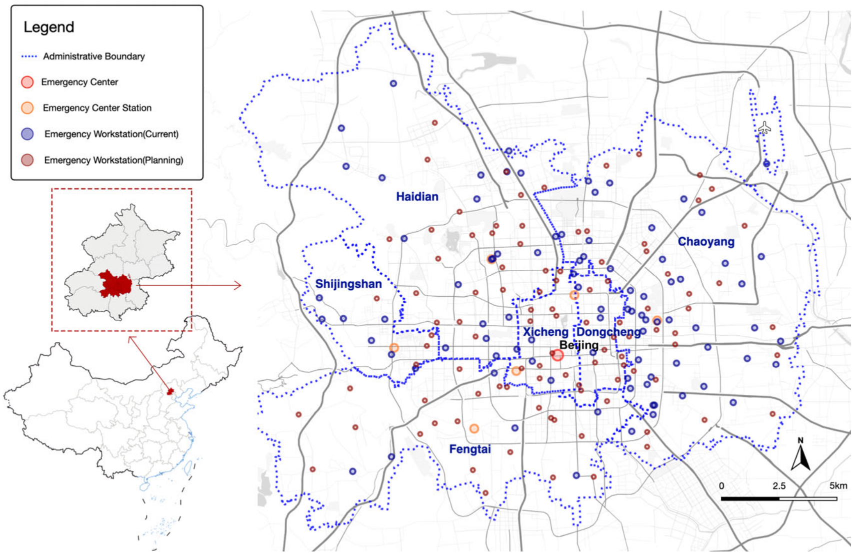


Figure 1. Spatial distribution of PHEMFs in the six central districts of Beijing.

3.1.2. Pre-Hospital Emergency Medical Facility Data

The emergency medical service system in Beijing includes three types of PHEMFs: emergency medical centers (EMCs), emergency central stations (ECSs), and emergency stations (ESs). The primary distinction is seen in the range of services offered and the size of the facilities built. EMCs are large, well-equipped facilities responsible for citywide dispatch commands. ECSs are medium-sized facilities, generally over 800 square meters, that manage, command, and provide training within designated areas. ESs are smaller, support first aid within their immediate areas, and are categorized into grade A and grade B based on the number of ambulances they can accommodate; grade A stations have six ambulance parking spots, while grade B stations have three [16].

To enhance EMS services, Beijing launched an upgrade plan in 2020, known as the Special Plan for Spatial Layout of Pre-hospital Emergency Medical Facilities in Beijing (2020–2022) [16]. It planned 456 emergency facility site locations for the entire city, including 278 new locations. Within our study area, there were 95 existing and 101 newly planned locations, as summarized in Table 1. The facility distribution included one EMC and six ECSs (one per district), with the newly planned ECS located in Xicheng. The remaining facilities were ESs, totaling 189 stations, with 89 existing and 100 planned. The spatial distribution of the facility locations is shown in Figure 1.

Table 1. PHEMFs in the six central districts.

	Total	EMC	ECS	ES			
				Existing	Planned	Grade A	Grade B
Dongcheng	12	0	1	4	7	1	10
Xicheng	18	1	1	4	12	4	12
Chaoyang	81	0	1	48	32	10	70
Haidian	45	0	1	20	24	6	38
Fengtai	29	0	1	6	22	6	22
Shijingshan	11	0	1	7	3	3	7
Total	196	1	6	89	100	30	159

3.1.3. Population Data

The population data were obtained from WorldPop [48]. The data were aggregated and constrained with buildings from the 2020 population, with a grid of 100 m × 100 m [49]. There were 172,968 grids with population data within the study area. This dataset showed its advantage in the high accuracy of the area with satellite-based settlement images, especially in highly developed urban areas [50], which is consistent with the study area of this paper.

3.1.4. Travel Time Data

Two main trip time collection methods are commonly used: GIS-based methods and open map-based approaches. GIS-based methods, using embedded spatial analysis tools [37,51–54], provide fast calculations but often ignore actual traffic conditions. In contrast, open map-based methods use real-time and historical speed data to calculate more accurate travel times [23,55]. A large number of studies using online map data in the field of traffic analysis and transport accessibility have emerged [23,36,55], demonstrating that the open map service can provide objective and accurate travel data.

The isochrones in this study were constructed using real-time travel data from the Amap platform [56], a major location-based service provider in China. Amap offers route planning based on real-time traffic conditions and user data to estimate vehicle speeds and predict road conditions. The location of each PHEMF was used as the route origin, the surrounding sample points of each facility were used as the route destinations, and the shortest travel time strategy was applied to the route requests.

The real-time travel time data could reflect real traffic congestion during the day. To make a comparison between different traffic hours, the data acquisition hours were further divided into three time periods due to the time-varying characteristics of urban traffic: midnight period (22:00–05:00 the next day), peak period (07:00–09:00 and 17:00–20:00), and normal period (other hours). The temporal analysis in the following sections is based on the three time periods. Each origin–destination pair's travel time was measured three times within the same period, and the average was used to ensure data reliability.

3.2. Analysis Method Design for Accessibility Evaluation

3.2.1. Isochrone Construction Method

An isochrone is defined as the reachable location from a fixed starting point within the given cut-off time by a specified mode of transport. In this study, the service area of each PHEMF was evaluated by applying isochrone in three defined periods. The radial-ray-based approach was used to construct the isochrones. This method involved drawing radial rays from the origin, which divided the surrounding area into equiangular segments. Sample points were then selected along these rays at regular intervals. The travel time from the origin to each sample point was computed using an open map platform with the travel mode set to driving (i.e., by ambulance). Then, the isochrone was constructed by connecting the farthest points from the origin with identical cut-off travel time.

Figure 2 illustrates the detailed steps of constructing an isochrone with a time threshold of T. (1) Determine the coordinates of starting point O. (2) Take the starting point as the center of the circle, distance D as the radius, and set the circle as the picking range of endpoints (where D exceeds the optimal straight-line distance within time T in an urban area). (3) Select N radial rays with an identical angle that are centered at point O ($\theta = 360^{\circ}/N$). (4) Along each radial ray, take the farthest point A as the first destination to calculate the travel time from point O to point A, t_{OA}. (5) If $t_{OA} > T$, take one step toward point O, calculate the coordinates of point B ($D_{OB} = D_{OA}$-d), and calculate t_{OB}. Repeat this process until the travel time is less than or equal to T ($t_{OB} \leq T$), then point B is the farthest reachable point on this ray. (6). Repeat steps 4 and 5 for each ray to obtain the collection of the farthest reachable points in N lines. (7). Construct the isochrons of time T by connecting the farthest reachable points in all directions.

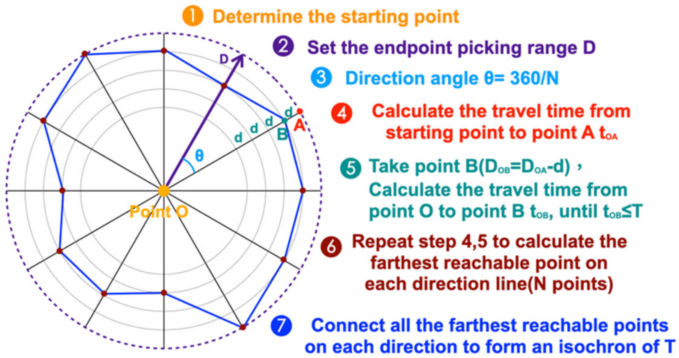


Figure 2. Steps of constructing isochrone of threshold time T.

The parameters in the isochrone construction steps affected both the result accuracy and calculation efficiency. A larger value for N (number of radial rays) and a smaller value for d (step size) improved the precision of the isochrone but also increased the number of API requests, thereby reducing computational efficiency. To find a balance between accuracy and efficiency, we conducted experiments with different parameter combinations. First, step size d was set to 100 m, which is smaller than the typical city block size in Beijing's central districts. Then, with the maximum driving speed within the urban street of 60 km/h and the largest time threshold being 10 min in this study, the farthest driving distance was 10 km. Therefore, the picking range D should be less than 10 km. We randomly selected 10 facility points from the PHEMF set as test points and calculated the farthest distance reachable in all directions. The results indicated that 6 km was the smallest integer value for D. Regarding the direction angle between radial rays, θ = 5, 10, 20 (corresponding to N = 72, 36, 18), was tested on the randomly selected test points. The number of API requests ranged from 1100 to 1500 per PHEMF when θ = 10, and it was halved when θ = 20 and doubled when θ = 5. Additionally, the isochrone results were more starlike when θ = 5, while θ = 20 produced less detail. Thus, θ = 10 (N = 36) was selected as the optimal parameter to ensure accurate isochrone representation while maintaining manageable computational demands.

3.2.2. Accessibility of PHEMF

The cumulative opportunity measure (COM) was applied to measure the accessibility of PHEMF. It counts the number of populations that the ambulance can reach, starting from each PHEMF within travel time T. The isochrone of time T in the period h ($h \in \{midnight, peak, normal\}$) obtained for a PHEMF i was treated as its service area within time T; its covered area was expressed as $AR_i^{T,h}$. The population within the service area $P_i^{T,h}$ was calculated as

$$P_i^{T,h} = \sum_j f\left(c_{ij}^h, T\right) Pop_j \quad (2)$$

$$f\left(c_{ij}^{h}, T\right) = \begin{cases} 1 \;\; if \; c_{ij}^{h} \leq T \\ 0 \;\; if \; c_{ij}^{h} > T \end{cases} \tag{3}$$

where $f(c_{ij}^{h}, T)$ is the impedance function, it denotes the isochrone of time T in the period h of location i. c_{ij}^{h} denotes the travel time from i to j in the period h, Pop_j is the number of populations in grid j, and j is the population grid within the isochrone-covered area.

3.2.3. PHEMF Accessibility Sensitivity to Traffic

Traffic congestion significantly impacts ambulance travel times, thereby influencing the critical time available for first aid. During midnight hours, when traffic is minimal, travel times are shortest, resulting in the largest coverage area for isochrones. Conversely, during peak hours, especially in densely developed metropolitan areas, traffic congestion leads to extended travel times, which reduces the coverage area of isochrones. This variation in coverage area between the peak and midnight periods is influenced by traffic patterns, which affect response times and, consequently, the effective service area of each facility. Thus, it can serve as an indicator of how sensitive each PHEMF is to traffic conditions. To quantify this sensitivity, we introduced the accessibility sensitivity to traffic (${S_i}^T$) as an indicator to identify the most traffic-sensitive facilities. ${S_i}^T$ was calculated using the following formula:

$$S_i^T = \frac{A_i^{T,midnight} - A_i^{T,peak}}{A_i^{T,midnight}} \tag{4}$$

where ${A_i}^{T,midnight}$ is the T isochrone coverage area of PHEMF i during the midnight period, ${A_i}^{T,peak}$ is the T isochrone coverage area of PHEMF i during the peak hours.

This metric allowed us to evaluate how traffic congestion impacted the accessibility of PHEMFs, providing insights into the variability of service coverage and identifying the facilities that were most impacted by traffic congestion. It also implies the importance of considering traffic conditions in future planning.

3.2.4. Equity Assessment

In Section 3.2.2, the accessibility of each PHEMF was calculated by measuring the area and population that a single facility served within a given time T from the supply side. It was also necessary to measure accessibility from the demand side. The demand side accessibility was used to assess the equity among the population.

In the traditional cumulative opportunities approach, the value was calculated by setting the demand point as the origin and summing up the number of reachable supply facilities within the threshold time. This method is simple but with its limitation of lack of accuracy, especially under the condition of limited resources. The value of reachable opportunities decreased when the competition for them increased, and the traditional cumulative opportunity method overestimated the actual accessible opportunities. In the case of an emergency, one may not expect an ambulance when all ambulances are on missions, even if the emergency station is quite near. To reflect the degree of competition for limited opportunities, a competition component was incorporated into the traditional cumulative opportunity method to assess the effective accessibility of population grids.

The method used the supply–demand ratio; it first estimated the share of opportunities proportional to the size of service demand for every supply location, then summed up the proportional opportunities in locations that were covered in each population grid. In the context of emergency medical services, opportunity refers to the likelihood of an ambulance reaching a location in time. The calculation was expressed as follows,

$$A_i^{T,h} = \sum\nolimits_j \frac{g\left(c_{ij}^{h}, T\right) E_j}{P_j^{T,h}} \tag{5}$$

$$g\left(c_{ij}^{h}, T\right) = \begin{cases} 1 \ \ if \ c_{ij}^{h} \le T \\ 0 \ \ if \ c_{ij}^{h} > T \end{cases} \quad (6)$$

where $A_i^{T,h}$ is the effective accessibility at time T in the time period h of location i (ambulance available to an individual person in grid i). $g(c_{ij}^{h}, T)$ is similar to Equation (3), denotes the isochrone of PHEMF j of time T in the time period h could cover the grid i. E_j is the number of ambulances of PHEMF j. $P_j^{T,h}$ is the total population within the service area of PHEMF j of time T in the time period h, expressed by Equation (2). This method is simple in calculation and retains its practical significance. The result was expressed in opportunities (ambulances) per person.

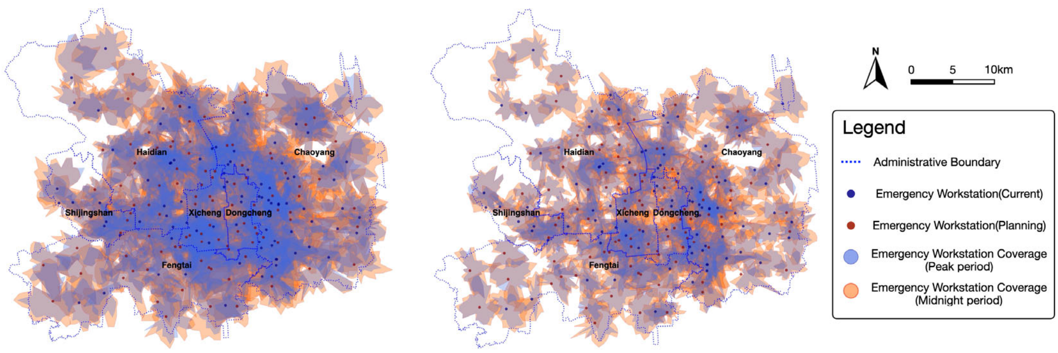
4. Results Analysis

Emergency response time can be divided into three periods: call time, gathering time, and road time. According to the statistics of the Beijing EMS, the median response time was 16.5 min in 2005 [57], 19.18 min in 2008, and 22.26 min in 2017 [58]. The average response time was around 15 min in 2021 [59], 16.04 min in 2022 [60], and 12.20 min in 2023 [61]. The first two phases, which take place inside emergency stations and centers, are influenced by the qualifications and proficiency of the response team. The longest and most challenging to control is road time—the duration for an ambulance to arrive at the incident site. The median time from the emergency call to ambulance departure is around 4 min [58]. The median ambulance driving time in Beijing was 10.6 min in 2005 [57], 14.75 min in 2008, and 17.35 min in 2017 [58].

To meet the target of "average response time less than 12 min" in the Special Plan, the time from emergency call to ambulance departure should be controlled to 2 to 4 min; thus, the road travel time of ambulances should be less than 10 to 8 min. Based on these time ranges, this paper calculates the multiple time threshold isochrone coverages of PHEMFs during three time periods (midnight period (22:00–05:00 the next day), peak period (07:00–09:00 and 17:00–20:00), and normal period (other hours). The results are as follows.

4.1. Isochrone Coverage Results

Table 2 shows the total area and population coverage results of isochrones with different travel time thresholds in the three time periods. Figure 3 visualizes the isochrone results for 10-min and 8-min travel times, using color to distinguish between peak and midnight periods. The coverage result for 9-min travel time fell between the results for 10 and 8 min, and the normal period coverage fell between the peak and midnight periods. Therefore, only the isochrone coverage results for 10 and 8 min during the midnight and peak periods were visualized to better illustrate the disparities in the data.



(**a**) (**b**)

Figure 3. Isochrone results for different travel time thresholds: (**a**) 10 min, (**b**) 8 min.

Table 2. Area and population coverage of isochrones in different periods.

Periods	Coverage	Travel Time Threshold		
		10 min	**9 min**	**8 min**
Peak	Area (km^2)	1105.55	1018.95	837.62
	Area Proportion	80.39%	74.09%	60.91%
	Population (Million)	15.91	15.14	12.95
	Population Proportion	93.83%	89.31%	76.41%
Normal	Area (km^2)	1127.79	1043.0	879.9
	Area Proportion	82.01%	75.84%	63.98%
	Population (Million)	16.04	15.36	13.41
	Population Proportion	94.65%	90.64%	79.08%
Midnight	Area (km^2)	1202.22	1144.00	1035.49
	Area Proportion	87.42%	83.19%	75.30%
	Population (Million)	16.58	16.25	15.41
	Population Proportion	97.81%	95.90%	90.91%

Note: Coverage area/population refers to the coverage area/population of all isochrones within the six central districts. The coverage proportion refers to the ratio of the coverage area/population within the central six districts to the total area/population of the central six districts.

It could be seen from the results that, within a 10-min travel time, PHEMFs covered the vast majority of the urban area, with 87.42% coverage at midnight and 80.39% area coverage during peak hours. The population coverage performed even better, reaching 93.83% during peak hours and 97.81% in the midnight period. However, the coverage significantly decreased within an 8-min travel time, accounting for 75.30% of the area at midnight, and only 60.91% of the urban area and 76.41% of the population during peak hours, presenting more uncovered areas and populations.

In addition, Figure 3a illustrates a high rate of overlap in the coverage of isochrones within the central urban area for the 10-min threshold (the darker the color, the more overlapping the layers). The areas with the highest rate of overlap were found around district borders, including the border between Dongcheng and Chaoyang District, the northern border of Fengtai District, and the southeast border of Haidian District. Conversely, the coverage overlap rate for 8-min isochrone was significantly lower, with primary coverage overlap areas in the southwest of Xicheng District, the vicinity of the Dongcheng District and Chaoyang District borders, and the eastern portion of Shijingshan District.

4.2. Temporal–Spatial Characteristics of Isochrones

The statistics of the isochrone coverage results of 196 PHEMFs in different periods are shown in Figure 4. As illustrated in Figure 4a,b, the area coverage distribution of the isochrones varied across different periods. The midnight period (blue) displayed a relatively normal distribution with a tight relationship between the median and mean values. The distribution was right-skewed for normal and peak periods (orange and green), with a significantly reduced number of facilities with large area coverage. In the comparison of the area coverage during the peak and midnight periods, the mean values of 10-min and 8-min travel time thresholds decreased by 43.57% and 46.47%, respectively. The population coverage was similar, as shown in Figure 4c,d, with right-skewed distributions during peak and normal periods and a flatter distribution during the midnight period. This result reflects the fact that many emergency facilities have large area coverage but small population coverage, and their area coverage results are majorly affected by the travel time threshold.

By comparing population coverage during the peak and midnight periods, the mean values of 10-min and 8-min travel time thresholds decreased by 44.9% and 50%, respectively. Since 10-min isochrones covered almost twice the area and population of 8-min isochrones in all periods, increasing the travel time threshold significantly expanded the population coverage results of PHEMFs.

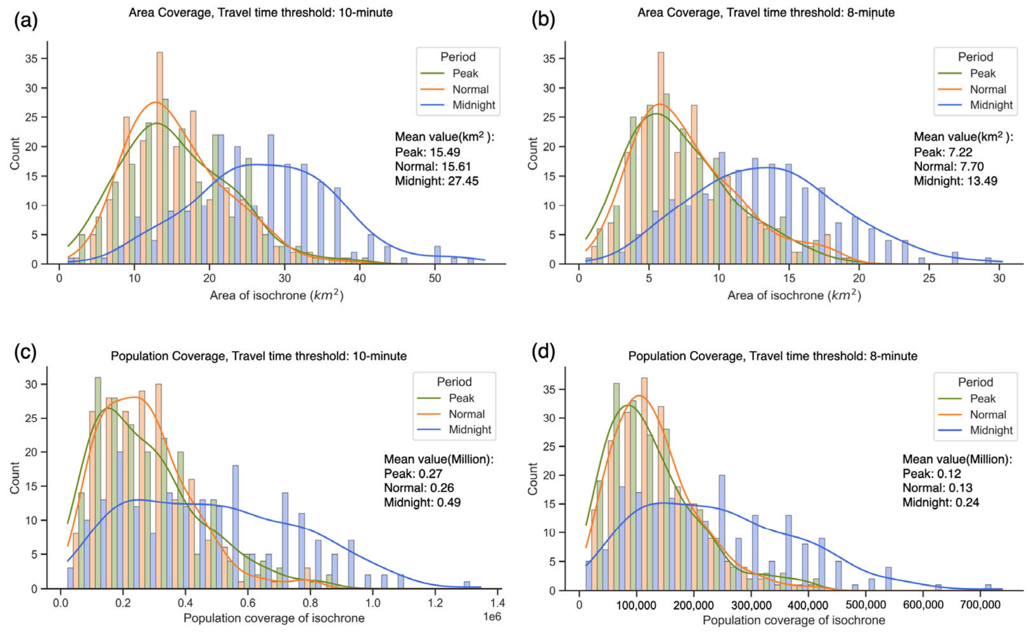


Figure 4. Isochrone distribution: (**a**) area coverage of 10 min, (**b**) area coverage of 8 min, (**c**) population coverage of 10 min, (**d**) population coverage of 8 min.

This result also showed that traffic conditions had a major influence on the isochrone coverage results, with little variation between the peak and normal periods, indicating congested traffic during non-midnight hours, making it challenging for ambulances to arrive quickly. Meanwhile, extending ambulance travel time effectively increased PHEMF service areas.

Figure 5 shows the geographical distribution of the isochrone coverage results. Table 3 categorizes these results into four groups based on their coverage characteristics. Type 1 facilities had a large area and large population coverage; they were mainly located in the area around traffic hubs, particularly in the northeastern region between the Third and Fourth Ring Roads. Type 2 facilities were located primarily in the outer areas of the central six districts, including the northeast of Chaoyang District, the south of Fengtai District, and the northwest of Haidian District, etc. These areas typically had a lower population density and lower emergency facility density. Facilities with high population coverage, including Type 1 and Type 3, were generally found near the borders of the six districts, particularly at the boundaries of Dongcheng and Xicheng Districts, as well as the southern boundary of Haidian District. Type 4 facilities, which had a small area and population coverage, were mainly located in the central areas of each district.

This distribution was significantly influenced by the underlying traffic patterns and population distribution within the city. Type 1 facilities were located near major traffic hubs, where road networks were denser and more efficient, facilitating quicker response times despite high traffic volumes. Type 2 facilities, on the other hand, were positioned in the outer regions of the central districts, where population density was lower, and traffic congestion was less intense. This allowed these facilities to cover larger geographic areas with fewer people, compensating for the longer travel distances required to reach emergency incidents. Type 3 facilities were typically found near district borders where population density was high, but traffic congestion limited extensive coverage. Finally, Type 4 facilities, characterized by their limited area and population coverage, were situated in central urban areas, where the population density was highest and road networks were most congested. The extremely heavy traffic in these areas restricted isochrone coverage within central district regions. To meet the high demand in these areas, additional emergency facilities are necessary. The distribution of these isochrones highlighted the crucial role of traffic conditions and population density in shaping the accessibility and efficiency of emergency medical services.

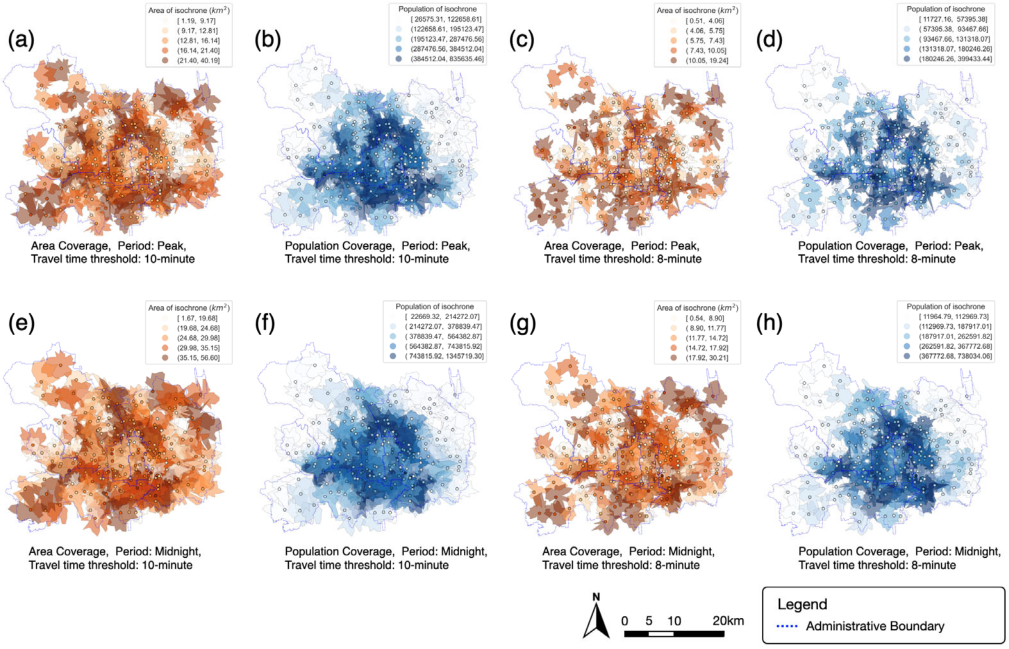


Figure 5. Spatial distribution of isochrones: (**a**) area coverage of 10-min isochrones in the peak period, (**b**) population coverage of 10-min isochrones in the peak period, (**c**) area coverage of 8-min isochrones in the peak period, (**d**) population coverage of 8-min isochrones in the peak period, (**e**) area coverage of 10-min isochrones in the midnight period, (**f**) population coverage of 10-min isochrones in the midnight period, (**g**) area coverage of 8-min isochrones in the midnight period, (**h**) population coverage of 8-min isochrones in the midnight period.

Table 3. Area and population coverage characteristics.

Type	Area Coverage	Population Coverage	Major Locations
1	Large	Large	Around traffic hubs (Near the Third Ring and Fourth Ring Roads)
2	Large	Small	Edge area of central six districts
3	Small	Large	Around borders between six districts
4	Small	Small	Middle area of each district

As shown in Figure 5, isochrone coverage overlapped significantly in the central urban area. Particularly around the border area of Dongcheng District and Xicheng District, which exhibited low area coverage but high population coverage. A comparison of the spatial distributions across different periods revealed that Type 1 locations remain relatively stable, maintaining high coverage throughout all periods due to their advantageous traffic locations. This further demonstrated the significance of the traffic to PHEMF's coverage. Conversely, some type 4 facilities had a limited area and population coverage across all periods. Their isochrones had poor coverage capacity and overlap with other facilities' isochrones. It could be integrated with the nearby facilities, which would lower operational costs without compromising service quality.

4.3. Traffic Sensitivity Analysis

Further calculating the accessibility sensitivity to the traffic of each PHEMF according to Equation (4), the results are presented in Figure 6. Accessibility sensitivity measures the proportion of area change rate between the peak and midnight periods. A higher value indicates larger area shrinkage during the peak period, demonstrating high sensitivity to traffic conditions, and vice versa.

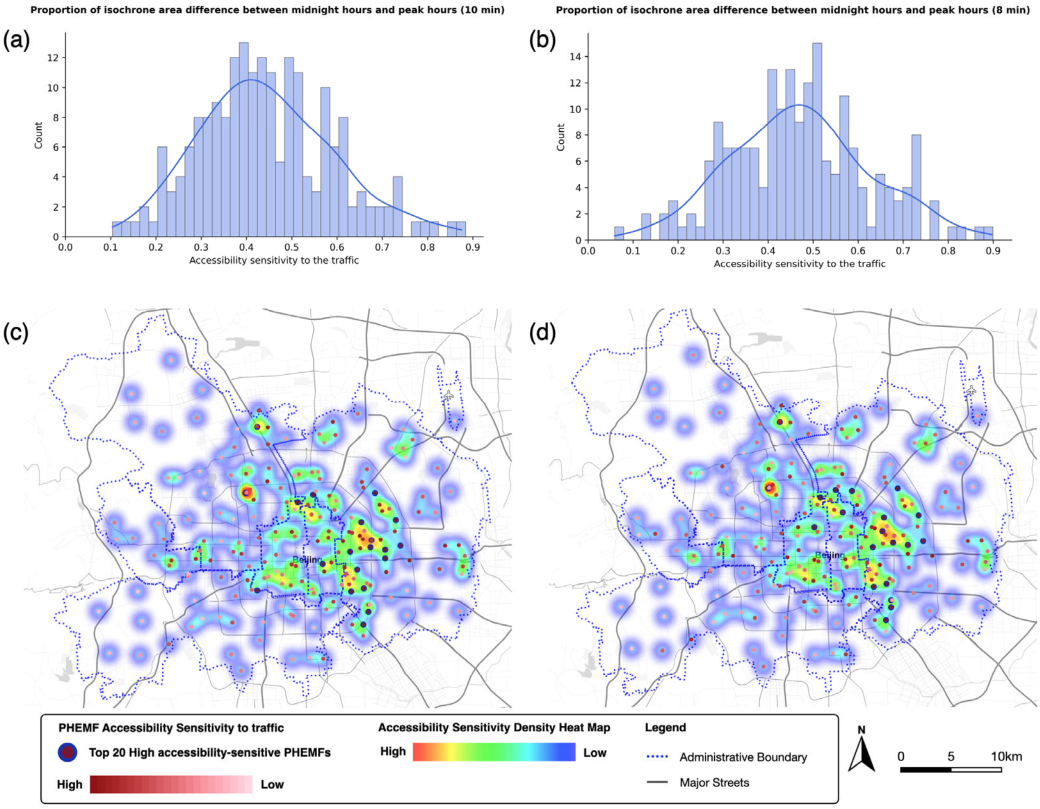


Figure 6. Distribution of PHEMF accessibility sensitivity to traffic: (**a**) 10-min travel time threshold, (**b**) 8-min travel time threshold, (**c**) accessibility sensitivity density heatmap with a 10-min travel time threshold, (**d**) accessibility sensitivity density heatmap with an 8-min travel time threshold.

The statistical results presented normal distribution patterns, with mean accessibility sensitivity around 40% and 50% for 10-min and 8-min travel time thresholds, respectively. This finding suggests that during peak times, the area coverage of the majority of PHEMFs shrank by about 50%. Additionally, the sensitivity to traffic decreased as travel time increased.

PHEMFs with accessibility sensitivity larger than 70% were identified as highly accessibility-sensitive facilities. There were 11 and 19 high accessibility-sensitive PHEMFs with a 10-min and 8-min threshold, respectively, mainly located in Chaoyang District, including the boundary region with Dongcheng District, the area between the East Third Ring Road and the Fourth Ring Road, and the northeast area between the Fourth and Fifth Ring Roads, as shown in Figure 6c,d. Furthermore, a hotspot appeared in Haidian District, located at the traffic hub between the Third and Fourth Ring Roads.

4.4. Equity Assessment Results

From the demand perspective, patients who can reach more PHEMFs within a certain time threshold have a higher chance of receiving critical medical care during emergencies. The available emergency services of each PHEMF can be represented as the available number of ambulances, the number of emergency personnel, the number of medical equipment, and so on. Each PHEMF is built and equipped according to a grade-based standard, with the fixed ambulance space representing the maximum service capacity. There are four grades of PHEMFs in Beijing: the EMC and ECSs are equipped with 30 fixed ambulance spaces, the Grade-A ESs have 6 f, and Grade-B ESs have 3. The available ambulances for each population grid (100 m × 100 m) was calculated using the method described in Section 3.2.4, with results presented in Figure 7.

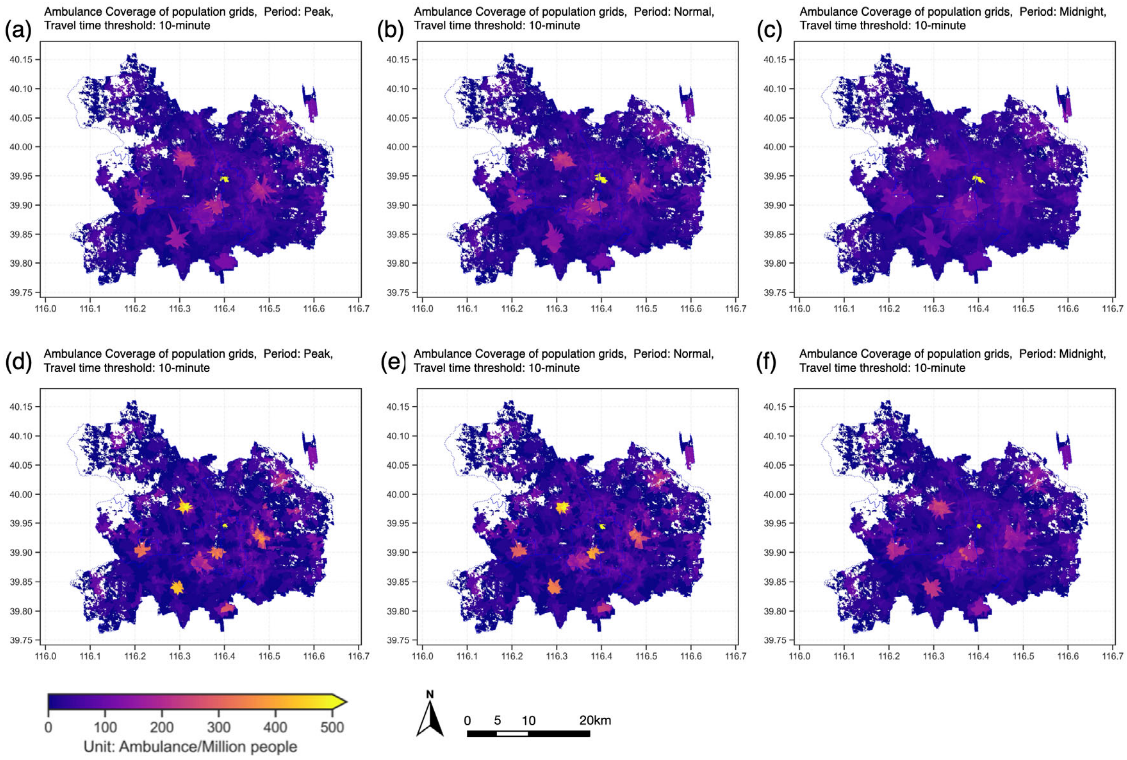


Figure 7. Accessibility of population grids with different travel time thresholds in different periods: (**a**) 10-min isochrones in the peak period, (**b**) 10-min isochrones in the normal period, (**c**) 10-min isochrones in the midnight period, (**d**) 8-min isochrones in the peak period, (**e**) 8-min isochrones in the normal period, (**f**) 8-min isochrones in the midnight period.

As shown in Figure 7, all subgraphs used a uniform color scale for easier comparison. In general, the central area of the study area had more emergency service opportunities than the outer regions. The 8-min travel time threshold showed more disparities in emergency service opportunities compared to the 10-min travel time threshold. In the peak period, as shown in Figure 7a,d, several extremely high-value regions (colored in bright yellow) existed, resulting from the reduction in coverage area during peak times. It was the calculation result of a large number of fixed ambulance spaces (EMC and ECS) but a small isochrone area coverage and small population coverage. For example, DC-001, an EMC with 30 ambulance slots, served only 36,720 population grids during peak hours, resulting in an extreme value of 816.9 ambulances per population grid.

The uneven value distribution, indicating inequality in accessibility, was more noticeable at peak and regular periods. In addition, as shown in Figure 3, there were more isochrone overlaps during the midnight hour; however, there was no obvious rise in the accessibility value of population grids compared to the peak hour. The reason lies in the high population density in the urban area, resulting in a small number of ambulances per population value and, thus, a small increment in the isochrone overlap regions. This phenomenon indicates that PHEMFs with large service area coverage and population coverage do not have an accessibility advantage in the context of resource competition. At the same time, traffic circumstances had a major impact on the service coverage of these facilities, particularly during peak hours. This results in high accessibility in local neighborhoods but an uneven distribution throughout the entire city.

Equal access to emergency services is vital for EMS planning. This analysis result provided evidence for future EMS planning and PHEMF site selection strategies. Therefore, setting more small-scale PHEMFs equipped with fewer ambulance spaces can offer better and more equitable emergency services than fewer large-scale PHEMFs equipped with more ambulances in urban areas.

5. Discussion

As a time-sensitive service, the location of pre-hospital emergency medical facilities (PHEMF) and traffic conditions directly influence service coverage and rescue efficiency. This study evaluated the accessibility of PHEMFs within Beijing's six central districts under the Special Plan by applying isochrone measures. The radial-ray-based approach and open map platform travel data used in this study showed the advantage of reflecting temporal characteristics during peak hours, midnight hours, and normal hours of the day, providing a more reliable analysis of accessibility patterns. The conducted multi-period isochrone analyses examined both the demand and supply aspects of emergency medical services, providing insights and suggestions for future planning.

Regarding the overall isochrone coverage, the coverage area for 10 min of driving was quite high, covering over 80.39% of the region at all times. In contrast, the coverage area for 8 min of driving was rather low, covering just 60.91% of the area during peak hours. This discrepancy highlights the presence of areas with low emergency service accessibility, particularly on the periphery of the study area. To address this, planning additional emergency stations in these underserved areas could improve overall coverage.

Moreover, there was a substantial overlap in isochrone coverage, with dense coverage overlap areas mostly concentrated at the intersection of different administrative districts. This resulted in an oversupply of services in certain areas, increasing operational costs, and leading to inefficient resource allocation. This phenomenon was primarily due to the current planning approach, which is based on administrative divisions. Each administrative district tends to place its facilities near its regional boundaries to meet service coverage rate requirements, resulting in overlapping coverage at these administrative boundaries. Therefore, the urban medical emergency facilities network should be designed holistically, with service coverage calculated from a city-wide perspective. Breaking the restriction of administrative boundaries is more conducive to the effective allocation of resources and efficiency optimization.

Traffic conditions significantly impacted isochrone coverage, with smooth traffic substantially increasing the coverage area. Nonetheless, the traffic in the central urban area of Beijing is relatively congested during non-night hours, with little difference observed between peak and normal periods. Facilities with larger isochrone area coverage were generally located on the periphery of the central urban area and near rapid transit nodes, while facilities in the urban core area tended to have smaller isochrone coverage areas. Therefore, future planning should adopt different strategies for various urban areas. To leverage traffic convenience, future medical emergency stations could be established near traffic hubs in less densely populated regions. In contrast, in densely populated regions, which are mostly located in the central areas of the city, the planning strategy should be adjusted to reduce the scale of a single facility but increase the local facility density and reserve isochrones overlapping. This approach aims to minimize the long service response time caused by traffic congestion.

The accessibility sensitivity to the traffic of each PHEMF was identified by calculating the change rate of the coverage area at midnight and peak periods. The higher the accessibility sensitivity to traffic, the more obvious the reduction in service area during peak hours. The calculation showed that the shorter the travel time, the more the number of facilities is sensitive to traffic. Extending the travel time can not only effectively expand the service coverage of ambulances but also reduce the number of highly traffic-sensitive facilities. Therefore, it is recommended to minimize the medical emergency system's acceptance, information transmission, and departure times to maximize ambulance driving time and broaden the range of services that PHEMFs can provide. Therefore, minimizing system acceptance, information transmission, and departure times is crucial to maximizing ambulance driving time and service range.

One possible planning approach for PHEMFs with high traffic sensitivity involves meeting coverage requirements with numerous small area coverage stations and adding more station sites surrounding the current stations. Additionally, increasing mobile vehicles as temporary emergency stations during peak hours in traffic-sensitive areas can also expedite service response times. There are two types of PHEMFs with low accessibility sensitivity to traffic: one is the facility with a larger isochrone coverage area at all times, and the other is the facility with a smaller isochrone coverage area at all times. For the former, expanding their construction scale can help meet demand within their service areas and support nearby facilities. For the latter, integrating these facilities with nearby ones can reduce operational costs without compromising overall service coverage. Furthermore, newly planned PHEMF sites are better suited to areas with less traffic.

Accessibility and demand competition significantly impact the availability of emergency medical supplies from an equity standpoint. This is especially crucial during disasters like earthquakes or the COVID-19 pandemic, where high demand for EMS poses a barrier to the equitable distribution of medical resources. PHEMFs with large area and population coverage have less competitive advantage but are more susceptible to traffic, which is consistent with the traffic sensitivity analysis results. Thus, increasing the number of small-scale stations in areas with high population density may be advantageous for both population equality and overall coverage rates. Traffic conditions significantly influence planning outcomes, necessitating future strategies to address uncertainties and improve accessibility and efficiency.

6. Conclusions

This study used isochrone measures to evaluate the accessibility of PHEMFs within Beijing's six central districts under the Special Plan. The analysis results revealed several key findings and areas for potential improvement.

The findings indicate that while the 10-min isochrone coverage was high, the 8-min coverage was insufficient, particularly during peak hours, highlighting gaps in service accessibility in the current plan. This disparity underscores the need for additional emergency stations in underserved areas to enhance overall coverage.

The current planning approach resulted in significant isochrone coverage overlap at administrative district intersections, leading to service oversupply and increased costs. Addressing this requires a city-wide planning perspective, breaking administrative boundaries to optimize resource allocation.

Traffic conditions were a critical factor affecting service coverage. Congestion reduced coverage in central areas, while facilities near traffic hubs in less populated regions showed better coverage. Future planning should strategically place emergency stations considering traffic patterns, with more stations near traffic hubs in less dense areas and increased facility density in urban cores to mitigate congestion impacts.

The sensitivity analysis highlights the importance of extending travel times to expand coverage and reduce traffic sensitivity. Minimizing system acceptance, information transmission, and departure times is crucial to maximizing ambulance driving time and service range.

In conclusion, while the current planning approach meets several objectives, challenges remain in service availability and equity. Addressing these issues requires integrated and flexible planning strategies that account for traffic conditions and population distribution. Future research should focus on refining these strategies and exploring innovative solutions to enhance the accessibility and equity of emergency medical services in urban areas.

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Zhou; funding acquisition, Ying Zhou. All authors have read and agreed to the published version of the manuscript.

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