Measuring Spatial Accessibility to Hospital Beds in Isfahan Using the Gaussian-Based Two-Step Floating Catchment Area (G2SFCA) Model: Towards Evidence-Based Urban Health Planning

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Keywords: Spatial Accessibility , G2SFCA, Hospital services , GIS, Gini coefficient.

Abstract

With advancements in healthcare services, spatial equitable access has become a fundamental requirement for healthcare justice in effective urban planning. However, hospital capacity—more specifically, the number of hospital beds—is often unevenly distributed, leading to the necessity of establishing new hospitals in underserved areas. This study evaluates the spatial potential of access to hospital beds in Isfahan County using the Gaussian-Based Two-Step Floating Catchment Area (G2SFCA) model. This approach accounts for the gradual decline in accessibility with increasing distance while incorporating actual hospital bed capacity as the supply factor. Population data, hospital locations, and bed numbers were integrated and analyzed within a GIS environment. The findings from the G2SFCA model and the Gini coefficient (0.49) reveal a spatially unequal distribution of access to hospital beds across the study area, with peripheral zones experiencing significantly lower access. Therefore, merely increasing the number of hospital beds is insufficient to resolve the imbalance. A strategic reevaluation of healthcare facility locations, guided by population needs and spatial indicators, is essential. These results provide a valuable foundation for enhancing urban planning and supporting spatial equity in healthcare-related decision-making.

1. Introduction

Hospitals are among the most vital urban services, as quick and easy access to them during emergencies plays a crucial role in saving lives. This highlights the necessity of achieving spatial justice in the distribution of healthcare services. Spatial justice refers to the equitable access of all social groups—regardless of social class, income level, race, or gender—to essential urban services such as healthcare (Chang & Liao, 2011; Tsou et al., 2005).Access to healthcare services depends on three key elements: population, service availability, and distance. In a developing city like Isfahan, the imbalance between supply and demand remains a major challenge, resulting in unequal access across different urban areas (Liu et al., 2022). This inequality not only creates disparities in public health outcomes but also undermines the overall efficiency of the healthcare system—an issue particularly evident in densely populated or deteriorating urban neighborhoods (Guagliardo, 2004). In Isfahan, hospital beds are not distributed evenly or fairly, leading to spatial injustice in access to medical services. This inequality contributes to longer travel times, overcrowding in some hospitals, and ultimately, a decline in the quality of care.

Several factors drive this spatial imbalance, including the concentration of large hospitals in central areas, the neglect of actual hospital capacity in analytical models, and the lack of location-allocation frameworks based on spatial characteristics and population needs (Hu et al., 2020; Tao, Cheng, & Liu, 2020). Despite efforts to improve healthcare infrastructure, the absence of accurate, data-driven tools for analyzing access patterns remains a major barrier. Hence, there is a growing need for models that simultaneously account for geographic location, real service capacity, and demographic features to provide a realistic picture of access to hospital beds.

Various methods have been used in previous studies—such as Network Analysis, Gravity Models, and the Two-Step Floating Catchment Area (2SFCA) method (Tao, Cheng, Du, et al., 2020; Ye et al., 2012)—with 2SFCA being among the most widely adopted. While it considers both supply-demand scales and spatial proximity, its use of a fixed catchment radius imposes artificial thresholds, assuming equal access within a set distance and zero access beyond it (Xu et al., 2025). Moreover, it fails to reveal service gaps among vulnerable groups such as the elderly, low-income individuals, or those without private transport.

Additionally, the standard 2SFCA assigns equal capacity to each service center, ignoring real-world competition for limited resources, especially in areas with multiple nearby facilities or high demand (Wan et al., 2012). In contrast, the Gaussian-Based Two-Step Floating Catchment Area (G2SFCA) model introduces a distance decay function that better reflects people's behavior and preference for nearby services. As distance increases, the likelihood of choosing a facility declines gradually—not abruptly—providing a more realistic measure of access (Liu et al., 2024). This study employs the G2SFCA model, enhanced with a Gaussian decay function, to calculate the level of access to hospital beds for each population block in Isfahan. The model allows for nuanced analysis of low-access zones and serves as an effective tool for urban planners and policymakers in identifying underserved areas, guiding resource allocation, and informing decisions on hospital expansion or new facility locations.

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2. Data and Method

2.1 Study Area

This study focuses on the metropolitan area of Isfahan and its surrounding cities, including Najafabad, Khomeinishahr, and Falavarjan, located in the central region of Iran. This area is recognized as one of the country's major population, economic, cultural, and healthcare hubs. The total study area covers approximately 1,200 square kilometers and includes dense urban cores, expanding suburban zones, and lower-density peripheral areas. Population distribution across this region is highly uneven. Central districts—particularly within the city of Isfahan—exhibit high population density, whereas peripheral areas such as parts of Khomeinishahr or Falavarjan are less densely populated. This heterogeneity significantly influences healthcare accessibility and underscores the importance of spatial analysis in evaluating service distribution.

Within the metropolitan region, 44 hospitals with various functions have been identified, comprising a total of 7,192 hospital beds. The distribution of these healthcare facilities is also uneven, with most hospitals concentrated in central, high-density areas, while peripheral regions have limited access to such services. The area's transportation infrastructure includes a broad network of arterial roads, city streets, local passageways, and public transit systems such as buses, taxis, and, in some zones, a metro system. Additionally, the Zayandehroud River, which flows through central Isfahan, along with its numerous bridges, plays a key role in shaping movement patterns and connectivity across different urban areas.

In summary, the interplay of demographic patterns, diverse spatial structures, transportation systems, and the unequal distribution of healthcare facilities makes this metropolitan area a suitable case for applying the G2SFCA method to assess spatial access to hospital beds.

2.2 Data Source And Processing

In this study, multiple datasets were utilized to assess access to hospital beds across the Isfahan metropolitan region. Population data were derived from the 2016 National Census conducted by the Statistical Center of Iran, providing demographic information at the block level. Hospital-related data—including hospital names, precise geographic locations, and the number of available and active beds—were collected from official sources such as the Ministry of Health and Medical Education, as well as through field surveys.

For spatial accessibility analysis, GIS tools like the Service Area function are commonly used to delineate the service coverage of hospitals. However, the resulting street network layers often suffer from issues such as incompleteness, outdated data, and limited applicability in areas with complex street networks or mixed land use. Moreover, they often omit newer roads, pedestrian paths, and alleyways (Liu et al., 2022; O'Neill et al., 1992).

Given the study's reliance on precise urban accessibility data, we opted to use open-source, up-to-date online services instead of relying on incomplete local datasets. One such platform is OpenRouteService (ORS), developed by Heidelberg University and based on OpenStreetMap data (OpenRouteService, 2025). ORS offers a wide range of capabilities, including routing, service area definition, travel time analysis, and public service accessibility evaluation.

In this research, we used ORS's Isochrone module to delineate 10-minute travel time zones around each hospital. This module generates contour polygons representing the areas reachable by a person or vehicle within a specified time, and it supports overlap analysis between service areas—making it an effective tool for examining spatial access to healthcare facilities.

In the data preprocessing phase, hospital point data were merged with bed capacity information. Using ORS's Isochrone module, 10-minute service areas were generated for each hospital. Travel distances and times between population units and hospitals were then calculated using Python scripts. These scripts, built with specialized libraries, extracted optimal routes and travel times over the transportation network. The analysis assumed travel by private vehicle or ambulance—reflecting the most common modes of emergency patient transport. Based on existing medical studies and emergency service standards, a 10-minute threshold was used as an acceptable access time to hospitals (Golden and Odoi, 2015; Jang et al., 2021). This threshold served as the basis for defining hospital service areas within the G2SFCA model.

Demand locations were defined using 2016 census statistical blocks to accurately represent population distribution. Subsequently, hospital catchment areas were extracted, and the population within each zone was identified to implement the first step of the G2SFCA model. In the second step, the supply-to-demand ratio for each facility was calculated, and distances were weighted using a Gaussian function, as detailed in the methodology section.

2.3 The G2SFCA Method

The Two-Step Floating Catchment Area (2SFCA) model is one of the most widely used methods for assessing spatial access to public services, especially healthcare. First introduced by Radke and Mu (2000), it is an effective tool for evaluating geographic accessibility to public facilities (Hu et al., 2020). By combining service capacity with population demand, this model measures the supply-demand balance within defined geographic zones and provides a realistic picture of population access to resources. A key feature of the 2SFCA method is its use of threshold constraints—meaning only facilities located within a certain distance or travel time are considered in the accessibility calculation (Liu et al., 2023).

A central concept in this model is the Catchment Area, referring to the area a service center (such as a hospital) can effectively serve. This area is typically defined based on travel time or physical distance and plays a crucial role in calculating accessibility. By focusing only on the zones within a hospital's effective reach, the model allows for more accurate measurement of service influence.

The 2SFCA method consists of two main steps:

Step 1: For each service provider (e.g., hospital), a catchment area is defined based on a travel time or distance threshold. Within this area, the supply-to-demand ratio is calculated by dividing the hospital's capacity (e.g., number of beds, S_j) by the population (P_k) within its catchment (Equation 1).

$$R_j = \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} p_k} \tag{1}$$

Step 2: For each population location i, the overall accessibility score (A_i) is computed by summing the supply-to-demand ratios (R_j) of all facilities within the catchment area of that population block (Equation 2).

$$A_i = \sum_{j \in \{d_{ij} \leq d_0\}} R_j = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j}{\sum_{k \in \{d_{kj} \leq d_0\}} p_k} \tag{2}$$

This two-step process allows the model to simulate actual access to healthcare services based on spatial distribution of both population and facilities (Yang et al., 2022).

Since the introduction of the 2SFCA model, several improved versions have been developed to address its limitations—particularly its simplistic treatment of distance. A common enhancement involves incorporating distance decay using a Gaussian function, which models a gradual decline in service accessibility as distance increases, leading to more realistic results (Liu et al., 2024).

To overcome the fixed-threshold limitation, the Gaussian Two-Step Floating Catchment Area (G2SFCA) model was introduced. This version replaces equal weighting with distance-decay weighting, meaning that the farther a population center is from a service provider, the less impact that provider has on accessibility (Equations 3 & 4). The Gaussian function is used to weight distances in both steps of the model.

$$g(d_{ij}) = \begin{cases} \dfrac{e^{\frac{-\left(\frac{d_{ij}}{d_0}\right)^2}{2}} - e^{-\frac{1}{2}}}{1 - e^{-\frac{1}{2}}}, & d_{ij} \leq d_0 \\ 0 \quad , & d_{ij} > 0 \end{cases} \tag{3}$$

$$GA_i = \sum_{j \in \{d_{ij} \leq d_0\}} \frac{S_j \, g(d_{ij})}{\sum_{k \in \{d_{kj} \leq d_0\}} p_k \, g(d_{ij})} \tag{4}$$

In these equations, $g(d)$ is the Gaussian distance decay function, d_0 is the distance threshold, and d_{ij} is the travel distance between location i and service j. The function ensures a smooth and continuous decay in accessibility values, allowing marginal areas within the threshold to still contribute—albeit with reduced weight (Zhou et al., 2022).

In this study, after extracting the 10-minute isochrone area for each hospital, the supply-to-demand ratio was calculated by dividing the number of hospital beds by the population within each service area. Then, for each census block, these ratios were summed across all accessible hospitals. The Gaussian function was used to gradually weight distances, yielding a realistic and continuous measure of spatial access.

The final output represented each census block's accessibility score as a numerical value, reflecting both proximity to healthcare and available capacity. These results were organized into a spatial layer using QGIS, enabling further analysis, such as evaluating spatial distribution patterns, identifying underserved zones, and examining spatial equity.

To aid interpretation and statistical analysis, the accessibility scores were classified into five categories using the Equal Count (Quantile) method. These categorized results will be presented in the results section alongside visual maps.

2.4 Assessing Spatial Inequality Using the Lorenz Curve and Gini Coefficient

To evaluate the degree of spatial equality or inequality in the distribution of access to hospital beds, Lorenz curves and the Gini coefficient were used—two widely accepted indicators in inequality analysis. These methods provide both a numerical measure and a graphical representation of the concentration or dispersion of access across different geographic areas. The Gini coefficient is a numerical index that quantifies the degree of concentration or inequality in a given distribution. It is particularly useful for determining whether access to a specific service—such as hospital beds—is equitably shared among the population. The coefficient ranges between 0 and 1:

- A value closer to 0 indicates a more equal and fair distribution.
- A value closer to 1 reflects greater inequality, suggesting a highly concentrated and unbalanced distribution of resources.

To calculate the Gini coefficient, the cumulative relationship between population and access must first be analyzed. This relationship is graphically illustrated using the Lorenz curve (Figure 1).

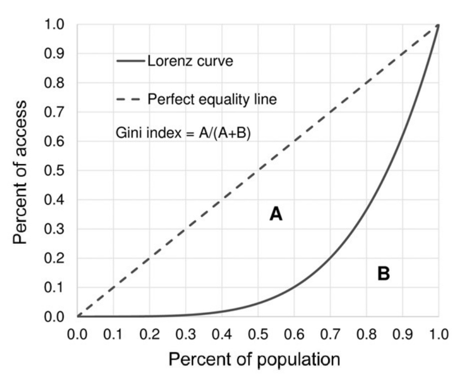

Figure 1. Lorenz Curve and Gini Index

If all areas have equal access, the curve will appear as a straight diagonal line, representing perfect equality. In contrast, the presence of inequality causes the curve to bow downward. The area between the Lorenz curve and the line of equality forms the basis for calculating the Gini coefficient.

In this study, the output data from the G2SFCA model served as the basis for evaluating spatial equity in access to hospital beds. First, the accessibility values per capita for each area were sorted in ascending order. Then, the cumulative percentages of the population and the cumulative accessibility index were calculated for each zone. These values were compiled into a table, and the Lorenz curve was plotted using Microsoft Excel. Finally, the Gini coefficient was calculated based on the area between the Lorenz curve and the line of perfect equality. This quantitative analysis provides a clear picture of how equitably healthcare services are distributed across the study area and helps identify underserved or disadvantaged regions.

3. Results and Analysis

This section presents the results of implementing the G2SFCA model for the city of Isfahan and its surrounding areas. The analysis includes the accessibility map, spatial classification of regions, Lorenz curve, Gini coefficient, and an examination of spatial inequality patterns in the distribution of healthcare services.

The G2SFCA model was executed within the QGIS environment, and the final accessibility map—representing population access to hospital beds—was classified into ten categories using the Graduated classification method (Figure 2). This classification visually differentiates areas with high access from those with limited access. The map analysis reveals that central parts of Isfahan, especially areas near clusters of healthcare facilities, enjoy the highest levels of accessibility. Additionally, eastern Najafabad and southern Khomeinishahr rank relatively high due to their proximity to urban hospitals and efficient road networks. These areas generally benefit from better hospital coverage and shorter travel times to medical services. In contrast, areas in the north and northwest of Isfahan, western Khomeinishahr, and southwestern peripheral zones exhibit the lowest accessibility levels. These regions are typically farther from the nearest hospitals and, in some cases, suffer from inadequate road infrastructure or high population density, resulting in limited access.

The findings of this study are particularly relevant for emergency and urgent care planning and can inform future decisions regarding the construction of new medical facilities, the development of rapid transit systems, or the optimization of hospital locations in underserved areas. Overall, the analysis demonstrates that hospital services in the study area are unevenly distributed, and spatial inequality patterns are clearly evident. Leveraging the results of such models can greatly support equity-driven urban health planning and promote more just allocation of healthcare resources.

The final accessibility map produced using the G2SFCA model (Figure 2) reveals a heterogeneous and uneven spatial distribution of access to hospital beds across the Greater Isfahan area and its surrounding cities, including Khomeini Shahr, Najafabad, and Falavarjan. These disparities result from the interaction of multiple factors, such as the geographic location of hospitals, their bed capacity, local population density, and the efficiency and availability of urban transportation networks. In areas such as Safa and along Shahid Kharrazi Highway, a high level of accessibility is observed—largely due to efficient transportation infrastructure that facilitates quick access to medical centers. Similarly, central districts benefit from a relatively dense distribution of hospitals, leading to higher accessibility levels compared to peripheral zones. In contrast, some parts of Najafabad and Falavarjan demonstrate acceptable levels of accessibility despite having fewer hospitals. This is mainly due to lower population densities, which allow existing hospital capacity to meet local healthcare demand.

However, areas such as Baharestan, Amir Kabir, and Bagh-e Abrisham show very low accessibility due to the absence of nearby hospitals. These regions are significantly underserved and particularly vulnerable in times of medical emergencies. Overall, the findings suggest that hospital accessibility in the study area is not solely determined by proximity or the number of hospitals. Instead, it is shaped by a combination of spatial and demographic factors. These insights can be instrumental in reevaluating the spatial allocation of healthcare resources and in developing transportation infrastructure in underserved areas.

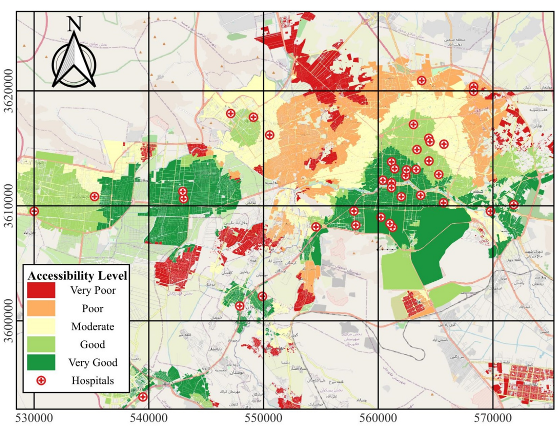

Figure 2. Hospital bed accessibility levels in Isfahan using the G2SFCA method

Based on the G2SFCA model results, population accessibility to hospital beds in the Greater Isfahan region was classified into five categories, ranging from very low to very high access. This classification, based on calculated accessibility index values, is summarized in Table 1.

Accessibility Level	Accessibility Score Range	Population	Population (%)
Very Poor	0.0–0.0038	441534	9.1%
Poor	0.0038– 0.012	1201586	25.0%
Moderate	0.0121– 0.0233	1186347	24.6%
Good	0.0233–0.0402	934453	19.4%
Very Good	0.0402–0.0711	1042784	21.7%

Table 1. Hospital bed accessibility levels and population share

The results indicate that the largest population share falls into the low access (25.0%) and moderate access (24.7%) categories—together accounting for nearly half of the study area's total population. Moreover, approximately 9.2% of the population—more than 441,000 people—reside in areas with very low accessibility, making them the most vulnerable during emergencies or in need of immediate care. In contrast, only 21.7% of the population (over one million people) benefit from very high accessibility. This distribution highlights a clear spatial inequality in healthcare services, with access to hospital beds heavily influenced by geographic location. The observed pattern likely stems from the concentration of hospitals in central, well-developed urban areas and the lack of medical infrastructure in peripheral districts—particularly in the southwest and southeast of the study region.

The spatial accessibility patterns derived from the G2SFCA model are consistent with findings from previous studies (e.g., Liu et al., 2024; Sun et al., 2024), and a visual comparison between the accessibility map and the actual distribution of major hospitals and population density further confirms the robustness and reliability of the results.

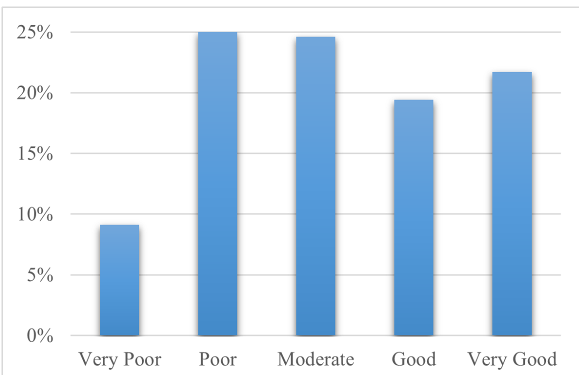

Figure 3. Population percentage by hospital bed accessibility levels.

As shown in Figure 3, approximately 58.7% of the population falls within the very poor, poor, or moderate accessibility categories, indicating that nearly three-fifths of residents experience limited or insufficient access to hospital beds. Specifically, the "poor" and "moderate" levels each account for about a quarter of the population (25.0% and 24.6%, respectively), while 9.1%—over 440,000 individuals—are situated in areas with very poor accessibility, placing them at high risk during medical emergencies. In contrast, only 41.1% of the population resides in areas with good or very good access. Notably, the "very good" category includes 21.7% of the population, suggesting that just over one-fifth of the region's residents benefit from optimal hospital bed accessibility. The "good" category represents 19.4%, pointing to a relatively moderate share of the population with acceptable, though not ideal, access.

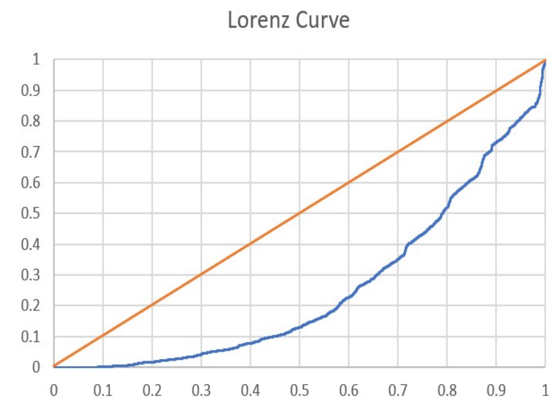

Figure 4. Lorenz curve illustrating inequality in hospital bed accessibility

To assess the degree of spatial equity in hospital bed accessibility, this study applied widely used inequality measures, namely the Gini coefficient and the Lorenz curve. The calculated Gini coefficient was 0.4938, indicating a moderate to high level of inequality in the distribution of access to hospital beds across the study region (Qureshi et al., 2024; Guo et al., 2019). Given that the Gini coefficient ranges between 0 (perfect equality) and 1 (perfect inequality), a value close to 0.49 suggests that access to hospital beds is highly uneven, with substantial portions of the population underserved.

As shown in Figure 4, the Lorenz curve further supports this observation. The curve deviates markedly below the line of equality, visually confirming that a disproportionate share of healthcare access is concentrated among a relatively small segment of the population. Notably, the lowest 50% of the population, ranked by access, receives significantly less than 50% of the total access to services, indicating a clear spatial concentration of hospital resources in certain urban cores and inadequate access in peripheral or disadvantaged zones.

These results underscore the importance of evidence-based planning and equity-oriented policy interventions to reduce health disparities and enhance accessibility in rapidly growing metropolitan areas like Isfahan.

4. Discussion and Conclusion

From an urban planning and public health policy standpoint, the findings emphasize the critical need for the spatial redistribution of healthcare resources, the establishment of new hospital facilities in underserved areas, and the promotion of spatial equity within the urban health system. Policymakers should prioritize regions classified as having low or very low access in order to promote more balanced health outcomes across the metropolitan area.

This study offers several key advantages over previous research. First, the use of the G2SFCA method enables a more realistic assessment of hospital bed accessibility, primarily because it incorporates a continuous, distance-decay weighting rather than a binary cutoff. This leads to results that are less prone to binary thinking compared to traditional methods such as 2SFCA. Second, by emphasizing spatial distance as a critical factor in determining access, the analysis achieves greater spatial accuracy. Third, unlike many earlier studies that focused solely on the geographic location or area of hospitals, this research accounts for the actual service capacity by incorporating the number of available hospital beds, providing a more precise estimate of healthcare delivery potential.

Moreover, the integration of GIS technology in this study allowed for a clearer visualization of spatial access patterns, as well as classification and analysis of population groups based on different levels of access. This combination of spatial and demographic analysis serves as a practical decision-making tool for urban managers and health policymakers, offering actionable insights for improving equitable healthcare distribution across the region.

This study is among the first to apply the G2SFCA model using real hospital bed data and 10-minute travel-time isochrones derived from OpenRouteService in an Iranian metropolitan context. The approach provides a replicable framework for other cities facing similar spatial inequality challenges in healthcare access.

Despite its strengths, this study has several limitations that could be addressed in future research. First, the model considers only one mode of transportation—private vehicles—while in many areas, a significant portion of the population may rely on public transit or walking (Hu et al., 2020; Ni et al., 2019). Incorporating multiple transportation modes into the model could provide a more accurate estimate of accessibility. Furthermore, restricting accessibility to a ten-minute travel time under normal conditions may overlook important factors such as emergency situations, hourly variations in traffic congestion, and the special needs of vulnerable population groups (e.g., the elderly or individuals with disabilities) (Guo et al., 2019; Shao & Luo, 2022). Additionally, the model assumes that hospital beds are always available, ignoring service fluctuations during peak hours, holidays, or health crises. Another limitation is the model's exclusive focus on the number of hospital beds and spatial proximity, without incorporating variables such as healthcare quality, physician expertise, or hospital type (e.g., general vs. specialized), all of which may influence patients' choices.

Given these constraints, future studies are encouraged to adopt more multidimensional approaches to accessibility analysis—incorporating diverse transportation modes, real-time traffic data, and equity-focused metrics for vulnerable populations. Moreover, developing models capable of simulating forward-looking scenarios, such as demographic changes or the construction of new healthcare facilities, would offer valuable tools for policymakers aiming to enhance spatial equity. Such models can assist urban and healthcare planners in evidence-based resource allocation, optimal facility siting, and strategic health service planning. In effect, spatially sensitive, anticipatory analyses can shift the focus from reactive interventions to proactive measures, contributing to more equitable and sustainable urban health systems. This kind of approach holds significant potential for supporting socially just and future-resilient policy development.

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