Received December 21, 2020, accepted January 1, 2021, date of publication January 8, 2021, date of current version January 15, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3049814

Urban Public Transport Accessibility to Medical Services From the Perspective of Residents' Travel: A Hybrid Assessment Based on the Whole Process

XIN FU[1], YONGJIE QIANG[1], JIANWEI WANG[1], XIAOXUAN ZHAO[1], FENG-JANG HWANG[2], AND CHI-HUA CHEN[3,4], (Senior Member, IEEE)

[1]College of Transportation Engineering, Chang'an University, Xi'an 710064, China
[2]Transport Research Center, School of Mathematical and Physical Sciences, University of Technology Sydney, Ultimo, NSW 2007, Australia
[3]College of Mathematics and Computer Science, Fuzhou University, Fuzhou 350108, China
[4]Key Laboratory of Intelligent Metro of Universities in Fujian, Fuzhou 350108, China

Corresponding authors: Yongjie Qiang (2018223011@chd.edu.cn) and Jianwei Wang (wjianwei@chd.edu.cn)

This work was supported in part by the Fundamental Research Funds for the Central Universities under Grant 300102230501, in part by the Major Theoretical and Practical Problems Research Project of Social Science Circles in Shaanxi Province in 2020, Project name: Research on coupling mechanism and congestion management strategy of urban comprehensive transportation network system based on hypernetwork, under Project 2020Z033, in part by the Key Research Base Project of Philosophy and Social Science of Education Department of Shaanxi Province, Project name: Research on Taxi Governance through the Background of the Internet under Project 19JZ008, and in part by the National Natural Science Foundation of China under Grant 61906043.

ABSTRACT Equitable access to efficient medical services via public transport has always been one of the most important issues of healthcare in urban development. To accurately measure the urban public transport accessibility to medical services (PTAMS), this research proposes a hybrid assessment method based on multiple public-transport related indicators, including time, cost, and walking rate, which considers the whole process of residents' public transport travel. The presented assessment technique is then applied in a case of Xi'an, China. Through the classification of medical facilities and PTAMS levels, the results show that: (a) PTAMS value of 3,080 residential areas in Xi'an are highly consistent with the standard normal distribution; (b) More than 80% of residential areas can obtain high PTAMS when considering the use of Class 1 (large-scale) hospitals, while the high PTAMS of Class 2 (small-scale) ones can only cover less than 40% residential areas; (c) There is obvious spatial heterogeneity in the distribution of PTAMS in Class 2 hospitals and a serious lack of medical equity; (d) Among large hospitals, the private ones retain higher PTAMS and equitability, making themselves best choice for residents, which is opposed to the government's purpose of establishing public hospitals; (e) PTAMS of most residents substantially dropped about 4% during the morning peak-hour. However, subway protects PTAMS of nearby residents. This research provides references and suggestions on how to improve residents' PTAMS under the existing public transport network and medical facilities layout.

INDEX TERMS Public medical facilities, public transport, spatial accessibility, residents, VIKOR, entropy weight method.

I. INTRODUCTION

Social public infrastructure services cover the healthcare, education, entertainment, transportation, and other fields of a city [1], which play an important role in enhancing the level of urban development and the living standards of citizens [2].

The associate editor coordinating the review of this manuscript and approving it for publication was Michail Makridis.

In the increasingly urbanized environment, rapid population growth, deterioration of traffic conditions, land use disorder, and other factors have led to uneven distribution and insufficient supply of medical facilities, which are closely related to residents' lives [3]. Then the availability of urban medical facilities limits residents' rights to obtain basic medical resources, which in turn will result in social inequity of medical services [4]. Thus, it is critical for all residents to get access to the equitable distribution of medical facilities, as well as health care services in the process of urban development [5]. It has been suggested to realize this goal from five dimensions: accessibility, availability, accommodation, acceptability, and affordability [6]. Since the accessibility to healthcare services is one of the indispensable dimensions, investigating the medical accessibility for providing efficient and equal medical services is crucial.

Furthermore, it was considered that public transport is also an extremely important part of public facilities and a basic condition for the normal operation of a city [7]. The primary access to medical services for most civil populations, including the middle- or low-income people with low mobility, would be public transport. Therefore, how to evaluate the accessibility to medical services via public transport is well worth studying. In the past, the research on public transport accessibility (PTA) can be divided into three types, i.e. access to stations, networks accessibility, and access to activities [8], which consider the accessibility to public transport services. However, our study is aimed at utilizing PTA to measure the accessibility to public transport users' specific destinations, which is the accessibility via public transport [9]. Therefore, public transport accessibility of medical services (PTAMS) is proposed to describe PTA with medical facilities as the destination.

However, previous studies have paid more attention to PTAMS with only bus (or subway), mostly focusing on a single and classic indicator of time [10], but ignoring others. Public transport is composed of lines and stations with different modes [11], transfer between different public transport modes is a behavior that often occurs during the actual travel. For the population using public transport, the key considerations that affect their decision-making in choosing public transport routes and reflect the comfort of traveling would include fare, travel time, and walking distance, which shall thus be the relevant factors in the study of PTAMS. On the other hand, residents are users of public transport and medical facilities, but they are rarely emphasized in the process of evaluating PTAMS, which shall be an important aspect.

Therefore, this paper proposes a novel perspective to measure PTAMS by considering multiple public-transport related indicators, such as time, cost, walking rate, etc., in different aspects. And the public transport system discussed in the paper includes a mixture of bus and subway. The purpose is to evaluate comprehensively PTAMS of residential areas, providing a reference for the location planning of them under the existing public transport network and medical facilities layout. Then the developed assessment method can help improve the equitability and efficiency of medical services for residents considering public transport. For specific steps, we first coordinated the conflict problems using multiple indicators by determining the weights. Then the multi-attribute evaluation and decision-making procedure is utilized to evaluate PTAMS.

Three potential academic contributions are drawn based on the proposed hybrid assessment method: (i) Be able to measure PTAMS in a multimodal public transport system based on "door to door" and consider the actual traffic information; (ii) PTAMS of all residential areas can be evaluated instead of considering medical facilities only; (iii) Multiple indicators are taken into account so that the multi-attribute evaluation and decision-making procedure can be constructed reasonably and comprehensively in the complex public transport system.

In this paper, Xi'an City in China is chosen as a case study for applying the proposed assessment method. The remainder of the paper is organized as follows. The second section provides the literature review, which summarizes the methods of measuring accessibility. In the third section, the research data and methods are presented to introduce the research region, the relevant data, and the developed method. The fourth section is the results. The fifth section is the discussion, presenting a spatiotemporal analysis based on the yielded assessment results. The conclusions and future work are given in the sixth section.

II. LITERATURE REVIEWS

Most past research considered the medical accessibility in urban areas and used the developed GIS platform to introduce relevant models for analysis. Some scholars introduced the commonly used two-step floating catchment area (2SFCA) method to quantify the accessibility to medical services in rural areas, verifying that the method is applicable to rural areas outside the city [12]. In addition to the 2SFCA method, the gravity model method has also been widely used. Some researchers calibrated the gravity coefficient of each hospital through the day and address of patients, so as to predict the impact of new medical facilities' opening on the distribution of existing medical service areas [13]. Though these two methods have been widely used in this field, they actually stem from the same principle [14] and have some defects. Several later studies thus improved the methods according to the actual scenarios considered in their work. By improving the existing FCA methods, two distance attenuation functions were proposed to explain the different treatment modes and an adjustment factor was introduced to solve the underlying demand, improving the measurement of spatial accessibility of the emergency medical system [15]; In addition, the data with a grid-based population and estimated travel time was acquired to evaluate the accessibility to hospitals [16]. Most research adopting the GIS platform, however, pays too much attention to the related spatial factors and ignores other influencing factors. Wang and Luo, therefore, considered some non-spatial factors, such as age, education, and income, in order to integrate the spatial factors of the accessibility to medical facilities and the non-spatial ones into a single approach for accessibility evaluation [17].

Regarding relevant methods used in space measurement for public infrastructure other than medical facilities, some scholars proposed a potential model based on multiple modes to measure the accessibility to urban facilities for families in each region, considering the different transport modes and destination attraction [18]; and some studies, by considering the population projections, locations of the fire stations, and the road network, calculated the relationship between residents' spatial accessibility to fire services and the population increase of the region with an improved 2SFCA method [19]; Hernandez *et al.* used a multilevel logistic model to evaluate the impact of job accessibility on unemployment, and concluded that the higher the job accessibility, the higher the personal outcomes [20]; Xu *et al.* crawled the travel time of four travel modes including public transport through Baidu Map and four baseline indicators were used to measure the accessibility of different levels of parks [21].

As for the PTA measurement, some scholars used a kernel-density 2SFCA method to simulate the declining trend in service capacity of hospitals with the increasing travel time, under both public transport and private driving conditions [22]; Liu *et al.* introduced the time spent on walking, transferring, waiting, and commuting from Hongqiao transport hub in Shanghai to all parts of the city as an indicator of accessibility to the public transport system [23]; Considering the time spent on taking public transport, e.g. walking from/to/between the station(s), waiting for the bus, on the way, etc., a multimodal gravity model with different time weighting was put forward to measure PTA [24].

To sum up, relevant accessibility measurement methods proposed in existing research have been relatively mature and systematic, and some of them have been used to measure PTAMS. However, most studies only consider a single indicator and focus on the perspective of facilities. Considering the characteristics of the public transport system, this paper proposes a hybrid PTAMS assessment model, which combines the VIKOR (VlseKriterijumska Optimizcija I Kaompromisno Resenje in Serbian) method and the entropy weighting method (EWM) by including the perspective of transport users. The VIKOR method considers the close degree of positive and negative ideal solutions of each evaluation scheme, as well as the maximization of group utility and the minimization of individual regret [25], [26] so that the decision-making result is relatively reasonable. The EWM lies in its clear calculation procedure and mathematical significance, which can avoid subjectivity [27]. Therefore, the combination of them is readily applicable in solving the ranking evaluation problem of complex systems [28], [29].

III. DATA AND METHODOLOGY

A. DATA DESCRIPTION

Xi'an, the most populous city in Northwest China [30], has become a medical resource concentration area with rapid urbanized development [31]. At present, there are 133 large high-level hospitals, 108 community primary hospitals, 222 community health service centers, and many other medical institutions of different scales [32]. In terms of public transport, the current public transport system in Xi'an is composed of bus and subway, 409 bus lines and 4 subway lines are in operation to meet people's daily travel demands. Detailed content can be seen in Table 1.

TABLE 1. Medical and public transport resources in Xi'an [32], [33].

Resources	Item	Value
Medical facilities	Large high-level hospitals (pieces)	133
	Community primary hospitals (pieces)	108
	Community health service centers (pieces)	222
Public transport	Operating vehicles (units)	8743
	Total of bus passenger (10,000 person-times)	135919
	Length of subway lines in operation (km)	126.7
	Total of subway passenger (10,000 person-times)	74624.64

Additionally, the bus fare is a one-ticket system, and the fees for different lines are not necessarily, generally 0.5¥, 1¥, 2¥, etc., while the subway adopts a mileage-based charging model with the starting price of 2¥ ($\leq$6km). Public transport charges are fixed at different time periods. Rich medical resources and perfect public transport infrastructure make Xi'an a very suitable case for our study.

Baidu Map and Amap (National geographic information travel service provider with the largest number of users in China) can provide people with the optimal planning route under the public transport travel mode in real time, and also provide API (Application Programming Interface) to facilitate people to obtain these data. The optimal planning route includes three situations: (a) Only use bus; (b) Only use subway; (c) Transfer between bus and subway. It depends on the real-time traffic information, how far you are from the nearest bus stop (subway station), etc. Through programming via python, firstly, we obtained the location information of all residential areas and medical facilities in the study area and put them into two data sets: departure and destination. Then, the optimal public transport routes from each residential area in the departure data set to each medical facility in the destination data set were collected in the morning and flat peak-hour for a week [34].

All medical facilities in our study are divided into two major classes according to the medical level and scale: Class 1 hospitals (large high-level medical facilities) and Class 2 hospitals (small general-level community medical facilities). Among them, Class 1 hospitals can be subdivided into four subclasses. The classification can be seen in Fig. 1.

For POI data, 3,080 residential areas, 103 Class 1 hospitals, and 172 Class 2 hospitals were determined as research objects. 103 Class 1 hospitals include 69 public hospitals and 34 private hospitals, or 78 general hospitals and 25 specialized hospitals.

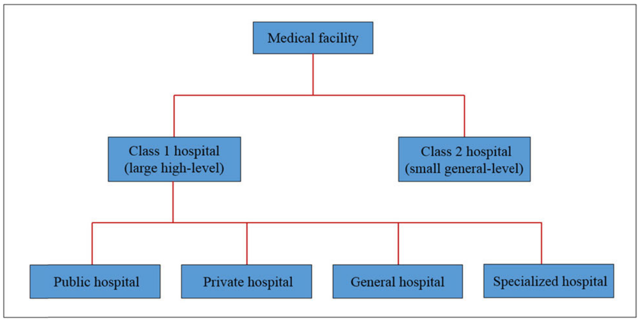


FIGURE 1. Classification of medical facilities.

For path data, as the main medical services are concentrated during the daytime, the data were continuously collected from 26 August 2019 to 30 August 2019 during the morning peak-hour (7 a.m. to 9 a.m.) and the flat peak-hour (10 a.m. to 5 p.m.). The typical peak hour of the area is determined by the average speed of all road sections obtained from Amap, which can be seen in Fig. 2. Four main fields were used: *cost* (C), *time* (T), *totaldistance* (TD), and *walkingdistance* (WD). The ratio of WD to TD was used to build a new field *walkingrate* (D), to measure the comfort of traveling by public transport; C and T are the fare cost and time cost, respectively. Additionally, the data of T obtained in different time periods takes into account the actual traffic status (Fig. 2), even for the same route, T will also change due to road conditions. So, these data contain spatiotemporal information. In the process of data processing, we first deleted the invalid routes with null values in the indicators. Then, the data of four indicators collected continuously for a week between the same departure and destination were averaged. From this, we got the average time, average cost, and average walking rate from each residential area to each hospital.

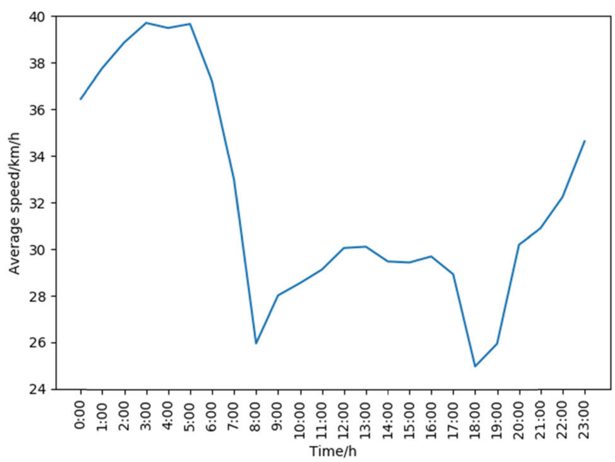
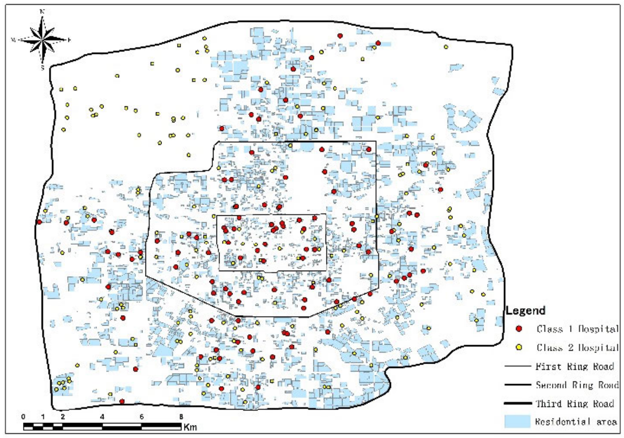
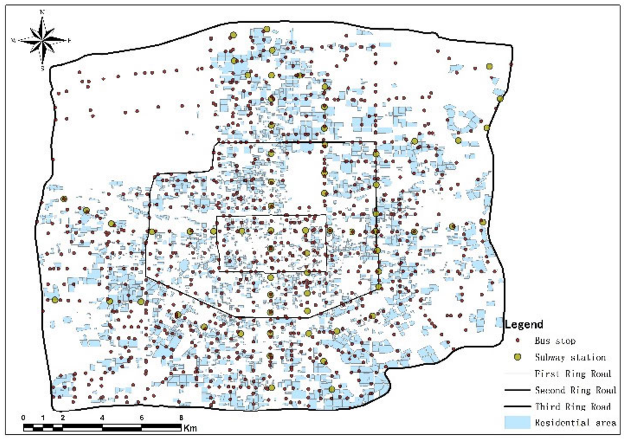


FIGURE 2. The average speed of the road network.

The fields of the above data are shown in Table 2. The study area is determined to be within the third ring road of Xi'an. The study area, medical facilities, residential areas, and public transport stations that have been put into use are shown in Fig. 3.



(a)



(b)

FIGURE 3. Study area and facility distribution. (a) Residential areas and medical facilities; (b) Residential areas and public transport stations.

B. METHODOLOGY

Considering the conflict between indicators of different aspects, each of them should be given the corresponding weight to determine its influence. Then the multi-attribute decision-making procedure is used to evaluate comprehensively each public transport route from residential areas to hospitals based on these indicators, obtaining the evaluating value. Some scholars have used the same method to integrate the degree centrality, closeness centrality, and betweenness centrality to comprehensively evaluate and rank the complex network nodes [29]. Therefore, the methodology is suitable for the complex system of public transport. Public transport routes are comprehensively evaluated under multiple criteria to obtain evaluation values. The mean value of all routes from the same residential area is its PTAMS.

In the proposed VIKOR-EWM hybrid assessment method, the EWM is used to solve the problem of multi-indicator conflict. Then the VIKOR is employed to deal with the prob-

TABLE 2. The fields of POI data and public transport route data.

Data Name	Number	Field Name	Remarks
POI Point Data	275	Name	Name of hospital
		Address	Address of hospital
		Latitude	Latitude of hospital's location
		Longitude	Longitude of hospital's location
POI Fence Data	3,080	Name	Name of residential area
		Address	Address of residential area
		Fence coordinates	Longitudinal and latitudinal coordinate series of residential area
Public Transport Route Data	826,938	Origin	Name of residential area
		Destination	Name of hospital
		Cost (C)	Cost of the public transport route
		Time (T)	Time of the public transport route
		Total distance (TD)	Total distance of the public transport route
		Walking distance (WD)	Walking distance of the public transport route
		Path coordinates	Longitudinal and latitudinal coordinate series of the public transport route

lem of multi-attribute decision-making considering the complex public transport system. The framework can be seen in Fig. 4.

The specific steps of the proposed model are shown as follows:

Step 1. Constituting and normalizing the decision matrix

The original decision matrix $\mathrm{R} = (r_{ij})_{m\times n}$ is constructed by evaluating m public transport routes with n indicators obtained from the path data, i.e.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}, \tag{1}$$

where r_{ij} is the value of the i-th route under the j-th indicator.

In order to eliminate the unit effect among the indicators, the normalized dimensionless processing method is adopted as follows:

$$r'_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}. \tag{2}$$

The standardized matrix $R' = (r'_{ij})_{m\times n}$ is obtained as follows:

$$R' = \begin{bmatrix} r'_{11} & r'_{12} & \cdots & r'_{1n} \\ r'_{21} & r'_{22} & \cdots & r'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r'_{m1} & r'_{m2} & \cdots & r'_{mn} \end{bmatrix}. \tag{3}$$

Step 2. Calculating the weight of the indicators

(i) Calculate the proportion P_{ij} for each of m routes under n indicators:

$$P_{ij} = \frac{r'_{ij}}{\sum_{i=1}^{m} r'_{ij}}. \tag{4}$$

(ii) Calculate the entropy value E_j for each of n indicators:

$$E_j = -\frac{1}{\ln m} \sum_{i=1}^{m} P_{ij} \cdot \ln P_{ij}. \tag{5}$$

(iii) Calculate the entropy weight W_j under each of n indicators:

$$W_j = \frac{1 - \mathrm{E}_j}{\sum_{j=1}^{n} (1 - E_j)}. \tag{6}$$

Step 3. Calculating the comprehensive evaluating value of each public transport route at different times

(i) For the normalized decision matrix R', calculate the positive ideal solution $r_j'^{*}$ and the negative ideal solution $r_j'^{-}$ of n evaluating indicators:

$$r_j'^{*} = \left[\left(\max_i r'_{ij} \,|\, j \in A\right) or \left(\min_i r'_{ij} \,|\, j \in B\right)\right]; \tag{7}$$

$$r_j'^{-} = \left[\left(\min_i r'_{ij} \,|\, j \in A\right) or \left(\max_i r'_{ij} \,|\, j \in B\right)\right], \tag{8}$$

where A is the benefit-type indicator set, and B is the cost-type indicator set.

(ii) Calculate the values of the best solution S_i and the worst solution R_i for comprehensive evaluation:

$$S_i = \sum_j^n W_j \left(r_j'^{*} - r'_{ij}\right) / \left(r_j'^{*} - r_j'^{-}\right); \tag{9}$$

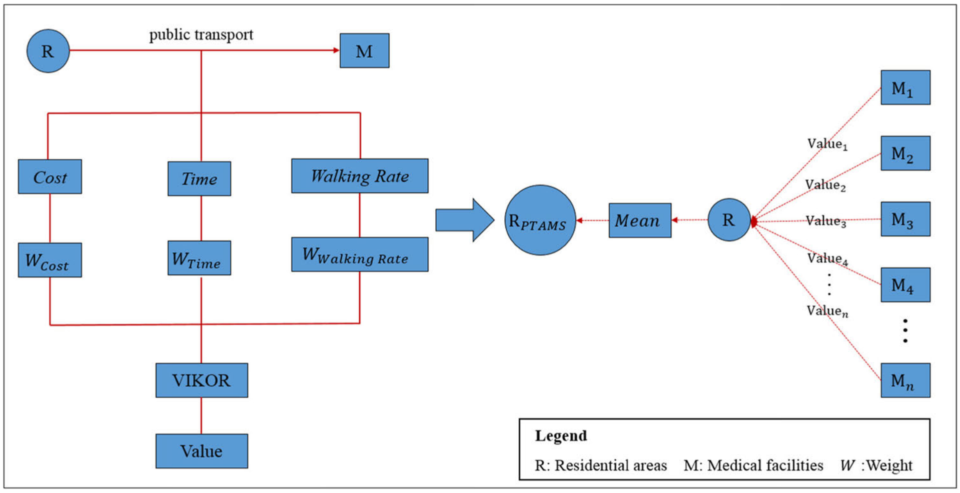


FIGURE 4. Framework of the VIKOR-EWM hybrid assessment method.

$$R_i = max\left[W_j\left(r_j'^* - r_{ij}'\right)/\left(r_j'^* - r_j'^-\right)\right], \quad (10)$$

where W_j is the weight of each indicator.

(iii) Calculate the comprehensive evaluating value $(Q_{hk})_t$ of the route from the h -th residential area to the k -th medical facility at different times:

$$(Q_{hk})_t = v\left(S_i - S^*\right)/\left(S^- - S^*\right) + (1-v)(R_i - R^*)/(R^- - R^*). \quad (11)$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$, t represents different times, and v, which is set at 0.5 in this study, represents the weight or maximum group utility value of the most-criteria strategy.

Step 4. Calculating PTAMS of each residential area at different times:

$$(PTAMS_h)_t = \frac{\sum_{k=1}^{q}(Q_{hk})_t}{q}. \quad (12)$$

where q represents the number of medical facilities, t represents different times.

Through the above formulated model, the quantitative PTAMS value has a negative correlation with PTAMS, i.e. the higher the generated value, the lower PTAMS.

IV. RESULTS

A. SPATIAL RESULTS OF PTAMS

After the data set constructed, the statistical description of C, T, and D is shown in Table 3. According to the mean and median, it takes less fare and time to Class 1 hospitals generally. However, the trip asks for a lot of walking, the walking distance accounts for a larger proportion of the total distance.

The weights were obtained through the EWM in Table 4, then PTAMS of 3,080 residential areas can be calculated. Fig. 5 shows their spatial distribution.

Distribution characteristics of PTAMS values can be seen in Fig. 6. The results in Fig. 6(a) show that the mean value of PTAMS to Class 1 and Class 2 hospitals are 0.22 and 0.19 respectively. PTAMS obtained by the same residential area to two classes of hospitals are generally at the same level. The Kernel Density Estimation (KDE) of the results can be

TABLE 3. The statistical description of public transport route data.

	Class 1 Hospital			Class 2 Hospital		
	C (¥)	T (s)	D (#)	C (¥)	T (s)	D (#)
Max	12.0	10535	84.37%	14.0	15465	82.62%
Min	0.5	373	0.04%	0.5	452	0.10%
Mean	2.8	3382	13.83%	3.3	4028	12.24%
Median	2.0	3188	11.52%	3.0	3840	9.91%
Std. Dev	1.2	1357	9.54%	1.4	1564	8.94%

TABLE 4. Weights of indicators.

	C	T	D
Class 1 Hospital	$W_1 = 0.225098$	$W_2 = 0.214534$	$W_3 = 0.560368$
Class 2 Hospital	$W_1 = 0.236299$	$W_2 = 0.194204$	$W_3 = 0.569498$

TABLE 5. Comparison of the data of the morning and flat peak-hour.

	Class 1 Hospital						Class 2 Hospital					
	Morning peak-hour			Flat peak-hour			Morning peak-hour			Flat peak-hour		
	C (¥)	T (s)	D (#)	C (¥)	T (s)	D (#)	C (¥)	T (s)	D (#)	C (¥)	T (s)	D (#)
Mean	2.22	2462	20.13%	2.25	2217	20.73%	2.23	2593	21.32%	2.26	2320	22.04%
Median	2.00	2346	17.62%	2.00	2143	18.27%	2.00	2473	18.96%	2.00	2240	19.77%
Std.Dev	0.63	878	11.37%	0.67	705	11.44%	0.67	875	12.00%	0.72	699	12.14%

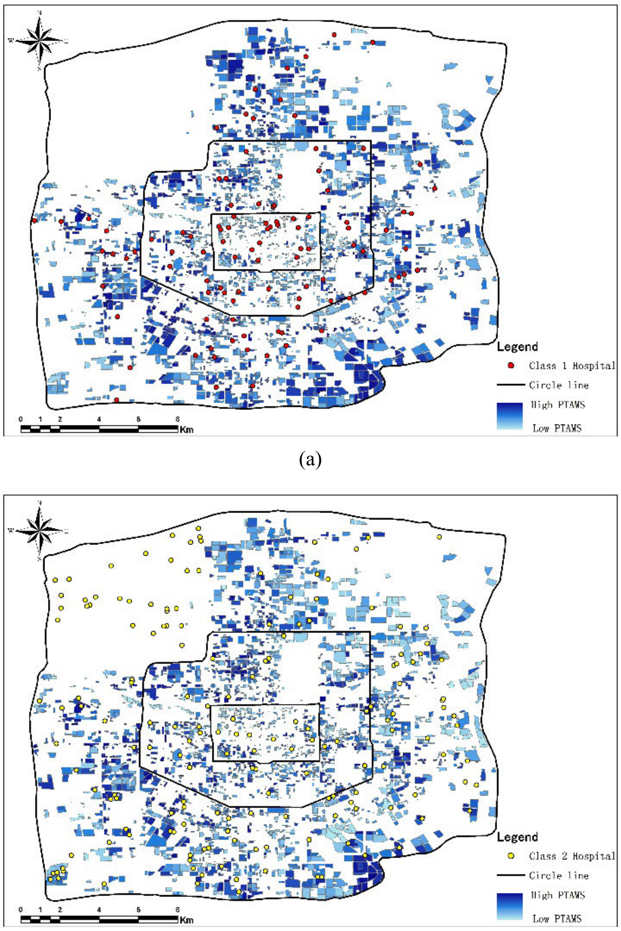


FIGURE 5. Spatial distribution of residential areas' PTAMS. (a) Class 1 hospitals; (b) Class 2 hospitals.

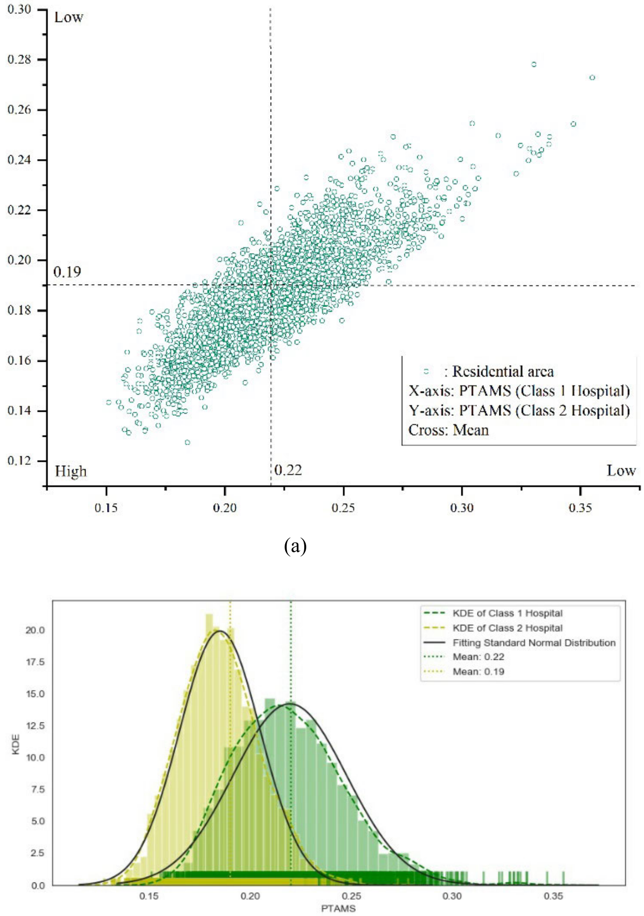


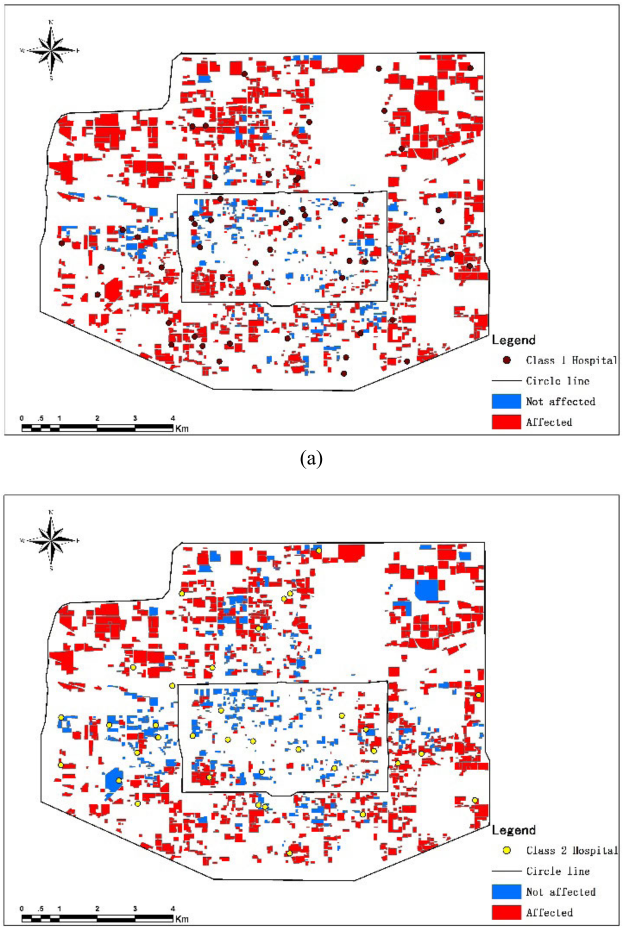
FIGURE 6. Distribution characteristics of PTAMS values. (a) Data distribution characteristics; (b) Statistical distribution characteristics.

seen in Fig. 6(b). PTAMS to Class 1 and Class 2 hospitals all show highly fit to the standard normal distribution, the Class 2 hospitals in particular. In addition, both peaks of KDE were slightly lower than their mean value, implying that PTAMS of a considerable number of residential areas are above the average level.

B. TEMPORAL RESULTS OF PTAMS

On the temporal scale, the reason why the area was selected as a special case for temporal analysis is that the high density of medical resources distributes along the second ring road in Xi'an. The same method is used to calculate PTAMS of each residential area in the morning and flat peak-hour respectively. The comparison of the data in the two periods can be seen in Table 5, in which T has increased significantly.

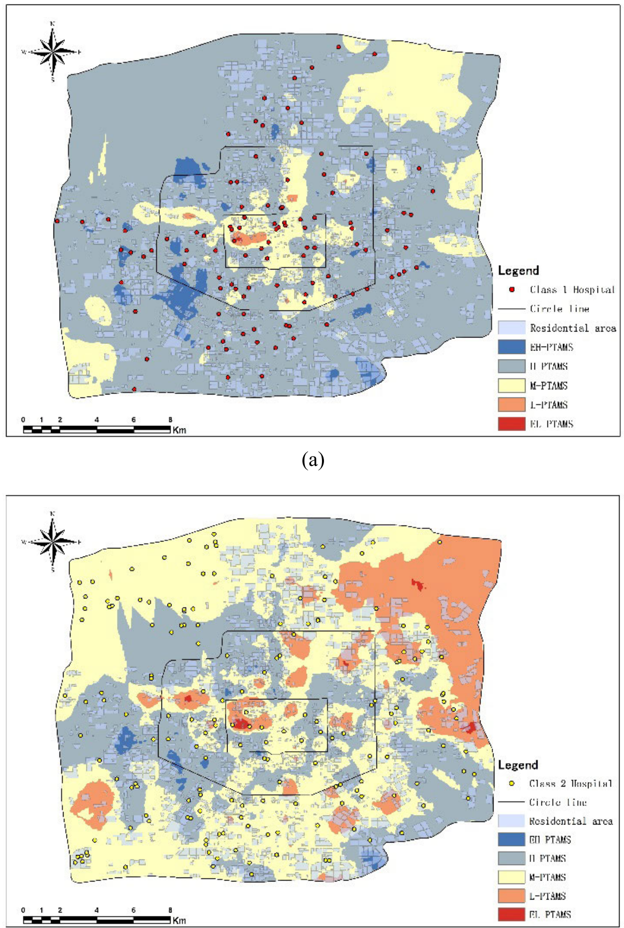
The comparative results of PTAMS show that the morning peak-hour has a significant impact on residents' medical treatment. With the urban traffic congestion increases, the running speed of each section is affected seriously, which may lead the optimal planning route to change compared



(a)

(b)

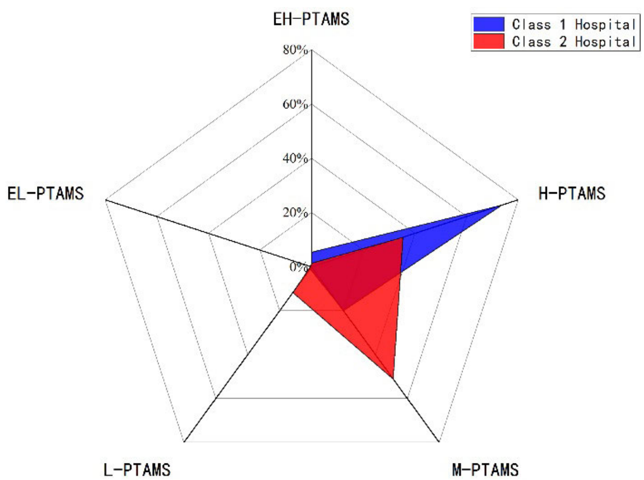
FIGURE 7. **Distribution of residential areas affected by the morning peak-hour. (a) Class 1 hospitals; (b) Class 2 hospitals.**



(a)

(b)

FIGURE 8. **Spatial pattern of residential areas' PTAMS. (a) Class 1 hospitals; (b) Class 2 hospitals.**



*Unit scale indicates the proportion of residential areas covered by different levels of PTA

FIGURE 9. **The proportion of residential areas covered by different levels of PTAMS.**

with the flat peak-hour. Therefore, most of their PTAMS has been damaged. Especially for the use of Class 1 hospitals, the affected residential areas are accounting for 81%, 12% higher than the other class, which can be seen in Fig. 7.

Among these affected residential areas, their PTAMS added value can be seen in Table 6. PTAMS decreases by about 4% overall compared with the flat peak-hour with the maximum damage close to 20%.

V. DISCUSSION

A. SPATIAL ANALYSIS OF PTAMS

1) CLASS 1 AND CLASS 2 HOSPITALS

Considering the distribution of different hospital classes, it is worth noting that when residents make access to variant medical needs, their PTAMS will also form different patterns. Therefore, Kernel Density Analysis [35] in GIS was used to analyze the spatial characteristics of PTAMS to different hospital classes. PTAMS is equally divided into five levels according to the kernel density value, namely EH-PTAMS (Extremely High PTAMS), H-PTAMS (High PTAMS), M-PTAMS (Medium PTAMS), L-PTAMS (Low PTAMS), EL-PTAMS (Extremely Low PTAMS) in Table 7. And Fig. 8 shows the spatial pattern based on Kernel Density.

Additionally, the proportion and accumulative proportion of residential areas covered by different levels of PTAMS is revealed in Fig. 9 and Fig. 10. With that in mind more residential areas can obtain high PTAMS when they

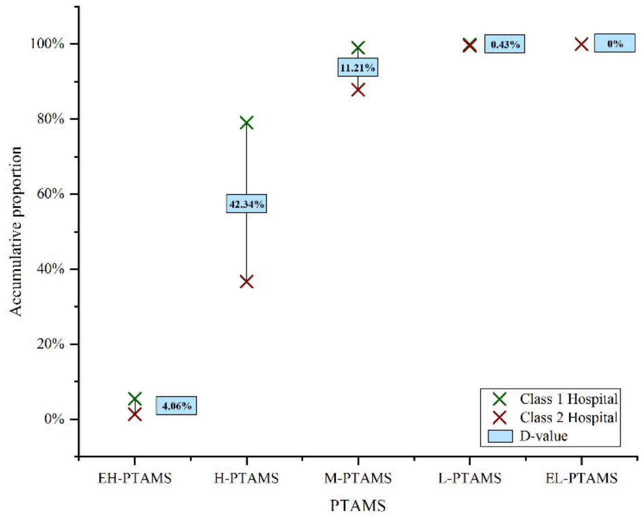


FIGURE 10. **The accumulative proportion of residential areas covered by different levels of PTAMS.**

choose Class 1 hospitals as the target of medical treatment, the accumulative proportion with EH-PTAMS, H-PTAMS are close to 80%. In contrast, the current situation of Class 2 hospitals is not friendly. The residential areas obtaining EH-PTAMS, H-PTAMS are less than half, mainly concentrating on M-PTAMS. Combined with Fig. 8, there is an obvious agglomeration phenomenon, showing extreme inequity compared with Class 1 hospitals.

TABLE 6. **The increase of PTAMS value of the affected residential areas.**

	Class 1 Hospital	Class 2 Hospital
Max	19.17%	21.79%
$Mean$	4.20%	3.81%
$Median$	3.59%	3.22%

Generally speaking, under the current medical pattern in Xi'an, the high-level service of large hospitals has a wider radiation range and higher equitability. By contrast, small community hospitals are more likely to serve small-scale residents in specific areas limited by the equitable medical service. Unquestionably, it in line with the community

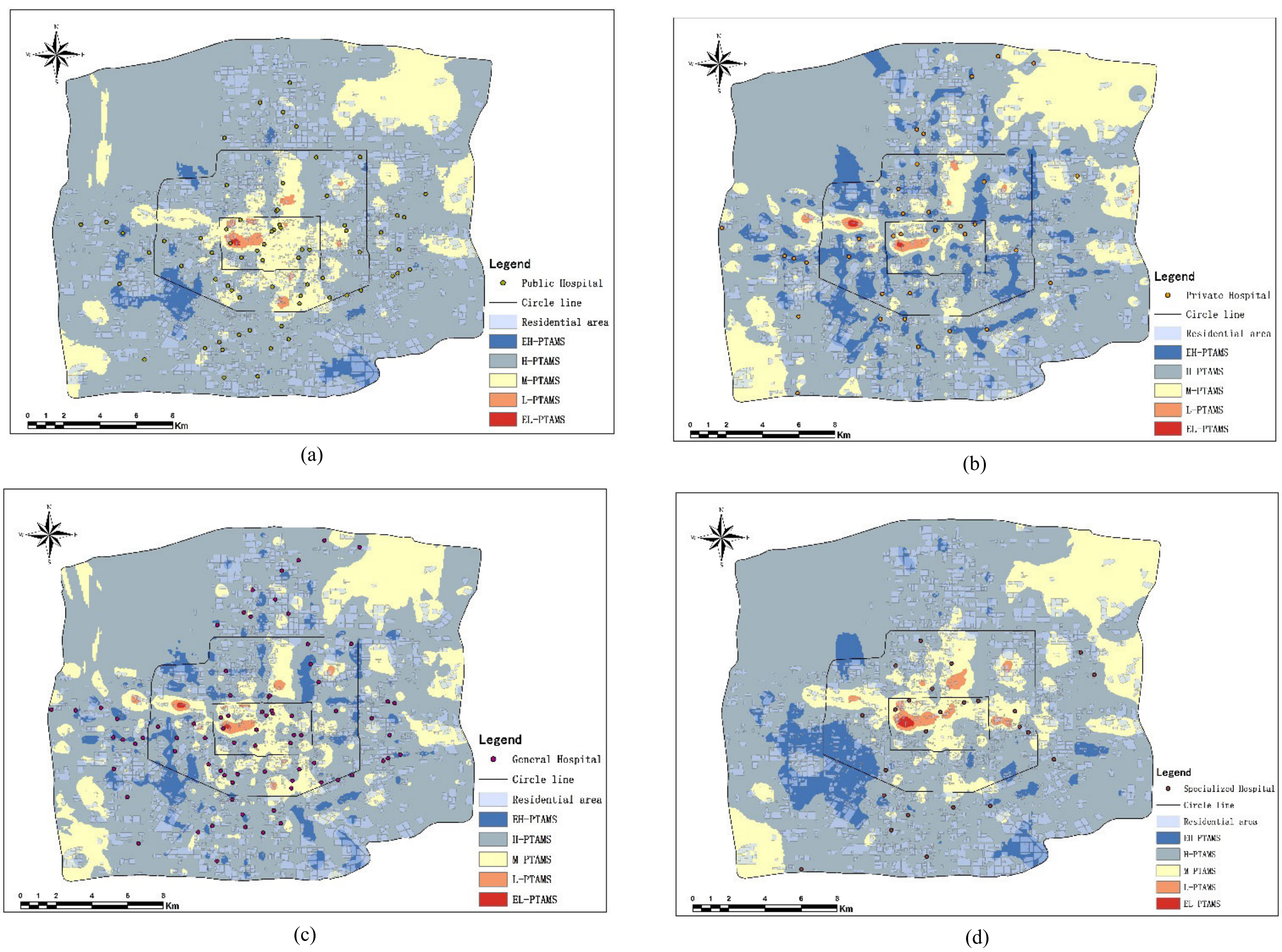


FIGURE 11. **Spatial pattern of residential areas' PTAMS. (a) Public hospitals; (b) Private hospitals; (c) General hospitals; (d) specialized hospitals.**

TABLE 7. Kernel density value range of PTAMS at different levels.

PTAMS	Class 1 Hospital	Class 2 Hospital
EH-PTAMS	0.150 - 0.192	0.14 - 0.16
H-PTAMS	0.192 - 0.234	0.16 - 0.18
M-PTAMS	0.234 - 0.276	0.18 - 0.20
L-PTAMS	0.276 - 0.318	0.20 - 0.22
EL-PTAMS	0.318 - 0.360	0.22 - 0.24

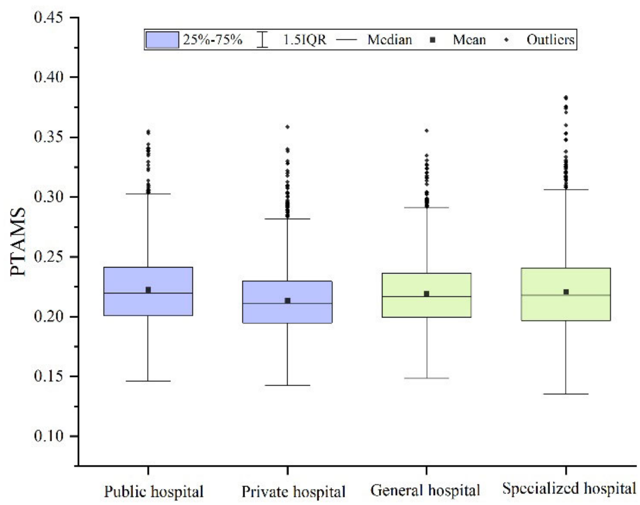
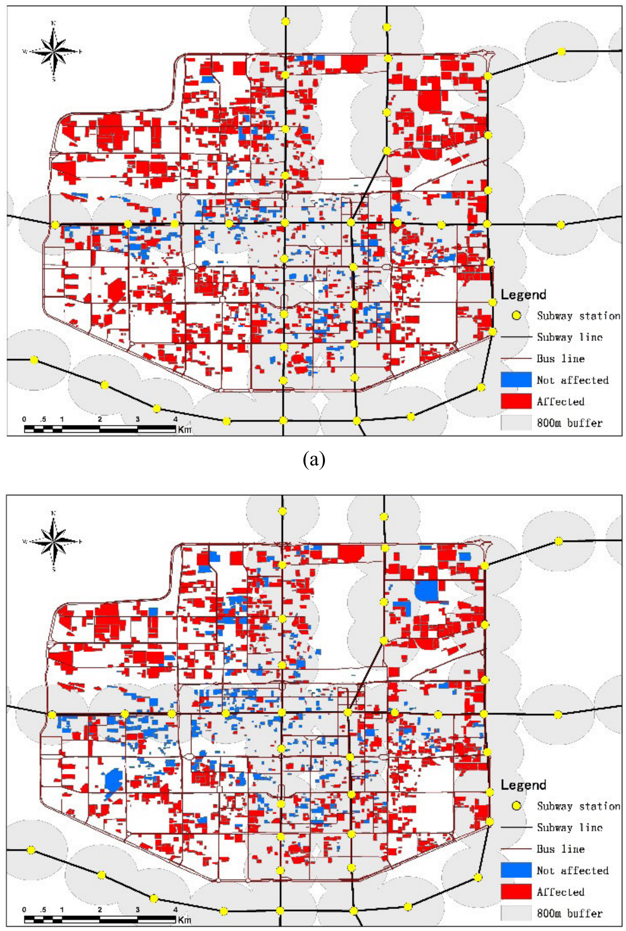


FIGURE 12. Box-plot of PTAMS for residential areas going to four hospital classes.



(b)

FIGURE 13. Distribution of residential areas affected by the morning peak-hour with public transport network. (a) Class 1 hospitals; (b) Class 2 hospitals.

hospitals' purpose of treating non-serious diseases and offering disease prevention for nearby residents [36].

2) PUBLIC, PRIVATE, GENERAL, AND SPECIALIZED HOSPITALS

Containing many hospitals with different functions and properties, Class 1 hospitals are divided into public hospitals, private hospitals, general hospitals, and specialized hospitals for further discussion. The results are shown in Fig. 11.

These four hospital classes all belong to the Class 1 hospitals, resulting in their distribution patterns of PTAMS are similar. The box-plot of PTAMS is shown in Fig. 12 to further reveal the differences between them.

After removing the outliers, the difference between the 25%-75% of PTAMS value in private hospitals tends to be the smallest while the median and mean are the lowest. Therefore, not only the overall PTAMS is the highest, but also the gap between them is relatively small in the process of residents choose private hospitals. By contrast, there are some inequities for residents to get medical services from public hospitals. This is not consistent with the government's purpose of setting up them. The location of public hospitals committed to proved equal convenience for more citizens with high accessibility. Realistically speaking, they fail in Xi'an city.

Similarly, for general hospitals and specialized hospitals, their mean and median are almost equal. However, the gap between the 25%-75% in general ones is smaller, that is to say, residents are more equitable in obtaining such medical resources than specialized ones.

B. TEMPORAL ANALYSIS OF PTAMS

Referring to the temporal results, the dynamic changes of the transportation system do have a significant impact on medical treatment. Presented in previous studies on the service scope of bus and subway, the threshold is 300 or 500 m of bus stops [37] in general, while that of subway stations is 800 m [38]. Due to the coverage area of 500 m service scope of bus stops is close to the whole city [37], the service scope of subway stations was set up alone according to the above standard. The noteworthy phenomenon is that the unaffected residential areas are evidently concentrated in the service

FIGURE 14. **The proportion of unaffected residential areas within the 800 m service scope of subway stations.**

scope of subway stations, which can be seen in Fig. 13. The proportion of these unaffected residential areas within the service scope of the subway system is shown in Fig. 14.

This phenomenon is worth discussing. There is no doubt Xi'an's public transport system is mainly formed by a combination of bus and subway. With the gradual improvement of the bus network and the high coverage rate of bus stops, the role of subway in the urban public transport system is highlighted. Bus is greatly affected by road conditions, passenger flow, and other factors. As a result, it is difficult to ensure the operation speed and punctuality rate. However, subway is free from road conditions which makes it runs fast and can ensure punctuality. In other words, subway protects the residents' PTAMS within the service scope at some special time.

VI. CONCLUSION

The accessibility and equitability of urban medical services for citizens have been constantly discussed. In the process of urban green and sustainable development, public transport is bound to become the mainstream mode of urban transport in the future. Based on the real-time optimal planning route data obtained from Baidu Map and Amap, this paper has adopted a hybrid assessment to explore the urban medical accessibility using public transport as the carrier. From the perspective of residents, the main conclusions involved are as follows:

In the spatial aspect, (a) PTAMS values of the residential areas in Xi'an are generally in line with the standard normal distribution as a whole, most of their PTAMS are higher than the average level; (b) Cumulatively 80% of residential areas can obtain high PTAMS when considering a Class 1, high-level hospitals, which is twice that of a Class 2, general-level hospital; (c) The distribution of different PTAMS levels in Class 2 hospitals has obvious spatial heterogeneity; (d) Among Class 1 hospitals, the overall higher PTAMS and equitability make private hospitals the best choice for residents, which is obviously contray to the government's purpose of setting up public ones.

From the temporal aspect, (a) The use of the special case during the morning peak-hour has proved that the dynamic changes of the public transport system have an impact on the residents' PTAMS, and the scope of impact on residents going to high-level medical facilities is larger; (b) During this special period, PTAMS of most residential areas drop by an average of about 4%; (c) However, the subway system can compensate the surrounding residential areas for the impact. More than 70% of unaffected residential areas are distributed around subway stations.

If more accurate data can be achieved by us in the future work, such as population data, economic income data, housing price data, etc., it will be more conducive to classify residents for further spatial analysis. In terms of temporal scale, we have only analyzed the special circumstances during the morning peak-hour, but the impact on urban medical care in other periods is unclear. In addition, it is worth noting that if data of real trajectory (emergencies, personal vehicles, or taxis, etc.) or real patients can be used to measure accessibility, the results will be more convincing and comparative. And these results can be applied to anomaly detection or prediction [39]–[41], such as medical selection under multiple spatiotemporal constraints, short-term medical isochronous prediction, etc. Taking into account the significance and importance of this topic, further research can be conducted to improve the equitability and accessibility of medical services for residents.

REFERENCES

[1] Y. Gao, L. Tian, Y. Cao, L. Zhou, Z. Li, and D. Hou, "Supplying social infrastructure land for satisfying public needs or leasing residential land? A study of local government choices in China," *Land Use Policy*, vol. 87, Sep. 2019, Art. no. 104088.

[2] Q. Liu, S. Wang, W. Zhang, J. Li, Y. Zhao, and W. Li, "China's municipal public infrastructure: Estimating construction levels and investment efficiency using the entropy method and a DEA model," *Habitat Int.*, vol. 64, pp. 59–70, Jun. 2017.

[3] Y. Wei, C. Huang, J. Li, and L. Xie, "An evaluation model for urban carrying capacity: A case study of China's mega-cities," *Habitat Int.*, vol. 53, pp. 87–96, Apr. 2016.

[4] M. Jin, L. Liu, D. Tong, Y. Gong, and Y. Liu, "Evaluating the spatial accessibility and distribution balance of multi-level medical service facilities," *Int. J. Environ. Res. Public Health*, vol. 16, no. 7, p. 1150, Mar. 2019.

[5] E. Pappa, N. Kontodimopoulos, A. Papadopoulos, Y. Tountas, and D. Niakas, "Investigating unmet health needs in primary health care services in a representative sample of the greek population," *Int. J. Environ. Res. Public Health*, vol. 10, no. 5, pp. 2017–2027, May 2013.

[6] R. Penchansky and J. W. Thomas, "The concept of access: Definition and relationship to consumer satisfaction," *Med. Care*, vol. 19, no. 2, pp. 127–140, 1981.

[7] Y. Sun and Y. Cui, "Evaluating the coordinated development of economic, social and environmental benefits of urban public transportation infrastructure: Case study of four chinese autonomous municipalities," *Transp. Policy*, vol. 66, pp. 116–126, Aug. 2018.

[8] R. Yang, Y. Liu, Y. Liu, H. Liu, and W. Gan, "Comprehensive public transport service accessibility index—A new approach based on degree centrality and gravity model," *Sustainability*, vol. 11, no. 20, p. 5634, 2019.

[9] Y. Zhang, W. Li, H. Deng, and Y. Li, "Evaluation of public transport-based accessibility to health facilities considering spatial heterogeneity," *J. Adv. Transp.*, vol. 2020, no. 3, pp. 1–10, Feb. 2020.

[10] J.-K. Guo, Y.-K. Qiu, J.-Y. Bai, and L. Wang, "Spatial differentiation and equalization of medical service based on accessibility of urban public transport: A case study of Dalian," *J. Highway Transp. Res. Develop. (English Ed.)*, vol. 13, no. 2, pp. 80–89, Jun. 2019.

[11] F. Ma, F. Ren, K. F. Yuen, Y. Guo, C. Zhao, and D. Guo, "The spatial coupling effect between urban public transport and commercial complexes: A network centrality perspective," *Sustain. Cities Soc.*, vol. 50, Oct. 2019, Art. no. 101645.

[12] S. Kanuganti, A. K. Sarkar, and A. P. Singh, "Quantifying accessibility to health care using two-step floating catchment area method (2SFCA): A case study in rajasthan," *Transp. Res. Procedia*, vol. 17, pp. 391–399, 2016.

[13] K. L. Teow, K. B. Tan, H. P. Phua, and Z. Zhu, "Applying gravity model to predict demand of public hospital beds," *Oper. Res. Health Care*, vol. 17, pp. 65–70, Jun. 2018.

[14] W. Luo and F. Wang, "Measures of spatial accessibility to health care in a GIS environment: Synthesis and a case study in the chicago region," *Environ. Planning B: Planning Design*, vol. 30, no. 6, pp. 865–884, Dec. 2003.

[15] K. Shin and T. Lee, "Improving the measurement of the korean emergency medical System's spatial accessibility," *Appl. Geography*, vol. 100, pp. 30–38, Nov. 2018.

[16] T. Huotari, H. Antikainen, T. Keistinen, and J. Rusanen, "Accessibility of tertiary hospitals in finland: A comparison of administrative and normative catchment areas," *Social Sci. Med.*, vol. 182, pp. 60–67, Jun. 2017.

[17] F. Wang and W. Luo, "Assessing spatial and nonspatial factors for healthcare access: Towards an integrated approach to defining health professional shortage areas," *Health Place*, vol. 11, no. 2, pp. 131–146, Jun. 2005.

[18] B. Tahmasbi, M. H. Mansourianfar, H. Haghshenas, and I. Kim, "Multimodal accessibility-based equity assessment of urban public facilities distribution," *Sustain. Cities Soc.*, vol. 49, Aug. 2019, Art. no. 101633.

[19] K. Kc, J. Corcoran, and P. Chhetri, "Measuring the spatial accessibility to fire stations using enhanced floating catchment method," *Socio-Econ. Planning Sci.*, vol. 69, Mar. 2020, Art. no. 100673.

[20] D. Hernandez, M. Hansz, and R. Massobrio, "Job accessibility through public transport and unemployment in latin america: The case of montevideo (Uruguay)," *J. Transp. Geography*, vol. 85, May 2020, Art. no. 102742.

[21] M. Xu, J. Xin, S. Su, M. Weng, and Z. Cai, "Social inequalities of park accessibility in shenzhen, China: The role of park quality, transport modes, and hierarchical socioeconomic characteristics," *J. Transp. Geography*, vol. 62, pp. 38–50, Jun. 2017.

[22] G. Cheng, X. Zeng, L. Duan, X. Lu, H. Sun, T. Jiang, and Y. Li, "Spatial difference analysis for accessibility to high level hospitals based on travel time in shenzhen, China," *Habitat Int.*, vol. 53, pp. 485–494, Apr. 2016.

[23] R. Liu, Y. Chen, J. Wu, T. Xu, L. Gao, and X. Zhao, "Mapping spatial accessibility of public transportation network in an urban area–A case study of Shanghai Hongqiao Transportation Hub," *Transp. Res. D, Transp. Environ.*, vol. 59, pp. 478–495, Mar. 2018.

[24] B. Tahmasbi and H. Haghshenas, "Public transport accessibility measure based on weighted door to door travel time," *Comput., Environ. Urban Syst.*, vol. 76, pp. 163–177, Jul. 2019.

[25] S. Opricovic and G.-H. Tzeng, "Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS," *Eur. J. Oper. Res.*, vol. 156, no. 2, pp. 445–455, Jul. 2004.

[26] S. Opricovic and G.-H. Tzeng, "Extended VIKOR method in comparison with outranking methods," *Eur. J. Oper. Res.*, vol. 178, no. 2, pp. 514–529, Apr. 2007.

[27] D. Zhu and Z. Qiao, "Fuzzy comprehensive evaluation method for the location selection of affordable housing based on entropy weight," in *Proc. Int. Conf. Multimedia Technol.*, Jul. 2011, pp. 1078–1080.

[28] A. Shemshadi, H. Shirazi, M. Toreihi, and M. J. Tarokh, "A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting," *Expert Syst. Appl.*, vol. 38, no. 10, pp. 12160–12167, Sep. 2011.

[29] Y. Yang, L. Yu, X. Wang, Z. Zhou, Y. Chen, and T. Kou, "A novel method to evaluate node importance in complex networks," *Phys. A, Stat. Mech. Appl.*, vol. 526, Jul. 2019, Art. no. 121118.

[30] J. Zhao, X. Jin, Z. Song, S. Song, W. Cui, C. Chen, and C. Shen, "Genetic distributions and diversity analyses of 23 Y-STR loci in Xi'an Han population," *Legal Med.*, vol. 41, Nov. 2019, Art. no. 101635.

[31] Z. Zeng, B. Song, X. Zheng, and H. Li, "Changes of traffic network and urban transformation: A case study of Xi'an city, China," *Land Use Policy*, vol. 88, Nov. 2019, Art. no. 104195.

[32] *2018 Xi'an Health Development Statistical Bulletin*. Accessed: Dec. 2019. [Online]. Available: http://xawjw.xa.gov.cn/xxgk/tjxx/5d777a10fd85082ba285221f.html

[33] *2019 Xi'an Statistical Yearbook*. Accessed: Dec. 2019. [Online]. Available: http://tjj.xa.gov.cn/tjnj/2019/zk/indexch.htm

[34] J. Chen, A. Li, Z. Fu, S. Li, and J. Wang, "Accessibility of public service facilities as influenced by public transport modes," *J. Geo-Inf. Sci.*, vol. 21, no. 7, pp. 983–993, 2019.

[35] C. Sun and W. Quan, "Evaluation of bus accessibility based on hotspot detection and matter-element analysis," *IEEE Access*, vol. 8, pp. 138800–138809, 2020.

[36] L. Song, C. Liu, and B. Li, "Optimal selection of location for community hospitals a case of Huilongguan region in Beijing," in *Proc. IEEE Int. Conf. Inf. Autom.*, Aug. 2015, pp. 2803–2806.

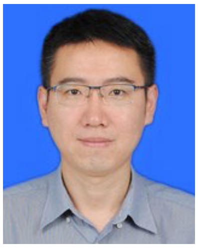
[37] M. Li and Y. Long, "The coverage ratio of bus stations and an evaluation of spatial patterns of major Chinese cities," *Urban Planning Forum*, vol. 226, no. 6, pp. 38–45, 2015.

[38] J. Zhao, W. Deng, Y. Song, and Y. Zhu, "What influences metro station ridership in China? Insights from nanjing," *Cities*, vol. 35, pp. 114–124, Dec. 2013.

[39] D. Kuupiel, K. M. Adu, V. Bawontuo, D. A. Adogboba, and T. P. Mashamba-Thompson, "Estimating the spatial accessibility to blood group and rhesus type point-of-care testing for maternal healthcare in Ghana," *Diagnostics*, vol. 9, no. 4, p. 175, Dec. 2019.

[40] S. Reshadat, A. Zangeneh, S. Saeidi, R. Teimouri, and T. Yigitcanlar, "Measures of spatial accessibility to health centers: Investigating urban and rural disparities in kermanshah, iran," *J. Public Health*, vol. 27, no. 4, pp. 519–529, Aug. 2019.

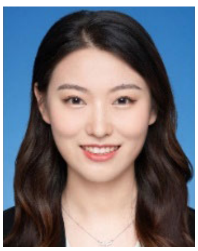
[41] F. Kamw, S. Al-Dohuki, Y. Zhao, T. Eynon, D. Sheets, J. Yang, X. Ye, and W. Chen, "Urban structure accessibility modeling and visualization for joint spatiotemporal constraints," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 1, pp. 104–116, Jan. 2020.



XIN FU received the Ph.D. degree in transportation planning and management from Chang'an University, in 2011. He is currently a Postdoctoral Fellow with the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (transportation geography), and a Visiting Scholar with the University of Washington. He is also an Associate Professor with the College of Transportation Engineering, Chang'an University, the Tutor of master's degree, and the Director of the Department of Big Data Management and Application. He has presided over four national and provincial projects, including One National Natural Science Fund, One Humanities and Social Science Fund of the Ministry of Education, One Xi'an Social Science Fund, and One Strategic Science and Technology Project of the Ministry of Transport. In addition, he has presided over five projects of prefecture-level and other types, and participated in more than ten projects of provincial and ministerial level and other types of scientific research. His research interests include transportation system planning, transportation geography, transportation network and spatial analysis, traffic big data technology and application, and so on.

YONGJIE QIANG received the B.S. degree in traffic equipment and control engineering from Nangtong University, in 2018. He is currently pursuing the M.S. degree in traffic and transportation engineering with Chang'an University. His research interests include traffic big data and transport geography.

JIANWEI WANG received the Ph.D. degree from the School of Economics and Management, Chang'an University, China, in 2004. He is currently a Full Professor with the College of Transportation Engineering, Chang'an University, the Director of the Institute of Regional and Urban Transportation Economics and the BIM Research Center, and the Vice President of Chang'an University. He has presided over and participated in more than 30 national, provincial, and ministerial level scientific research projects, published more than 70 articles, two books, and three translated works. His research interests include regional economy and transportation development, transportation planning, low-carbon transportation development planning and policy, transportation and logistics big data analysis and mining, transportation infrastructure BIM key technology and application, and so on.



XIAOXUAN ZHAO received the B.S. degree in rail transportation signal and control from Shandong Jiaotong University, in 2018. She is currently pursuing the M.S. degree in traffic and transportation engineering with Chang'an University. Her research interests include traffic big data and transport geography.

FENG-JANG HWANG is currently the Senior Lecturer (Level C, Associate Professorship equivalency in the North American system), the Leading PI of the Industrial Optimization Group, and the Program Director (Maths/Stats) with the Transport Research Center, Faculty of Science, University of Technology Sydney, Australia. He has published regularly in the leading journals, including IEEE Access, *Journal of Scheduling*, *Annals of Operations Research*, *Journal of the Operational Research Society*, *Computers & Operations Research*, *Discrete Optimization*, *Physica A: Statistical Mechanics and its Applications*, *International Journal of Sustainable Transportation*, and so on. His research interests include data-driven optimization, intelligent transportation and logistics, management information science, and computational intelligence. He has been serving as the guest editor for several Q1/Q2 SCI journals, including *Journal of Database Management*, *Mobile Information Systems*, *Intelligent Automation & Soft Computing*, *International Journal of Distributed Sensor Network*, and so on, as well as the general co-chair/session chair of several international conferences/workshops and invited to give more than 40 research talks and conference presentations.

CHI-HUA CHEN (Senior Member, IEEE) received the Ph.D. degree in information management from National Chiao Tung University, in 2013. He is currently a Full Professor with the College of Mathematics and Computer Science, Fuzhou University, and the Director of the Key Laboratory of Intelligent Metro of Universities in Fujian. He has published over 300 journal articles, conference articles, and patents. His contributions were published in IEEE Internet of Things Journal, IEEE Access, *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, *IEICE Transactions on Information and Systems*, *Physica A: Statistical Mechanics and its Applications*, and so on. He also serves as an editor for several international journals (e.g., IEEE Access, *IEICE Transactions on Information and Systems*, *Scientific Reports* (one of Nature Research Journals), *PLOS One*, *Journal of Database Management*, *Journal of Applied Statistics*, *Journal of Advanced Transportation*, *Wireless Communications and Mobile Computing*, *Security and Communication Networks*, *ISPRS International Journal of Geo-Information*, and so on). He also serves as a chair for several international conferences (e.g., WWW 2021 Workshop, DASFAA 2021 Workshop, IEEE APNOMS 2020, IEEE ICC 2020, IEEE BIBM 2020 Workshop, IEEE TrustCom 2020 Workshop, IEEE BigData 2020 Workshop, IEEE ICCE-TW 2020, IEEE IS3C 2020, and so on). His research interests include the Internet of things and machine learning.