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Analyzing Walking Accessibility of Rail Transit Stations Using Space Syntax: A Case Study of Beijing's Urban Area

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1 Introduction

1.1 Research Background

The first Beijing Subway line was officially opened for operation on January 15, 1971, making Beijing the first city in China to open a subway. As of March 2023, there are 27 Beijing subway operating lines, with an operating mileage of 807.0 kilometers and 475 stations (including 81 transfer stations). In 2022, the annual passenger volume of Beijing Subway was 2.262 billion. By 2025, Beijing Subway will form a rail transit network with 30 lines operating and a total length of 1, 177 kilometers. Beijing's transportation network is relatively complete, including subways, buses, taxis, and self- driving vehicles. The subway system covers a wide area and can easily reach major areas and attractions in the city.

1.2 *Significance of research*

As one of the world's largest and busiest rail transit systems, Beijing subway serves as a vital artery in the city's transportation network. Understanding the walkability of its stations can provide critical insights into how effectively the rail transit system integrates with the urban environment. The practical significance of this study mainly includes the following points. Firstly, improving transportation efficiency and urban sustainability: Studying the walking accessibility of rail transit stations can help improve the efficiency of the entire urban transportation system and reduce reliance on motor vehicles, which in turn can help reduce traffic congestion and environmental pollution and promote sustainable urban development.

Secondly, optimize urban planning and land use: By analyzing walkability, it can provide key data support for urban planners to help them better plan urban spatial layout, optimize land use, and improve public transportation services.

Thirdly, improve residents' quality of life: Improving the walking accessibility of rail transit stations can enable more residents to enjoy convenient public transportation services. Finally, promote social equity and inclusion: Ensuring good walkability of rail transit stations is especially important for low-income groups, which can help reduce transportation inequalities and promote social equity and inclusion.

2 Research Methodology

The main research methods of this study are kernel density analysis and sDNA space syntax modeling.

2.1 Study area

The study selected the administrative districts where Beijing rail transit stations and lines are located and the adjacent administrative districts as the research area. Finally, administrative districts were selected: Dongcheng District, Xicheng District, Haidian District, Chaoyang District, Shijingshan District, Fengtai District, Shunyi District, Changping District, Tongzhou District, Daxing District, Mentougou District and Fangshan District. A schematic diagram of the study area is shown in Fig. 1.

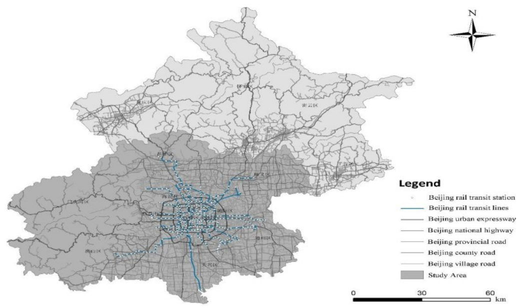

Figure 1 Study Area

2.2 Data source and preprocessing

2.2.1 Data source

The road network data of this study comes from open street map, including urban expressways, national highways, provincial roads, county roads, and township and village roads. Rail transit station and line data come from the official website of Beijing Metro. Since this study studies the walking accessibility of rail transit stations, the selected road network should be a walkable road network. Based on the actual situation in Beijing, the road network data used in the study exclude Beijing ring roads, expressways and urban expressways because these roads do not have pedestrian capacity.

2.2.2 Data preprocessing

The simplest difference between the geographic coordinate system and the projected coordinate system is that the geographic coordinate system uses longitude and latitude as spatial measurements, while the projected coordinate system uses length units such as meters and kilometers as spatial measurements. The data acquired from OSM comes with a geographic coordinate system, while the subsequent experiments need to be transformed into a projected coordinate system for the subsequent experiments.

sDNA can analyze the accessibility of the road network, calculate the potential of street walking, bicycling, motor vehicles and public transportation use, so as to calculate the degree of traffic walking through the degree of walking proximity, the realization of the sDNA operation should be carried out prior to the PRAPARE operation, for the model operation to do a good job of data preparation.

2.3 Kernel density analysis

First, kernel density analysis is a tool used to evaluate the spatial density of phenomena within a specific area.

By counting the number of phenomenon points within a certain range around each phenomenon point, a density heat map is generated, thereby providing an intuitive way to understand the distribution pattern of spatial phenomena.

2.4 sDNA Spatial Syntax Model

Spatial syntax is a mathematical method used to describe and analyze spatial relationships. The basic principle is to divide the space into scales and spatial divisions,

to describe the quantitative relationship between spaces by mathematical topological relationships, and to explore the connection between human activities and spatial patterns.

sDNA is a GIS spatial syntax model, with the gradual improvement of spatial syntax, more and more model building plug-in applications have also made progress and derived different characteristics, the sDNA model applied in this study is feature- rich and has good compatibility with ArcGIS software to be widely used.

2.4.1 Street proximity

In sDNA, proximity represents the distance of a section of a street from other streets, which represents the level of accessibility of the area in the road network, and the higher proximity means the higher accessibility and the stronger center clustering effect. Compared with the street network analysis method, the difference is that the spatial syntax method can not only show the street accessibility, but also reflect the distribution of traffic flow, which is suitable for the study of site accessibility.

NQPD is a measure of global proximity and is calculated as follows:

$$NQPD(x) = \sum_{y \in Rx} \frac{(W(y)P(y))^{nqpdn}}{d_M(x,y)^{nqpdd}}$$

dM(x,y) is the shortest path distance, that is, the angular topological distance in angular analysis; if the point is within the search radius in discrete space, *P(y)* is 1, otherwise it is 0, and is determined by the ratio of radius to road segment length is determined, and the ratio is between 0 and 1; *W(y)* is the road segment weight; *nqpdn* and *nqpdd* default to 1, representing the numerator of *NQPD* and the denominator of *NQPD* respectively.

There is another MAD operation to calculate local proximity, which represents the proximity of the street network to the central selection point within a certain radius, calculated as follows:

$$\mathrm{MAD} = \frac{\Sigma_{y \in R_x} d_M(x,y) W(y) P(y)}{\Sigma_{y \in R_x} W(y) P(y)}$$

MAD represents the proximity centrality of the street network within a certain calculation radius; *P(y)* is the weight of *y* within the set search radius *r*. In continuous space analysis, *P(y)* $\in [0, 1]$, in discrete space analysis, *P(y)* is either 0 or 1; *W(y)* represents the proportion of fold *y* within the search radius ; *d(x,y)* is the shortest topological path from node *x* to node *y*. In sDNA, proximity centrality is calculated as "distance" rather than "proximity", and larger values mean further distance rather than closer, which means lower accessibility. Therefore, when calculating the results, the reciprocal of MAD is selected to represent the local proximity.

2.4.2 Street traversability

Traversability refers to the frequency with which a street is used as part of the shortest path between any two other streets, thereby validating its potential for traversal. The higher the traversability, the greater the likelihood that the street will be chosen as a thoroughfare in actual travel scenarios. The formula for spatial syntactic traversability is presented as follows:

$$Betweeness(x) = \sum_{y \in N} \sum_{z \in R_y} W(y)W(z)P(z)OD(y,z,x)$$

Betweeness(x) is the street traversability, y and z are the endpoints of the geodesic line; x is the position of the node at which the penetration is measured; W(y)

and W(z) are the weights; and OD(zx) is the shortest topological path between y and z that passes through x within the search radius, and takes the following values.

The concept of traversability can be categorized into local traversability and global traversability, with 'betweenness' representing the global traversability formula. This characterizes the frequency with which a street network is traversed from a global perspective.

$$OD(x,y,z)\begin{cases} 1, \\ \frac{1}{2}, x = y \neq z, x = z \neq y \\ \frac{1}{3}, x = y = z \\ 0 \end{cases}$$

3 Results and analysis

3.1 Kernel density analysis of rail transit stations

The results of kernel density analysis on Beijing rail transit stations are shown in Fig. 2. Through kernel density analysis, we can visually see the concentration of stations in different areas. From the perspective of administrative districts, Beijing's Xicheng District, Dongcheng District, Haidian District and Chaoyang District all have a relatively high core density of rail transit stations, with Dongcheng District and Chaoyang District having the most dense distribution of rail transit stations.

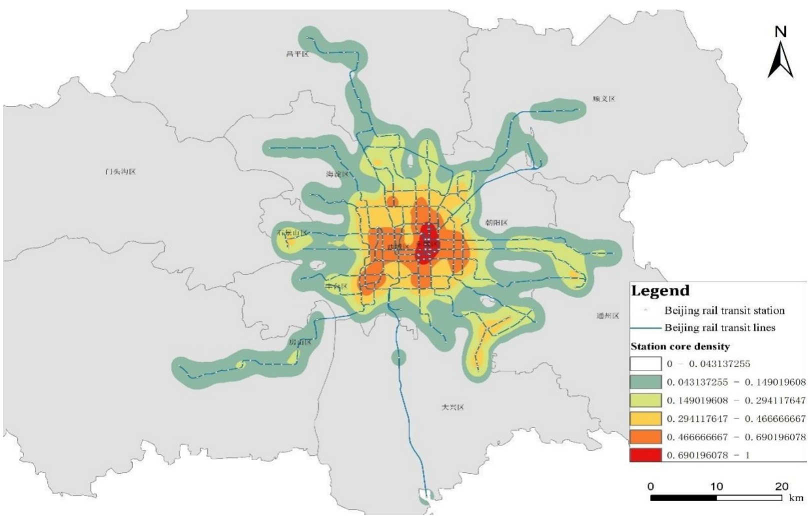

Figure 2 Core density of rail transit stations in Beijing

3.2 Road network walking proximity analysis

The calculation of proximity in the sDNA model is mainly based on the integration degree index in space syntax theory. By analyzing and calculating the walking proximity of the road network in the study area, we can determine how easy it is for a certain section of the road network to be accessible on foot to any location in the urban space. In this study, we selected the comfortable walking distance of 500 meters as the search radius for road network proximity, and used the sDNA model to conduct local proximity analysis. The research results are shown in Fig. 3. The walking proximity of the road network in the six districts of Beijing (Dongcheng District, Xicheng District, Chaoyang District, Haidian District, Fengtai District and Shijingshan District) is shown in Fig. 4.

A high-value road segment in the figure represents that the road segment has a

high walking proximity, and it is easier for people around it to reach the location by walking. According to the research results, the road network in central Beijing has a high walking proximity, and the road network with high walking proximity is distributed radially along the main arteries to the suburbs. Much of the suburban road

network has low walking accessibility.

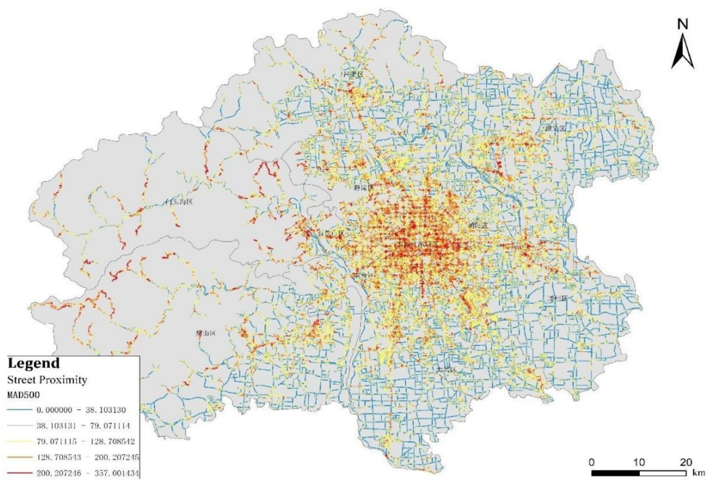

Figure 3 Road network walking proximity

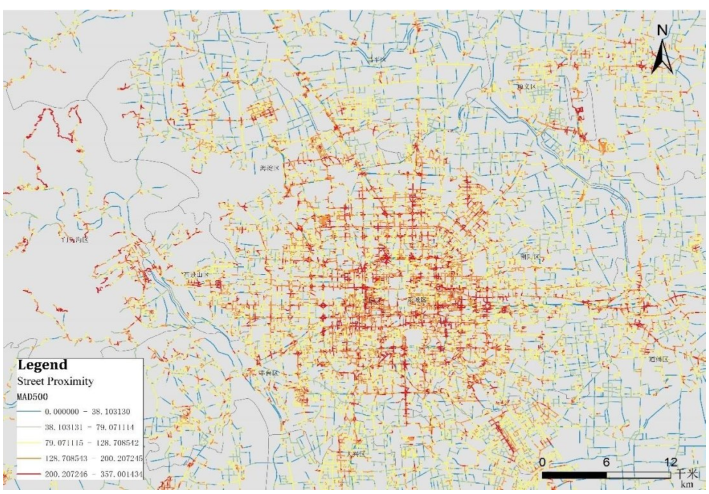

Figure 4 Walking proximity of road network in six districts of Beijing

3.3 Road network walking traversability analysis

Traversability is another important parameter provided by sDNA. It represents the probability of the road network being traversed by traffic flow within a specified search radius. A high traversability indicates that the road network has a strong throughput of pedestrian and vehicular flow; conversely, a low traversability suggests lower throughput of people and vehicles on the road network. We still choose a comfortable walking distance of 500 meters as the search radius to calculate the local traversability of the road network in the study area. The results are shown in Fig. 5, and the walking traversability of the road network in the six urban districts of Beijing is depicted in Fig.6.

From the analysis results, it can be seen that, at the pedestrian scale, unlike pedestrian proximity, the high-value sections of urban road traversability show a dispersed central distribution. Taking into account the current socio-economic status of the study area, regions with higher road network traversability are often found in CBDs, industrial parks, and business districts. Regions including the Guomao CBD, Xidan, Wangfujing, Wangjing, and Xi'erqi are characterized by high levels of pedestrian traversability, underscoring their role as key nodes within the city's pedestrian network.

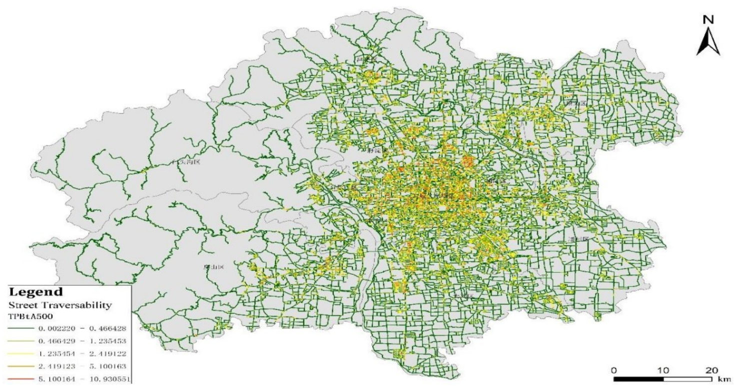

Figure 5 Road network walking traversability

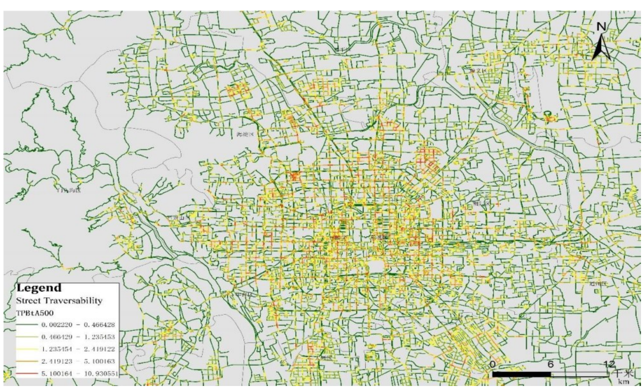

Figure 6 Walking traversability of road network in six districts of Beijing

3.4 Analysis of walking proximity to rail transit stations

According to the obtained walking proximity data of the road network in the study area and the point data of Beijing rail transit stations, the station point data and the walking proximity data of the road network are connected through spatial matching in ArcGIS. Through spatial connection, the walking proximity of the section where the rail transit station is located or the closest section is used as the walking proximity of the rail transit station. The walking proximity level map of Beijing rail transit stations is produced, as shown in Fig. 7 and Fig. 8.

It can be seen from the results that the rail transit stations located in the central urban area of Beijing have high walking proximity, and the rail transit stations in the central urban area of Tongzhou District also show high walking proximity. At the same time, the research results also show that transfer stations tend to have higher walking

proximity. Judging from the calculation results, among the ten rail transit stations with the highest walkability, there are 5 in Chaoyang District, 2 in Dongcheng District, and one each in Haidian District, Fengtai District, and Tongzhou District. Among the ten rail transit stations with the lowest walkability, 4 are in Fengtai District, 3 in Changping District, 2 in Daxing District, and 1 in Haidian District.

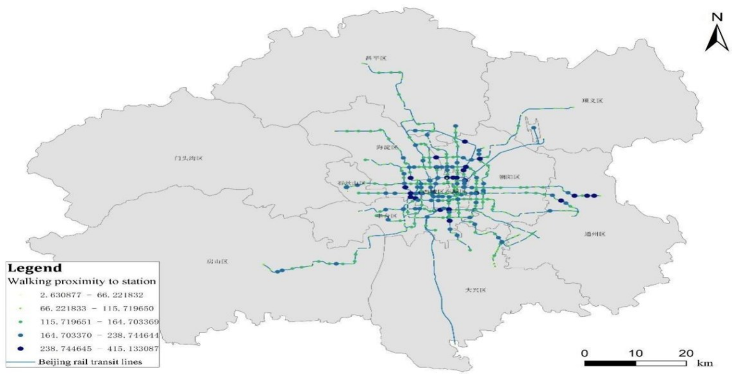

Figure 7 Walking proximity to rail transit stations

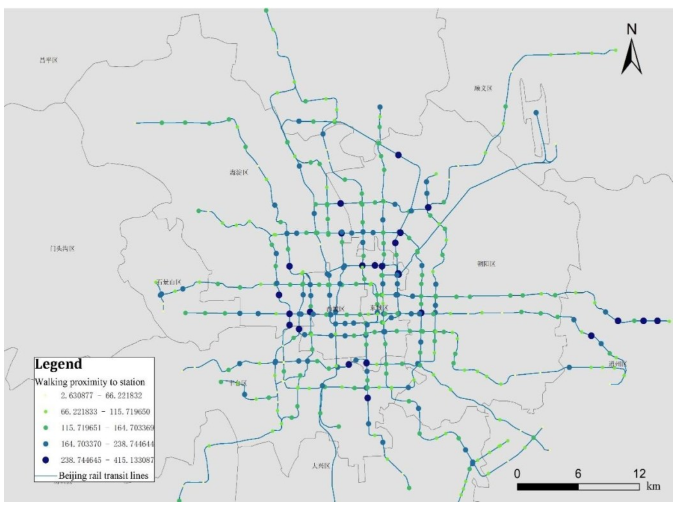

Figure 8 Walking proximity to rail transit stations in six districts of Beijing

3.5 Analysis of walking traversability to rail transit stations

In ArcGIS, the point data of rail transit stations is spatially connected to the road network walking traversability data, resulting in the production of maps illustrating the levels of walking traversability at rail transit stations, as shown in Fig. 9 and Fig. 10.

Table 1 Walking proximity to Beijing rail transit stations

Station name	administrative district	proximity	Station name	administrative district	proximity
Guangximen	ChaoYang	415.133087	DaXing Airport	DaXing	2.630877
Dongzhimen	DongCheng	375.235840	BeiAnhe	ChangPing	3.446121
MuDanyuan	HaiDian	357.476105	CiQubei	FengTai	3.577182
BeiShatan	ChaoYang	345.085083	YuanBoyuan	FengTai	8.212429
ShaoYaoju	ChaoYang	343.016052	DaXingxincheng	DaXing	9.708758
JiuKeshu	ChaoYang	307.909180	MaLianwa	HaiDian	15.095134
BeiYunhexi	TongZhou	305.921448	LangXinzhuang	ChangPing	16.45083
BeiJingnanzhan	FengTai	293.052948	FengTaizhan	FengTai	17.652296
DongXiayuan	ChaoYang	292.795013	LiBafang	FengTai	19.247078
DongZhimen	DongCheng	291.973694	BeiXinan	ChangPing	20.597879

Subsequently, an analysis is conducted on the extent to which rail transit stations are affected by the flow of pedestrian traversability.

Unlike walking proximity, stations located in the central urban area of Tongzhou District do not exhibit high levels of walking traversability. From an administrative division perspective, among the ten stations with the highest walking traversability, three are located in Xicheng District, three in Chaoyang District, two in Haidian District, and one each in Dongcheng District and Shijingshan District. Among the ten stations with the lowest walking traversability, three are in Chaoyang District, two each in Fengtai District, Haidian District, and Daxing District, and one each in Changping District, Shunyi District, and Shijingshan District.

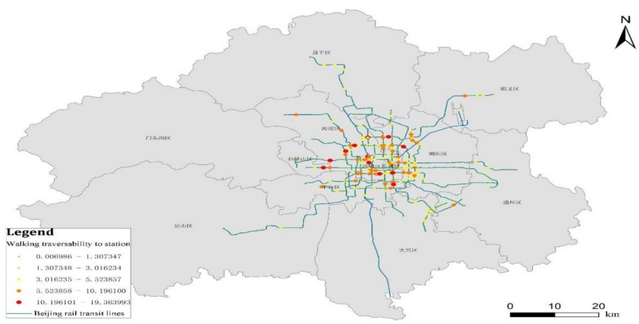

Figure 9 Walking traversability to rail transit stations

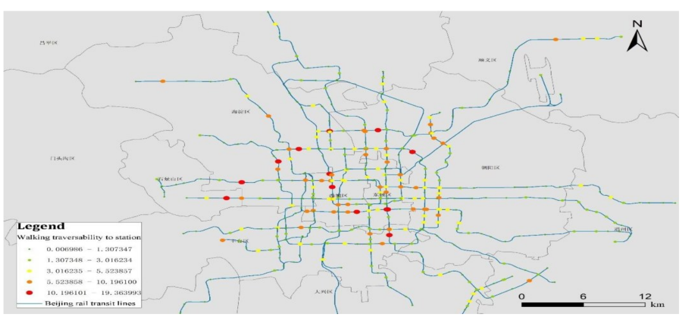

Figure 10 Walking traversability to rail transit stations in six districts of Beijing

4 Conclusion and discussion

In previous studies, most scholars have focused on measuring the accessibility and equity of rail transit, with less integration of urban road accessibility and the distribution of rail transit stations to analyze the walkability for nearby residents. This article first analyzes the walking accessibility within the urban road network of the study area, evaluating the walking proximity and traversability of different road segments, and then studies the specific walking accessibility at Beijing's rail transit stations by combining their location distribution.

Table 2 Walking traversability to Beijing rail transit stations

Site name	administrative district	traversability	Site name	administrative district	traversability
LiuDaokou	HaiDian	19.363993	HuaGong	ChaoYang	0.006986
AnLilu	ChaoYang	17.876881	ZiCaowu	HaiDian	0.018658
HuFangqiao	XiCheng	14.202493	GuoGongzhuang	FengTai	0.023777
BuChengmen	XiCheng	13.977006	BeiYuan	ChaoYang	0.031731
XiZhimen	XiCheng	13.917416	MaLianwa	HaiDian	0.036268
TaiYanggong	ChaoYang	13.665833	ShiSanling	ChangPing	0.037395
BaBaoshan	ShiJingShan	12.665314	YuanBoyuan	FengTai	0.048115
CiQikou	DongCheng	11.420302	GongHuacheng	ChaoYang	0.053218
TianCun	ChaoYang	11.301716	PingGuoyuan	ShiJingShan	0.076506
ChangChunqiao	HaiDian	10.659426	HouShayu	ShunYi	0.083495

4.1 Conclusion

Focusing on Beijing's rail transit stations as the subject of study, this research, based on spatial syntax model data, examines the walkability from a local perspective. The findings indicate that there is a varied spatial distribution of walking proximity and traversability within Beijing's urban road network; significant differences in walkability exist between different rail transit stations, which are closely related to their administrative district and specific locations.

4.2 Discussion

For stations with low walking proximity but high pedestrian traffic, measures such as expanding the density of the surrounding road network or placing more shared bicycles can be considered to improve the walkability of the site. For stations with high walking traversability, we can consider using the TOD model as a guide to strengthen the coverage of commercial facilities and daily convenience around the subway station. This study still has some shortcomings. First of all, rail transit stations often have complex pedestrian entrances and exits with a large number. However, for the convenience of research, we only regard the rail transit station as a point for analysis. Secondly, the study also needs to consider introducing POI data, population data and socioeconomic data for more detailed analysis. Finally, more comprehensive consideration needs to be given to how residents reach rail transit stations, such as shared bicycles.

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