Spatial Accessibility and Equity of Medical Facilities in Shanghai A Multi-Modal Transportation Network Perspective

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Abstract

The spatial equity of healthcare facilities is a critical indicator for evaluating the sustainable development of megacities. Traditional accessibility assessments relying on a single transportation mode fail to capture the true supply-demand dynamics within complex urban transit networks. Taking Shanghai as a case study, this research integrates road and public transit network data into a Multi-modal Two-Step Floating Catchment Area (Multi-modal 2SFCA) model to evaluate the spatial accessibility of medical facilities under both driving and public transit modes. Furthermore, a local spatial autocorrelation (Moran's I) model is applied to reveal the spatial clustering characteristics and disparities in accessibility. The results demonstrate a significant concentric decay structure in Shanghai's medical accessibility. Spatial autocorrelation analysis indicates that high-accessibility areas are heavily clustered in the central urban districts, whereas blind spots in the public transit network exacerbate the spatial deprivation of medical resources in peripheral areas. This study provides empirical evidence for optimizing public health resource allocation and synchronizing transportation network planning in megacities.

Keywords

Spatial accessibility; Multi-modal transportation; Two-step floating catchment area (2SFCA); Medical facilities; Shanghai.

1. Introduction

In the context of rapid urbanization and a deepening aging demographic, the equitable allocation of public medical resources has emerged as a core issue in urban governance[1]. Spatial accessibility serves as a primary metric for evaluating the rationality of public service facility layouts. Early spatial accessibility research heavily relied on Euclidean distance or assumed a single transportation mode for calculations. However, in the highly complex environments of megacities, residents' daily travel behaviors are highly diverse and multimodal. Simplified single-mode assessments inherently overestimate the actual accessibility for private vehicle owners while masking the spatial deprivation experienced by vulnerable groups who depend on public transit, ultimately leading to biased resource allocation decisions.

Common spatial accessibility analysis methods include spatial syntax, buffer analysis, cumulative opportunity models, cost-weighted distance methods, gravity (potential) models, and the two-step floating catchment area (2SFCA) method alongside its variations[2]. The emergence of gravity models and the 2SFCA method shifted the research focus from macro-level spatial efficiency to micro-level spatial equity and allocation rationality. Both approaches account for facility capacity and the distance decay between origins and destinations, though they differ in their handling of the distance variable. Through continuous development, the 2SFCA method—benefiting from its intuitive two-step search framework—has demonstrated higher operability and has been extensively optimized and applied in evaluating public service accessibility[3]. For instance, Tao applied an improved 2SFCA method via GIS, incorporating a gravity-based distance decay function and multi-level search radii[4]. Wang utilized an improved 2SFCA from a supply-demand balance perspective to analyze eldercare facilities in Nanjing at the street level[5]. Zhang integrated subjective and objective factors into supply capacity measurements, combined with 2SFCA, to analyze transit accessibility [6]. Nevertheless, these studies remained limited by their reliance on a single transportation mode. To overcome this limitation, the Multi-modal 2SFCA model was introduced, providing a more precise measurement framework by differentiating the travel impedance and population proportions associated with various commuting modes [7].

Building upon this framework, this study takes Shanghai as the research area with two primary objectives: (1) to evaluate the accessibility of medical facilities under both driving and public transit modes using the Multi-modal 2SFCA model combined with multi-source transit network data; and (2) to investigate the spatial heterogeneity and clustering characteristics of accessibility under these two modes, identifying areas of spatial mismatch between transit infrastructure and medical resources. The findings aim to provide actionable insights for enhancing spatial accessibility and equity in urban healthcare resource allocation.

2. Study Area and Data Sources

2.1. Study Area

As a municipality directly under the central government of China, Shanghai implements a three-tier administrative system comprising the city, districts, and towns/subdistricts. As of 2025, the city governs 16 districts. Despite the ongoing spatial expansion of the city and the noticeable trend of population decentralization towards suburban new towns, high-quality medical resources remain heavily concentrated in the central urban districts This imbalance has resulted in a pronounced spatial mismatch between medical service supply and demand, see Fig. 1.

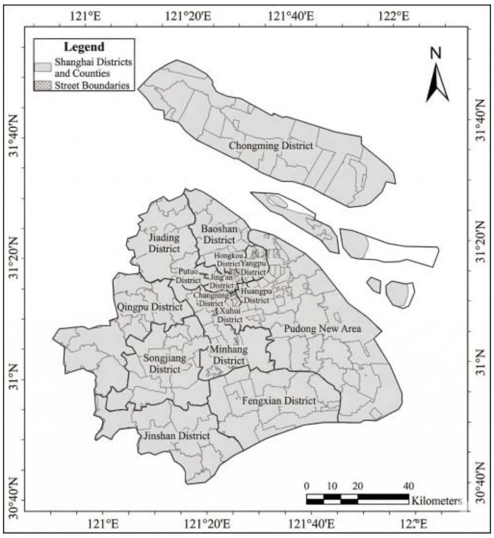

Fig. 1 Administrative divisions of Shanghai Municipality

2.2. Data Sources.

This study relies on three main categories of data:

Medical Facility POI Data: Extracted via web map APIs, this dataset includes the geographic coordinates and bed capacities (serving as the supply capacity indicator) of medical institutions in Shanghai, encompassing comprehensive hospitals, specialized hospitals, and community healthcare centers. A total of 447 valid data points were obtained.

Transportation Network Data: The road network data was sourced from OpenStreetMap (OSM), with specific travel speeds assigned based on road classifications (e.g., expressways, arterial roads, secondary roads). The public transit network dataset includes Shanghai's rail transit system and standard bus stop networks, see Fig. 2.

Demographic Data: To accurately reflect the spatial heterogeneity of population distribution at a fine scale, this study utilizes the 100m × 100m high-resolution global population raster dataset provided by WorldPop, aligned with Shanghai's administrative boundaries, see Fig. 3.

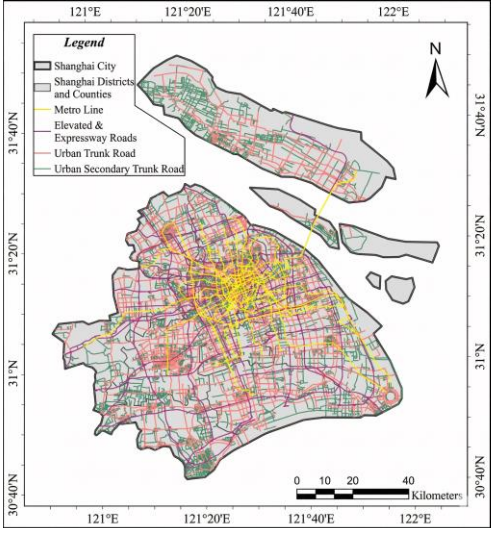

Fig. 2 Shanghai Transportation Road Network

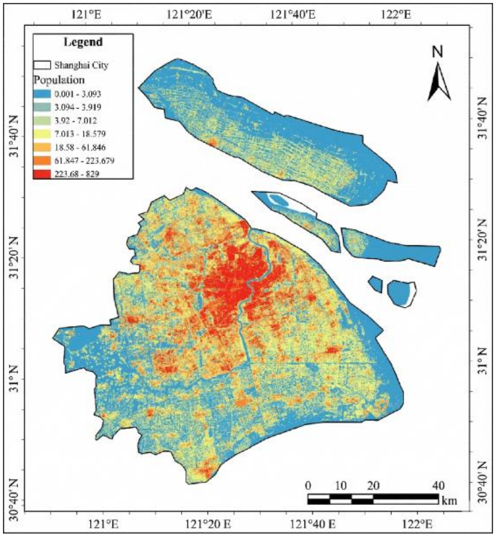

Fig. 3 Population density in Shanghai

3. Methodology

3.1. Multi-modal Two-Step Floating Catchment Area (Multi-modal 2SFCA)

This study introduces travel mode weights into the traditional 2SFCA framework. The calculation involves two steps:

Step 1: For each medical facility supply point j, a search radius is defined by the maximum travel time threshold D_0 for driving and public transit modes, respectively, to identify population demand points i within the spatial catchment area. A Gaussian distance decay function is applied to calculate the population demand equivalent under each transit mode, which is then used to determine the supply-to-demand ratio R_j:

$$R_j = \frac{S_j}{\sum_k \sum_{i \in \{d_{ij,k} \le D_0\}} P_{i,k} W\left(d_{ij,k}\right)} \tag{1}$$

Where S_j is the service capacity of medical facility j; k denotes the transportation mode (driving or public transit); $d_{ij,k}$ is the travel time from i to j under mode k; $P_{i,k}$ represents the population at demand point i choosing mode k; and $W(d_{ij,k})$ is the Gaussian distance decay weight function.

Step 2: For each demand point i the threshold D_0 is used again to search for accessible medical facilities j. The supply-demand ratios R_j of these reachable facilities are weight-summed to obtain the comprehensive spatial accessibility index A_i for that spatial unit:

$$A_i = \sum_k \sum_{j \in \{d_{ij,k} \le D_0\}} R_j W\left(d_{ij,k}\right) \tag{2}$$

3.2. Spatial Autocorrelation Analysis

To illustrate the spatial interdependence and heterogeneity of medical accessibility, a Local Moran's I index was utilized for cluster analysis[8]:

$$I_i = \frac{z_i}{\frac{1}{n}\sum z_i^2} \sum_{j \neq i} w_{ij} z_j \tag{3}$$

Where z_i and z_j are the standardized accessibility values for spatial units I and j , and w_{ij} represents the spatial weight matrix. The results categorize spatial clustering into four quadrants: High-High (H-H), Low-Low (L-L), High-Low (H-L), and Low-High (L-H).

4. Results Analysis

4.1. Spatial Accessibility Characteristics Under Driving and Public Transit Modes

Spatial visualization of the computational results was conducted using ArcGIS. As illustrated in Fig. 4 and Fig. 5, Shanghai's medical accessibility exhibits a pronounced "monocentric outward decay" spatial pattern overall; however, substantial differences exist between the two transportation modes.

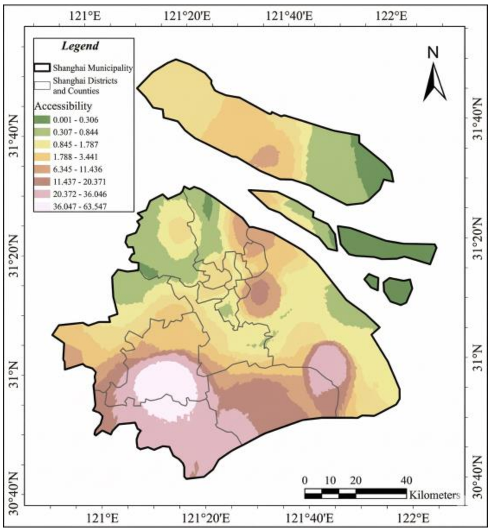

Fig. 4 Distribution of Healthcare Facility Accessibility in Shanghai under the Public Transport Mode

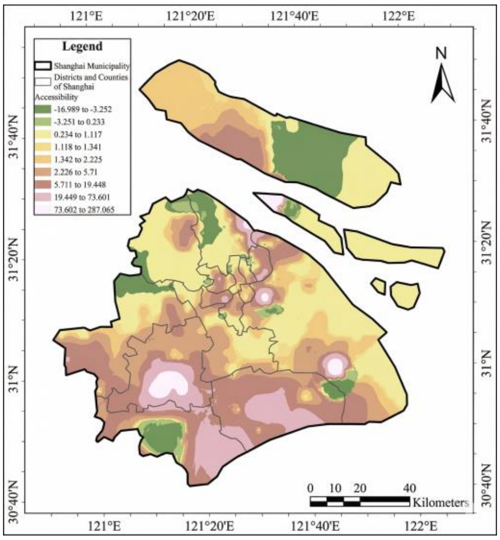

Fig. 5 Spatial Accessibility Distribution of Medical Facilities by Driving Mode in Shanghai

A comparison between Fig. 4 and Fig. 5 reveals that high-accessibility areas under the driving mode have a relatively broad and smooth service range, indicating that the vehicular road network effectively extends the coverage of centralized medical resources. Conversely, under the public transit mode, high-accessibility zones shrink drastically and adhere strictly to the alignments of the rail transit network. Notably, large segments of Chongming Island, western Qingpu District, and southern Fengxian District display extensive low-value areas (green zones) in transit accessibility, reflecting a rigid reliance on private vehicles. Car-less populations in these regions face severe structural barriers to accessing medical services.

4.2. Spatial Clustering and Disparities in Medical Accessibility

To further delineate the spatial mismatch of accessibility, a local Moran's I autocorrelation analysis was conducted using the accessibility outcomes from the driving mode, see Fig. 6.

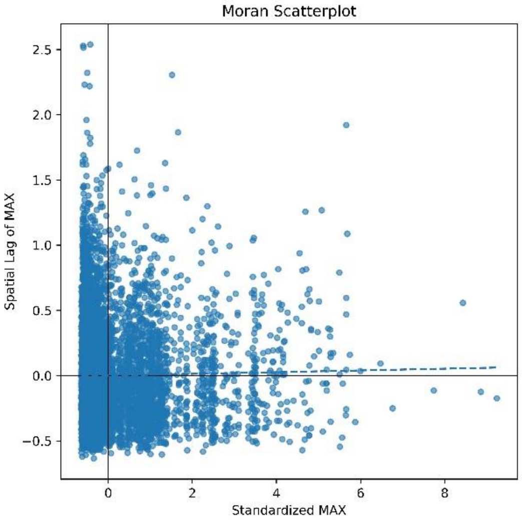

Fig. 6 Local Moran Scatter Plot of Medical Accessibility by Driving Mode

The Moran scatter plot indicates that the majority of data points are concentrated in the first (top-right) and third (bottom-left) quadrants:

High-High (H-H) Clusters (First Quadrant): Concentrated in the upper right, this pattern indicates that central urban districts such as Huangpu, Xuhui, and Jing’ an not only possess extremely high intrinsic medical accessibility but are also surrounded by areas with superior facility configurations, forming an absolute resource highland.

Low-Low (L-L) Clusters (Third Quadrant): A dense cluster of observation points exists in the lower left, representing areas predominantly located at the city boundaries and outer suburban rural zones. These peripheral subdistricts/towns lack high-quality local medical resources, and due to sparse road networks and poor terminal micro-circulation, they are unable to effectively share the services of adjacent regions.

5. Discussion

5.1. Transportation Mode Disparities and Spatial Equity

The findings highlight the double-edged nature of transportation networks in shaping the spatial distribution of medical resources. While the expansion of high-grade road networks has significantly improved overall physical accessibility, it masks underlying inequities among different social groups. The rapid decay pattern observed in the transit accessibility profile underscores that urban planners cannot rely solely on driving metrics for facility allocation. An overreliance on car-centric medical layouts will inevitably marginalize vulnerable populations, including the elderly and low-income demographics.

5.2. Policy Recommendations and Optimization Strategies

Targeting the identified L-L clusters and public transit blind spots, the following spatial optimization strategies are proposed:

First, urban planning should transcend the traditional "facilities per thousand people" metric, prioritizing transportation-disadvantaged areas for incremental medical resource allocation. For instance, in accessibility troughs like Qingpu and Fengxian, the density of community healthcare centers should be moderately increased, or the frequency of mobile medical clinics should be enhanced. Second, the synergistic planning of healthcare and transportation infrastructure must be strengthened. In regions where transit accessibility significantly lags behind driving accessibility, planning departments must optimize the micro-circulation of transit feeder routes. Establishing express bus services that directly connect remote residential areas to core regional hospitals is particularly critical for minimizing wait times and transfer impedance.

6. Conclusion

Employing a multi-modal 2SFCA method and spatial autocorrelation analysis, this study conducted a multidimensional assessment of medical facility spatial accessibility in Shanghai. The results reveal that the polarization of medical resource distribution in Shanghai remains severe, exhibiting a quintessential core-periphery structure. Transportation modes significantly alter accessibility outcomes; the extensive blind spots within the public transit network expose structural disadvantages in the city's peripheral zones. Furthermore, local Moran scatter plots validate the existence of significant spatial deprivation in outer suburban areas. By expanding the dimensions of traditional single-mode accessibility evaluations, this research provides vital decision-making support for the spatial optimization of medical facilities in megacities, guided by the dual imperatives of an aging population and sustainable, green transit development.

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