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Last Mile Problem Evaluation on Rail Stations Based on Spatial Big Data — A Case Study of Dongcheng and Xicheng Districts in Beijing City

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Rail transportation plays a crucial role in improving travel efficiency and reducing traffic congestion. Owing to the concentration of resources, Dongcheng and Xicheng districts in Beijing City face serious traffic congestion. Therefore, rail transportation has become essential for daily commuting in such a region. The convenience and user-friendliness of slow mobility systems around rail stations affect the travel experience and efficiency. It is also an important aspect of the current urban renewal on rail transportation upgrades in Beijing. Therefore, in this study, we focus on evaluating the last mile problems on slow mobility systems around rail stations for Dongcheng and Xicheng districts. We utilize internet and spatial big data to establish a slow mobility evaluation system, including indicators such as station vitality, population coverage, surrounding environment, accessibility, and detour coefficient by using the Python programming language, Feature Manipulation Engine (FME), and Geographic Information System (GIS) network analysis methods.

1. Introduction

With the acceleration of urbanization and population growth, the number of cars has increased considerably leading to increasingly severe urban traffic congestion. According to the Analysis Report on Major City Traffic in China,(1) Beijing ranks among the top four areas with severe congestion areas in terms of traffic congestion. As for Dongcheng and Xicheng districts located in Beijing, the road traffic system during peak hours on working days struggles to meet the travel demand. Therefore, the subway has become an important transportation mode owing to its punctuality and speed. The last section of the journey from the subway station to the destination, which is known as the "last mile" problem, determines the efficiency of daily commuting. The "Development Plan for Modern Comprehensive Transportation System during the 14th Five-Year Plan"(2) proposes the creation of a modern urban transportation system,

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aiming to develop a safe, continuous, and comfortable urban slow traffic system. On the other hand, the "Beijing Slow Traffic System Plan (2020–2035)"[3] proposes the deep integration of the slow traffic system with urban development, aiming to build a pedestrian- and bicycle-friendly city. With the continuous improvement in pedestrian and bicycle lanes and the development of public bicycle rental markets, the problem in traffic congestion has been alleviated to some extent, which also contributes to the improvement of urban residents' health and quality of life.[4] However, in Beijing's Dongcheng and Xicheng districts, which have a rather high density of social resources, there are issues such as lack of comfortable walking environments, inadequate service facilities, and long detours for the last mile commuting. Therefore, in this study, we address the aforementioned problems and evaluate last mile problems around rail transit stations on the basis of spatial big data.

2. Status of Research

The Beijing subway has now become the backbone system of urban public transportation, with a daily average passenger volume exceeding 10 million people. However, passengers often encounter problems. For example, it is not convenient or quick to get to the subway station or to reach their destinations after getting out of the station. Sometimes, the time spent on the last mile is even longer than that spent on the subway ride itself. How to develop refined connection designs and optimize the connection system, that is, to optimize the slow traffic system around the subway, has become an important issue in the construction of rail transit stations.

In the "Shanghai Metropolitan Transport White Paper",[5] compared with rapid and high-speed transportation, the travel mode with a speed ≤15 km/h is called the slow traffic system.[6] Guiding residents to adopt the travel modes of "walking + public transportation" and "bicycle + public transportation" could effectively solve the last mile problem, helping relieve the current situation of traffic congestion and improve the commuting efficiency.[7] "Walking + bicycle + public transportation" is not simply a "revival", but rather an initiative that subdivides travel modes, highlights the people-oriented concept, and combines ecological civilization.[8–11]

There is no clear definition of the final commuting area from the rail transit station to the destination. Related concepts include "Pedestrian Accessibility Catchment (PAC)",[12] "Transit-oriented Development (TOD) areas",[13] and "rail influence zones."[14] TOD defined it as a boundary of 400–800 m. In China, the rail influence zone is defined as an area approximately 500–800 m from the station, where walking to the station takes about 15 min. In this study, on the basis of previous research and considering the actual conditions of the study area, we define the areas that are within a 500 m walking distance and a 1000 m cycling distance around the rail transit stations as the research area.

3. Materials

In this study, we focused on 50 subway stations and 8 subway lines within the administrative boundaries of Beijing's Dongcheng and Xicheng districts. We analyzed seven indicators as follows.

- Build up the transportation network by the Geographic Information System (GIS) network method.
- Use Python to develop Dijkstra's shortest path algorithm and, on the basis of the transportation network, calculate the shortest path from each building within the slow traffic area to the subway station.
- Calculate the detour coefficient and population carrying capacity for each shortest path of every subway station on the basis of the shortest path from each subway station to each building.
- Calculate the number of residential communities within the slow mobility area, covering both Dongcheng and Xicheng districts, as well as individual blocks, within a walking distance of 500 m and a cycling distance of 1000 m.
- Calculate the green coverage within a 5 m buffer of the shortest path from each subway station to each building.
- Analyze the average passenger flow using passenger volume data and the maximum average passenger flow for each shortest path of every subway station over 24 h per week.
- Analyze the station vitality of subway stations on the basis of the density of various types of point of interest (POI) within a walking distance of 1000 m.

4. Evaluation Models

4.1 Accessibility model

4.1.1 Shortest path based on Dijkstra algorithm

A program was developed using the Python language to apply the Dijkstra[15,16] algorithm for shortest path analysis. On the basis of a multimodal transportation network, first, calculate the service areas of each subway station within a 500 m walking and 1000 m cycling distance. Then, extract all individual buildings within the service areas. Taking each subway station as the origin and each building as a destination, calculate the shortest path from the origin to each destination.

4.1.2 Pedestrian Route Directness (PRD) index

Calculate the average ratio of the shortest path distance to the Euclidean distance for each individual building within 1000 and 3000 m service areas from the subway stations using Eq. (1).

$$W\_index_i = \frac{\sum_j^n \frac{d_{j\_real}}{d_{j\_direct}}}{J_{total}} \tag{1}$$

Here, W_index_i represents the PRD index, which ranges from 1.0 to 1.2 and can generally satisfy the requirement of minimizing detours.[17,18] d_{j_real} refers to the actual walking distance to the jth individual building, while d_{j_direct} represents the shortest path to the jth individual building. J_{total} represents the total number of individual buildings.

4.2 Population capacity model

The total resident population covered by each station is calculated as

$$P_{total} = \sum_{i}^{n} p_i. \tag{2}$$

P_{total} represents the total resident population for the shortest path at a specific station. i denotes the ith individual building covered within the slow mobility area of the station, n represents the total number of individual buildings, and p_i indicates the resident population of the ith individual building.[19,20] By summing up all the shortest paths for a particular station, we obtain the total resident population served by that station using Eq. (2).

The weekly passenger volume for each shortest path is calculated as

$$P\_mean_{t\_kl} = \frac{\sum_{i}^{7} p_i}{7}. \tag{3}$$

Extract the passenger flow count during weekday and weekend morning peak hours (7:00–9:00 AM) within the shortest path zone (30 m buffer) for each subway station. $P\_mean_{t\_kl}$ represents the average total passenger flow count at time t for either weekdays or weekends, i corresponds to the ith day, and p_i denotes the total passenger volume for a specific path at time t on the ith day.

4.3 Green coverage model

The normalized difference vegetation index (NDVI) is a measure that allows vegetation to be separated from water and soil, providing an objective reflection of changes in vegetation coverage. Obtain the shortest path to each building within the 1000 m walking reach area, generate a 5 m buffer zone, and extract the green coverage within the buffer zone using Eq. (4).

$$Green\_cover_{index} = \frac{\sum tree\_area}{\sum land\_area} \tag{4}$$

$Green\_cover_{index}$ represents the green coverage ratio, $tree\_area$ indicates the vertical projection area of tree crowns, and $land\_area$ represents the area of the shortest path buffer zone.

4.4 Station vitality model

The station vitality model refers to the relative concentration of POIs within the service radius of subway stations compared with the entire district.(21,22) It reflects the differences in facilities and their quantity at different stations, which serves as a measure of vitality in terms of commercial, medical, and public services around subway stations [Eq. (5)].

$$E_i' = \sum_j^n \frac{k_{ij}}{K_j} R_j \tag{5}$$

E_i' represents the unnormalized vitality contribution of POIs. k_{ij} denotes the quantity of jth POI types per unit area within the service radius of station i, while K_j represents the quantity of jth POI types per unit area in the entire district. R_j is the weight indicating the vitality contribution of the jth POI type to subway station i. By normalizing E_i', we obtain the dimensionless density vitality of the station.

5. Discussion

The walking and cycling service zones of subway stations cover 15 and 60% of the total area of Dongcheng and Xicheng districts, respectively. Among the 32 blocks, the proportion of the 500 m walking coverage area ranges from 5 to 40%, with the Chongwenmen station having the highest coverage. The proportion of the 1000 m cycling coverage area ranges from 20 to 100%, with the Chongwenmen station having 100% coverage, making it the highest. The cycling coverage is divided into three levels on the basis of the coverage proportion: high (less than 30% coverage in 4 blocks), medium (30% to 60% coverage in 10 blocks), and low (more than 60% coverage in 18 blocks) (Fig. 1).

On average, the walking service range of each subway station covers 2 blocks, with 10 stations, including Dongwu, Chegongzhuangxi, and Wanzi, covering only one block. The service coverage of 10 subway stations, including Cai Shi Kou, Chongwenmen, and Dongsi, extends to 4 blocks. The cycling service range of each subway station covers an average of 4 blocks, with 13 stations covering fewer than 4 blocks and with 2 stations covering 7 blocks, which is the highest.

Within the walking service area, Wangfujing, Dengshikou, Xinjiekou, Dongwuyuan, and Andelibeijie stations have a relatively high proportion of paths with a detour factor between 1 and 1.2. Beixinqiao, Tian’anmendong, Changchunjie, Jishuitan, and Yongdingmenwai stations have higher detour costs than the other 45 subway stations. Within the cycling service area, Zhangzizhonglu and Tian’anmendong stations have high detour costs. Stations such as Beixinqiao, Tian’anmendong, and Yongdingmenwai show significant differences in detour factors between walking and cycling, indicating that some subway stations are less friendly to cycling and more friendly to walking, while others are less friendly to walking and more friendly to cycling (Fig. 2).

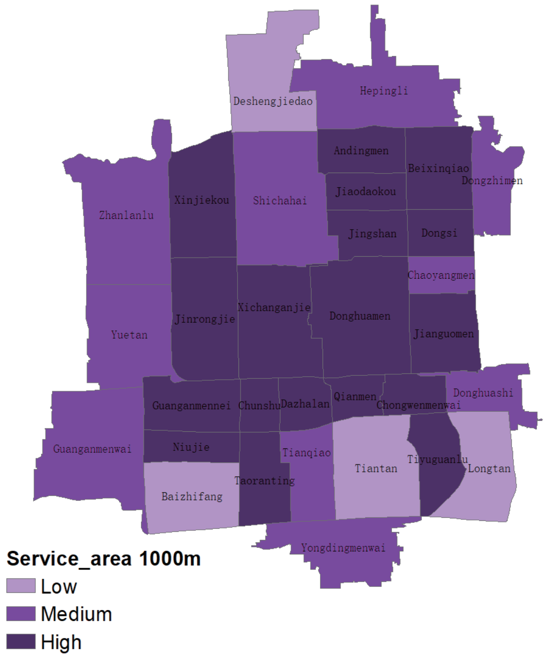


Fig. 1. (Color online) Proportion of cycling service coverage area in each block.

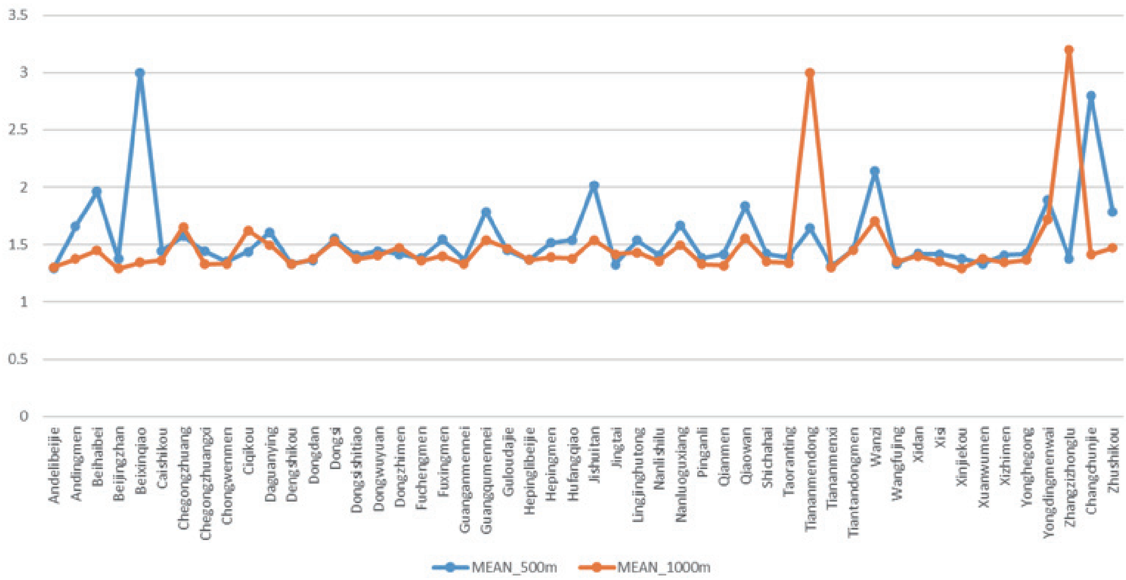


Fig. 2. (Color online) Average detour factor within walking and cycling service areas of subway stations.

Within the walking service area, Dengshikou, Guloudajie, Guangqumennei, Ciqikou, and Changchunjie stations cover a large number of permanent residents, ranking in the top five. Tiantandong, Tian'anmendong, Jishuitan, Andingmen, and Dongwuyuan stations cover a small number of permanent residents. Within the cycling range, Dengshikou, Guangqumennei, Caishikou, Daguanying, and Wangfujing stations cover a large population, ranking in the top five. Tian’anmendong, Jishuitan, Dongwuyuan, Tian’anmenxi, and Tiantandong stations cover a small population (Fig. 3).

There are 18 cycling commuting routes from subway stations that serve a population of more than 10000 permanent residents. Among them, the Caishikou subway station carries approximately 23000 people along one route, serving the highest number of permanent residents.

On weekdays (7:00–9:00 AM) during the morning peak hours, the passenger flow count around subway stations is significantly higher than that on weekends (7:00–9:00 AM) during the morning peak hours. Subway lines 1, 2, and 7 have high passenger flow counts. On weekends, stations such as Xizhimen, Chegongzhuang, Jishuitan, Chongwenmen, and Tian’anmendong, which are located on subway lines 1 and 2, have high passenger flow counts (Fig. 4).

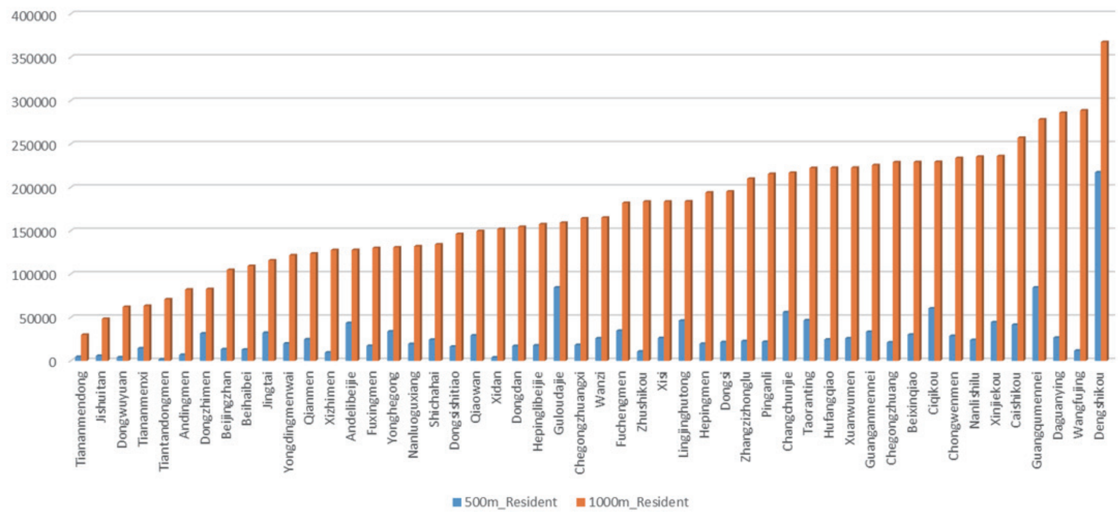
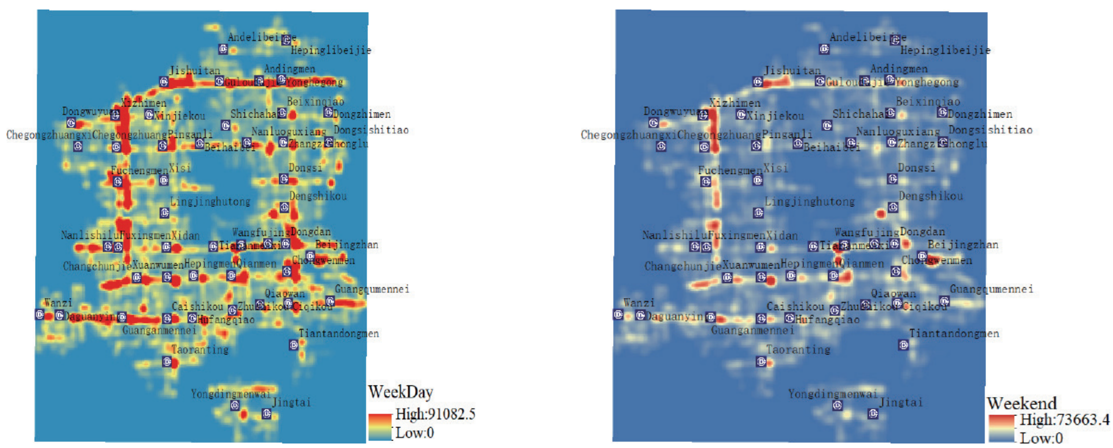


Fig. 3. (Color online) Number of permanent residents covered within service areas of subway stations.



(a) (b)

Fig. 4. (Color online) Distribution of passenger flow counts at subway stations from 7:00 to 9:00 AM: (a) Weekdays and (b) Weekends.

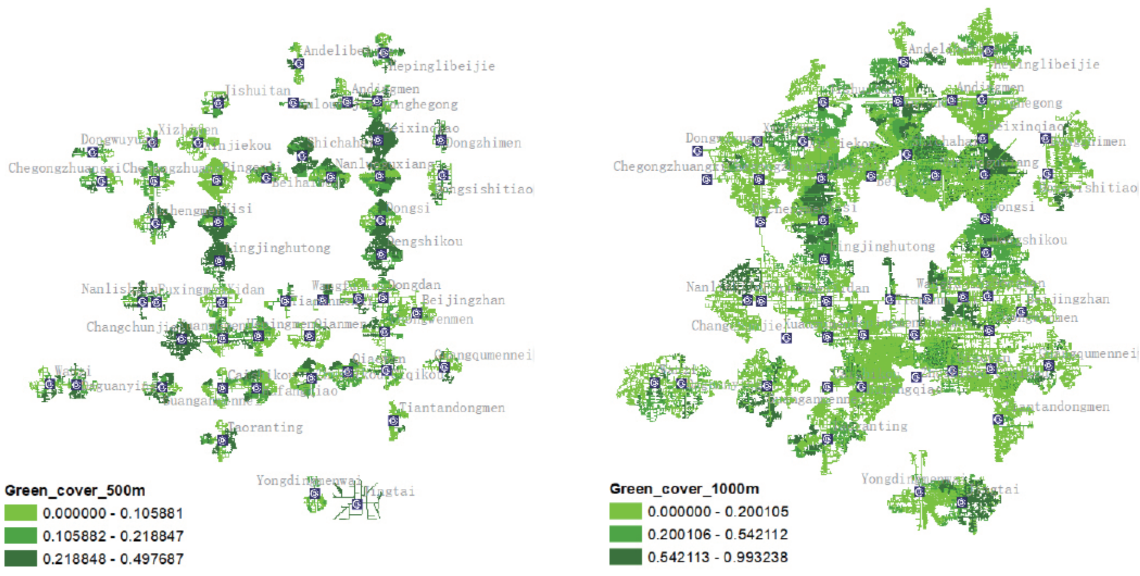
Within the walking service area, subway stations such as Beixinqiao, Shichahai, Xisi, Dengshikou, and Changchunjie have a high green coverage rate. There are approximately 3159 paths with a green coverage rate of more than 50% within the walking range, distributed among 19 subway stations. Jingtai and Andelibeijie stations have the highest proportion of paths with a green coverage rate of more than 50% (50 and 45%, respectively) (Fig. 5).

The shortest paths within the cycling range have a green coverage rate of 90% or higher at 25 subway stations, including Jingtai, Zhangzizhonglu, Wangfujing, Taoranting, Beihai North, Xisi, and Guanguomennei. The ratio of the number of paths with a green coverage rate of 50% or higher to the total number of paths at each station is as follows, with 15 subway stations having a ratio above 20%.

The density of 10 types of POI within a walking service range, including catering services, public facilities, companies and enterprises, shopping services, government and social organizations, healthcare services, living services, commercial residences, cultural and educational services, and transportation facilities is calculated for each subway station (Fig. 6).

Among them, there are 24 stations with a POI density higher than the average density in Dongcheng and Xicheng districts. By calculating the vitality value contributed by POI facilities and normalizing it, we obtain the heat map of station vitality values is obtained as shown in Fig. 7.

Among the top 3 highest-vitality subway stations, the Chongwenmen station area is dominated by shopping service POIs. The Xuanwumen station area is dominated by three types of facility: dining, shopping, and lifestyle services. The Dengshikou station area shows a more balanced distribution of the 10 facility types, with dining, shopping, lifestyle services, and public facilities as the dominant POI types. Low-vitality subway stations, including Yongdingmenwai, Andingmen, Andelibeijie, Zhushikou, and Caishikou, have POI densities that are approximately half of the average density in the Dongcheng and Xicheng districts (Fig. 8).



(a) (b)

Fig. 5. (Color online) Green coverage rate of each shortest path within the walking and cycling service ranges: (a) 500 and (b) 1000 m.

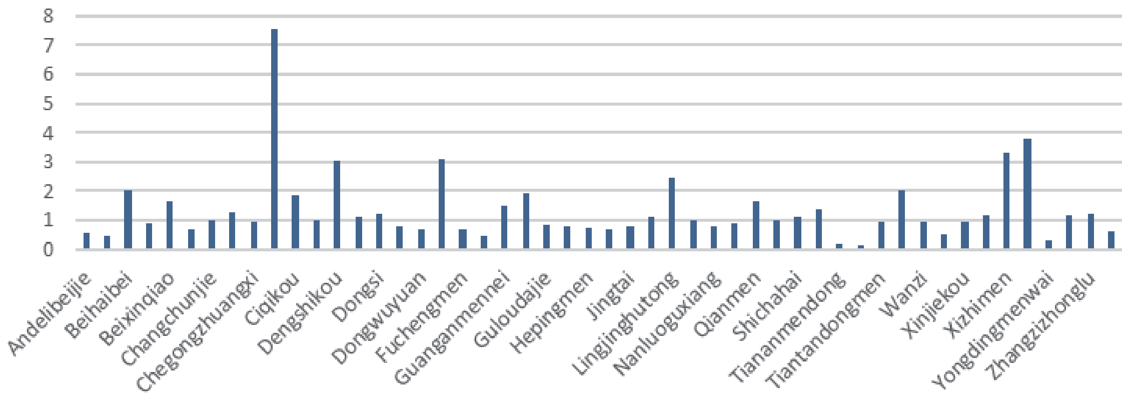


Fig. 6. (Color online) Distribution of POI density around subway stations.

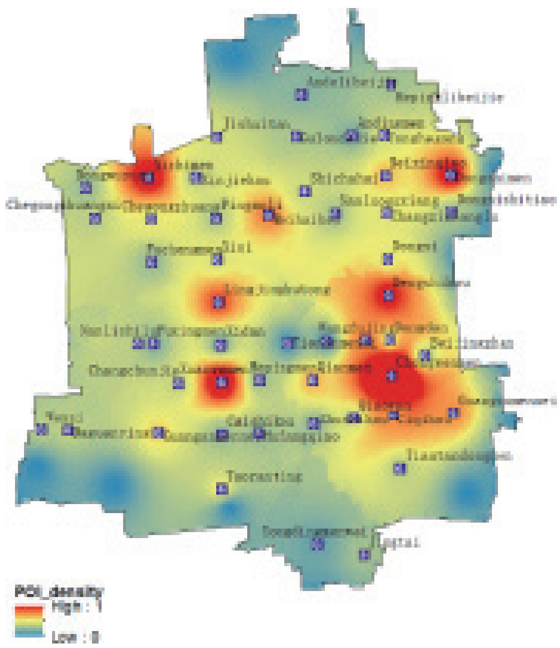


Fig. 7. (Color online) Distribution of station vitality.

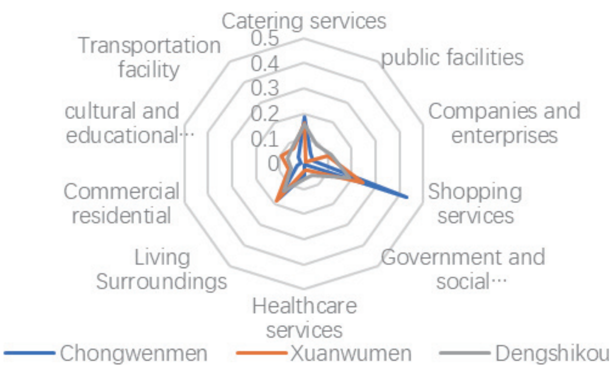


Fig. 8. (Color online) Distribution of dominant POI types in high-vitality stations.

6. Conclusions

In this study, we investigated the method of deep integration between big data and traditional spatial data, and established an evaluation system and algorithms, including accessibility, population coverage, green coverage, and site vitality evaluation models, which provide methodological references for slow traffic system evaluation. The preliminary research conclusions drawn from this study are as follows:

(1) The connection between stations and road transportation, such as buses and public bicycles, in areas with a low coverage of slow traffic service area, such as Longtan and Baizhifang stations, should be strengthened. The deployment of public bicycles and parking spaces based on demand should be increased to enhance the overall efficiency of green transportation.

(2) Stations such as Tian'anmendong exhibit a significant disparity in detour factors between walking and cycling, favoring only one mode of slow travel. It is necessary to optimize the surrounding pedestrian or cycling routes.

(3) Some commuting paths have high detour factors, low green coverage rates, and excessive population burden, which affect the slow travel experience. By combining urban renewal and the overall improvement of rail functions, internal road connections should be established, the number of road intersections should be increased, and road connectivity should also be enhanced. Greenery in roads with low green coverage should be strengthened to enhance the sensory experience of the slow traffic system. Various green travel modes should be planned and optimized for the slow travel space.

(4) Stations such as Zhushikou and Caishikou are commuter-type subway stations as determined on the basis of weekday and weekend passenger flows . The overall density of service facilities surrounding these stations is much lower than the average distribution in Dongcheng and Xicheng districts. The coverage of essential service facilities, such as living services, catering services, and transportation facilities, required by commuters, is relatively low.

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