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Study Urban Street Network with Centrality Analysis Using GIS (Case Study: Central Restricted Zone in Tehran)

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Abstract

The analysis of urban street centrality indices can be used for decision-making in transportation and traffic management in metropolitan cities. Centrality measurement is often used in urban network analysis related to urban development. In this paper, in the first step, centrality indices with a wide range of applications in the performance of the street network were examined, and two important known indices were used. Then, using the centrality toolbar in the geographic information system (GIS) environment, the necessary analysis was performed in the urban network of the studied area. The population of adjacent buildings was determined as the weight affecting the network elements (nodes and arcs). The results of the study were compared for the street network, medical centers, and at the scale of the district. The final result made it possible to identify a dense street network, main roads with high demand, and medical centers with more centrality. Also, the degree of correlation of these indices with each other and in relation to each district was determined. On the other hand, the possibility of clustering the entire districts was provided.

Keywords: Tehran Metropolitan City, Centrality Analysis on GIS, District, Transport Network

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1. Introduction

Tehran, as the capital, did not develop based on urban criteria. Uneven development is the main cause of high density of buildings and population, inequality in the distribution of the population, and the inadequacy of urban infrastructure services (Baghestani et al., 2024, 2025b). The inadequacy of the transport network relief is evident due to the accessibility problems in normal conditions, where in a minor event, such as a fire in a complex or snow, the pathways can affect the deterioration of the lowest level of service. In Tehran, 6% is occupied by old texture and 30% belongs to unsustainable texture (TDMMO, 2010). Moreover, several faults made this city vulnerable to earthquakes, especially in population centers. The experience of the Plasco incident, which occurred in a 17-story building fire in 2017, in which more than 200 people were injured and 20 people were killed, showed how the road network and access to it are important (Ahmadi, M., 2017). In this incident, the time to remove the debris took more than 9 days.

Many analyses have been conducted on the performance of road networks based on the Geographic Information System (GIS) environment, and in this regard, the use of street network analysis with the centrality tool has not been widely used. There are various indices for centrality. The two main indices that are widely used in transportation networks are Betweenness (B) and Closeness (C). These two indicators are examined in this article. This analysis is used for the central area of the city to assess its use in line with organizational policies to increase the resilience of Tehran (paying attention to district empowerment and using public participation in disaster management at this level. This research was developed with the aim of establishing the relationship between the degree of centrality and established medical centers and, as a result, dividing districts based on this tool. By determining the extent to which each district benefits from the centrality and road network indicators and the establishment of service and infrastructure centers, the levels of people's preparedness in normal or possible emergency conditions are determined for decision-makers (Baghestani et al., 2025a; Mahpour et al., 2025).

This measure, due to its preventive nature, will result in significant financial savings (Baghestani and Borhani, 2025). On the other hand, it is considered a suitable tool for the future development of infrastructure and services and road networks, or its location based on risk management. Also, appropriate physical and population planning for each area will be among its other advantages.

The remainder of this article is structured as follows. The next section provides a review of the existing literature, highlighting previous research on road network performance, centrality measures, and disaster resilience in urban contexts. This is followed by the methodology section, where the data sources, GIS-based analytical approach, and selected centrality indicators are described in detail. The subsequent section presents the results and discussion, focusing on the outcomes of the centrality analysis for Tehran’s central districts and their implications for accessibility, medical service distribution, and risk management. The article concludes with key insights and practical recommendations derived from the findings.

2. Literature Review

Seiwwuttanagul et al. (2016), in their study, used a centrality index to analyze the urban network in the Fukuoka urban area in Japan, and by considering the land use in the above urban area, the interaction was made between building information and street networks to better understand the urban spatial body. The results contributed to determining the shortest path between subway stations.

Some studies used the centrality index in unexpected situations. Kermanshah and Derrible (2017) used the centrality index, Betweenness (B), to study the impact of heavy floods on the performance of the transport network in New York and Chicago. The study calculated the network performance based on the network robustness against a 100-year flood and based on the reduced travel demand caused by removing some arcs and nodes. Using this centrality index, the study analyzed the network for the two cities before and after the incident and investigated the accessibility at distances of 1 km, 2 km, and 5 km using the service areas analysis tool on GIS. The results showed that the alternative routes to complete the trip in New York City outnumber those in Chicago, and the street networks of which are more severely impacted by the flood.

In another study, the effect of an extreme earthquake on the street network was examined by using multi-criteria vulnerability evaluation (Kermanshah and Derrible, 2016). These studies were conducted for San Francisco and Los Angeles. The study measured changes in the length of the road network, the Betweenness centrality index, accessibility, and travel demand to evaluate the vulnerability. The centrality index was used to measure the robustness of the network topology. The earthquake hazard was investigated using deterministic hazard analysis and ShakeMap software. The study used centrality index to measure the significance of a part of a path and the index results and their changes were evaluated before and after the incident for the two cities and the change rate of this index for Los Angeles and San Francisco indicated 87% and 10% decrease before and after the earthquake. In general, Los Angeles showed more vulnerability compared to San Francisco.

Further, the centrality index was used to assess the emergency services (Novak and Sullivan, 2013). The sensitive access index and close to the transport network were developed, showing the relative importance of each arc network with access to emergency services. The researcher used the weight graph between the origin and destination nodes. In this regard, the study took a unified approach on the physical location of urgency services based on street network topology and network engineering specifications such as road type, road capacity, traffic volume and travel speed. This index is obtained by minimizing the shortest distance of a node (origin) to the other nodes. The results indicated the importance of arc contribution regarding the shortest route to access the facilities.

In another study, Wang et al. (2011) focused on the relation between street centrality and land use in Baton Rouge, Louisiana. The centralized indices included Closeness, Betweenness and Straightness. The index distribution was shown based on population (residential) and employment (business) density distribution, and integrating the two using the Kernel density method in the study area for each centrality index on GIS. Then, the above indices were measured for a rectangular area consisting of 214,368 grid cells (462 rows by 464 columns) with 100m × 100m squares and choosing bandwidth in the ranges 1000 m, 3000 m, and 5000 m. The final variable, including the population, employment, and combined centrality measures, was fitted in the form of a model, where there were variables with a logarithmic scale on the length and the variables of the number of grid cells on the width of the diagram. The fitted model was then determined by a coefficient of determination. The exponential function indicated the best fitness among the various functions, including linear, power, exponential, and logarithmic. Among centrality measures, the Closeness showed the highest correlation with the land use, followed by the measure Straightness, and the index Betweenness, which accounts for the lowest correlation.

In another study, Porta et al. (2009) emphasized the relationship between the density of commercial and service activities and street centrality in Bologna, Italy. The centrality index included B, C, and S, which were used to measure their comparison using Kernel density estimation to convert to a single scale. Based on the results, a strong correlation was reported between the distribution of activities and the index, which is true with index C, with a lesser degree and the street centrality played a crucial role in shaping the urban structure and the land use. The shape file data in the ArcGIS included the city's street network, including 5448 streets and 7191 nodes or intersections. The study networked the study area to 10 x 10 meter cells and converted each of the indexes to the Raster format. The bump of the kernel function was considered as the centrality index of each piece of street in the cell. The bandwidth was considered in ranges h = 100 m, h = 200 m, and h = 300 m. The results indicated that the centrality index was a perfect tool for urban designing and planning, where the findings were used for location. The existence of a power function between the density distribution of business activities and Betweenness indicated that the position of a small number of businesses in one place was more satisfying than high business concentration across the vast city. Such distribution of activities is more visible in cities formed naturally than in those formed over time.

Furthermore, Crucitti and Porta (2006) focused on the relationship between spatial factors and the behavior of people in a comprehensive study of centrality indices in urban street networks, as well as multiple centrality evaluations. Some centrality indices, including degree, closeness, betweenness, straightness and information, were considered for 18 different cities around the world, which allow for categorizing big cities. A significant difference was found between self-organized cities and those developed by planning. Despite the differences in historical, cultural, economic, climatic and geographical features, among the selected cities, the indices B, C, and to some extent, S followed a similar but diverse distribution function for the cities under study. However, the clustering analysis laid the groundwork for a reliable classification based on the Gini coefficient and taking the population of nodes as weight into account.

The Open-Source Urban Network Analysis toolbar, including centrality measurement tools, was used in the ArcGIS 10 software environment (Sertsuk and Mekonnen, 2012). This toolbar fills the gap caused by the effect of adjacent buildings with their land use on the nodes and the surrounding arcs

Regarding the above-mentioned studies, the present study considered a new perspective through using the combination of all measuring indices referred to in GIS and adding innovative parameters of the research for a new purpose by considering the traffic management at the district level in Tehran. This technique was developed for the first time on a district scale in Tehran, based on the attention to local community empowerment of traffic management and public participation in disaster risk reduction, which is typically manifested on a district level.

This approach directs us to some results, such as the main street structuring for emergency transport, the time needed for rescue, and the ranking of districts based on the centrality index.

In summary, previous studies have demonstrated the value of centrality indices in analyzing urban street networks, assessing accessibility, evaluating vulnerability to natural hazards, and exploring the relationship between land use and network structure. While these works highlight the versatility of centrality-based approaches, most have focused on either citywide or regional analyses, with limited attention to smaller administrative units such as districts. Moreover, the integration of centrality measures with disaster risk management and traffic management at the local scale remains underexplored. Addressing this gap, the present study introduces an innovative approach by combining established centrality indices within a GIS framework and applying them at the district level in Tehran. By emphasizing community-based traffic management and public participation in disaster risk reduction, this research extends the existing body of knowledge and provides a novel perspective on enhancing resilience and preparedness in highly vulnerable urban contexts.

3. Methodology

3.1. Betweenness & Closeness Centrality Indices

A. **Betweenness Centrality** is a measure in graph theory that quantifies the importance of a node based on how often it lies on the shortest paths between other nodes in a network. Betweenness centrality for a node is determined by counting the number of shortest paths between all other node pairs that pass through that specific node, and then dividing it by the total number of shortest paths between those node pairs (Figure 1). Let G = (V, E) be a directed transportation network where V is the set of junctions and E is the set of directed links. The Betweenness centrality can hence be expressed by the following equation, which was first presented by Freeman (1977):

$$BC(v) \quad = \sum_{s,t \in V} \frac{\sigma_{S,T}(V)}{\sigma_{S,T}} \tag{1}$$

σs,t is the number of shortest paths between the origin vertex s ∈ V and the destination vertex t ∈ V. σs,t(v) is the number of routes from s to t that pass through the vertex v.

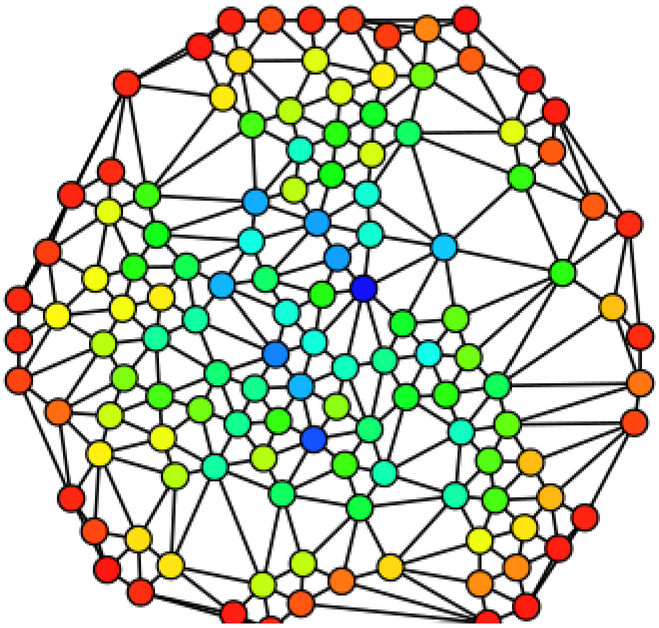


Figure 1. An undirected graph colored from smallest (red) to largest (blue) based on the betweenness centrality of each vertex.

In the relationship developed by Sertsuk and Mekonnen (2012), the following equation was proposed for this index:

$$Betweenness^{r}[i], \mathrm{B} = \sum_{j \in G-(i); d[j,k] \leq r} \frac{n_{jk}[i]}{n_{jk}} . W[j] \tag{2}$$

In these equations, the G is a graph which includes nodes and arcs, and the number of nodes (j) is extracted except for the node (i), which is available at a distance less than the radius r. d is the shortest distance between the two nodes (i) and (j), and (w) represents the weight in the node, and (j) indicates the size of the building, residents in the building, or the number of employees in the building (in this paper, residents in the building were considered). n_{jk} is the number of shortest paths between the two nodes (j) and (k), and $[n_{jk}]i$ includes the number of paths in which the node (i) is located. In such equations, d[j,k] is the shortest path between two nodes (j) and (k).

B. Closeness Centrality is a measure in network analysis that quantifies how close a node is to all other nodes in a network. It's calculated as the inverse of the sum of the shortest path lengths from a node to all other nodes in the network. A higher closeness centrality score indicates that a node is more central and can access and influence information in the network more quickly (Figure 2). Closeness was defined by Bavelas (1950) as the reciprocal of the farness:

$$C\,(x) \quad = \frac{1}{\sum_y d(y,x)} \tag{3}$$

Where d(y,x) is the distance (length of the shortest path) between vertices x and y. When speaking of closeness centrality, people usually refer to its normalized form, which represents the average length of the shortest paths instead of their sum. It is generally given by the previous formula multiplied by N-1, where N is the number of nodes in the graph, resulting in:

$$C\,(x) \quad = \frac{\mathrm{N}-1}{\sum_y d(y,x)} \tag{4}$$

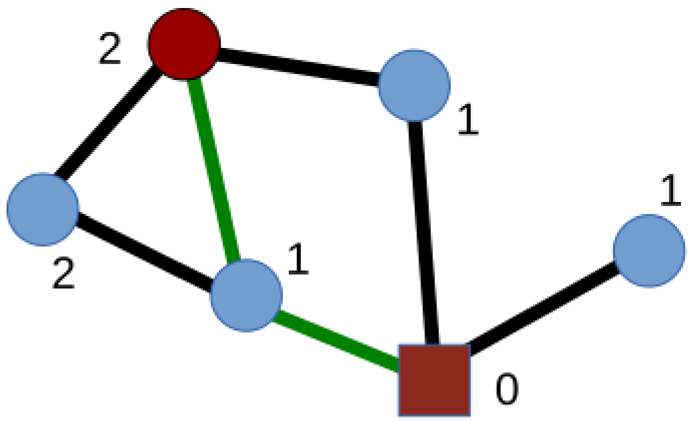


Figure 2. The number next to each node is the distance from that node to the square red node as measured by the length of the shortest path. The green edges illustrate one of the two shortest paths between the red square node and the red circle node. The closeness of the red square node is therefore 5/ (1+1+1+2+2) = 5/7

In the relationship developed by Sertsuk and Mekonnen (2012), the following equation was proposed for this index:

$$Closeness^r[i], \mathrm{C} = \frac{1}{\sum_{j\varepsilon G-(i);d[i,j]\leq r}(d[i,j].W[j]} \tag{5}$$

In this equation, the parameters are similar to those mentioned in the equation.

3.2. Study Area

The study area included many parts of regions 12 and 11 and a part of the southern regions 6 and 7 among 22 regions in Tehran (Figure 3) (Baghestani et al., 2025) involving 3174 hectares, Due to its location in the business center, some limitations are imposed on public vehicles to control access and regulate the traffic flow during 6:30 a.m. to 5 p.m. during working days. Table 1 indicates the results of the traffic index in rush hours in the morning. The study estimated these indices based on a weighted mean (each region in the study area) and used these data to determine the travel speed as one of the main parameters of the travel cost in the street network analysis. Some researchers used this parameter as a constant value for the entire network (Luo et al.,2003; Schuurman et al., 2006), and some implemented it separately for each link due to its status, such as street direction, stopping time at the intersection (Neutens, 2015; Luo et al., 2003). The present study considered the region type (region 4) and road type (arterial and district) to determine the following 8 speed groups (Figure 4) to be applied in the network.

Table 1. Car-equivalent traffic indices for the Central restricted zone and its vicinity during the morning peak hours (TCTT, 2015)

Area	%Ave. Speed (km/h)	Delay in Total Trip	%Slow & Critical	%Excess Road Capacity
Region 6	15	69.4	53.2	22.6
Region 7	17.1	65.7	50.9	22.5
Region 11	14.1	68.9	60.1	22.7
Region 2	11.9	72.6	62.8	26.1
Case Study Area	13.3	70.8	59.1	24.6
Tehran Municipality	26.4	51.8	30.8	11.7

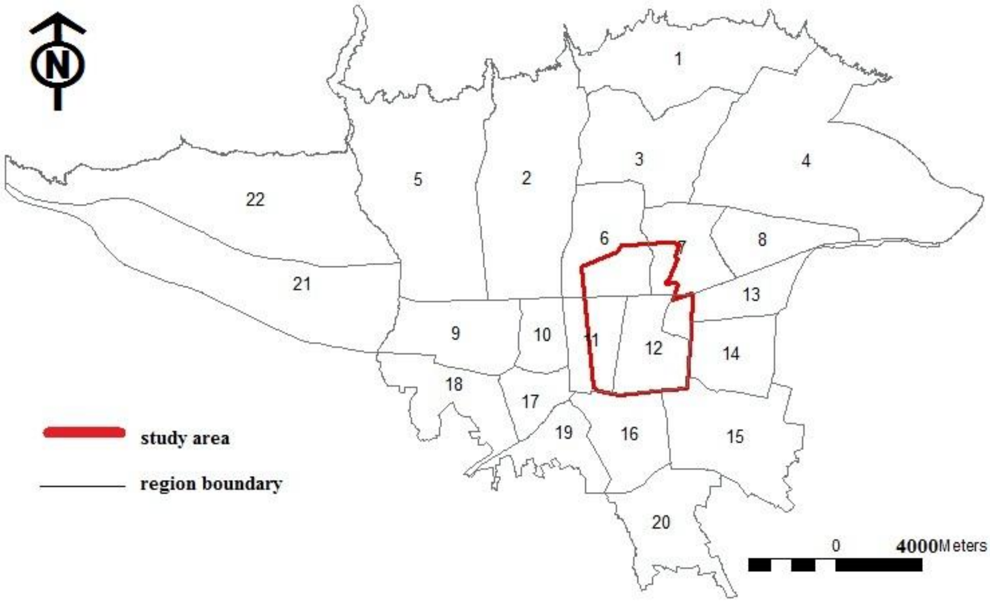
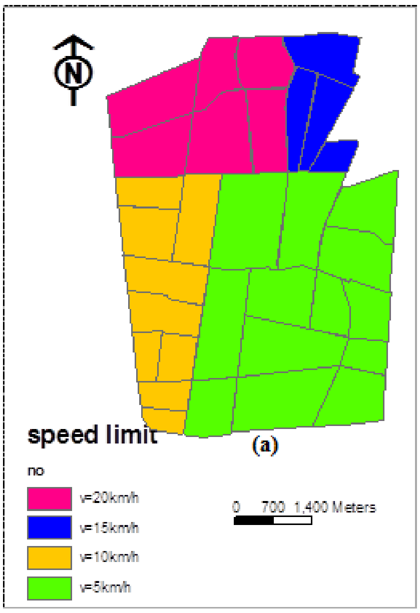


Figure 3. Study area and demarcation of Tehran regions (Baghestani et al., 2025)



No	region	Street type	V(km/h)
1	6	arterial	15
2		local	10
3	7	arterial	20
4		local	10
5	11	arterial	15
6		local	5
7	12	arterial	10
8		local	5

(b)

Figure 4. Determination of the travel cost (speed limits) (a) by region and street type(b)

Tehran is segmented into smaller areas called districts. The population consisted of 527000, involving 6.5% of the population in Tehran (SCoI, 2016), with a density of 175 people per hectare (62% more than the average in Tehran). There are 32 urban districts with an average of 100 hectares. The average population density is 204 people per hectare (16% more than the study area and 89% more than Tehran). The south and northeast districts in the study area have the densest population. The residents in the building were used as the weight of the building adjacent to the streets.

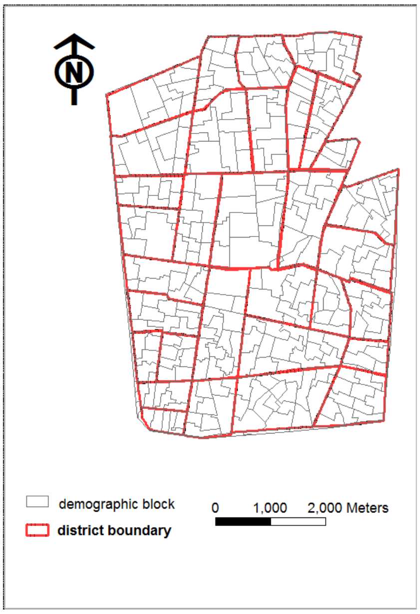


Figure 5. District position and demographic block

3.3. Data Analysis Method

The method used in the present study was as follows: first, the data were collected in the GIS software, including road network information, population, buildings, and medical centers, and then processed in the study area. The boundary of 32 districts in the area, as well as the center of the geometrical area, was specified. Second, the proper network was provided to use the extension of software network analysis. Due to the disconnection of the network and subsidiary and the main streets in the data, they were modified and retrieved by coding through a programming interface in a software environment (Figure 6) (Pouryari et al., 2022).

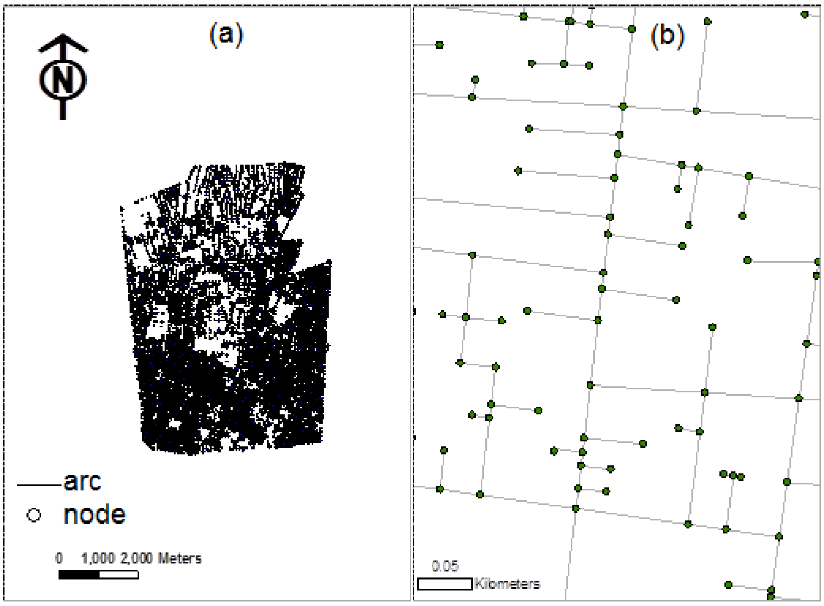


Figure 6. Street network status (a) and arcs and nodes (b)

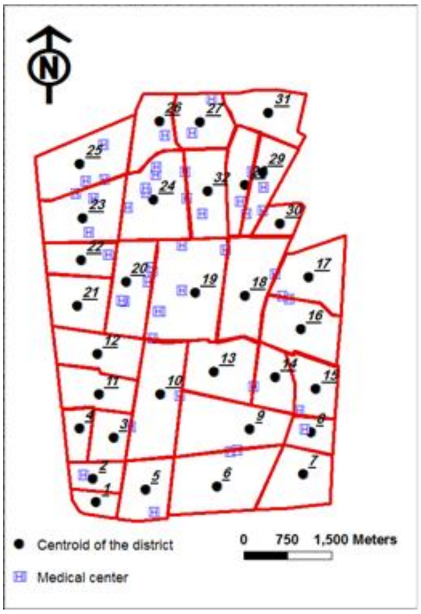


Figure 7. Demarcation of districts and their numbers, with the position of medical centers in the study area

Third, the travel cost was determined based on the travel speed. Next, the building weight (number of people per block) was considered, and the centrality indices were analyzed at the district, street network, and medical center level, and the results were obtained. Due to the value dispersion of each index, the scales were unified based on determining at the district level and comparing districts. CN $= \frac{C_I}{C_{Imax}}$, $C_I = \frac{\sum_{k=1}^{n} C_k}{n}$) where the C represents the centrality index, k indicates the population block, n is the number of district population blocks, and I shows the number of districts. This process was followed for 2. The mean results of each index were expressed for each cluster, and the analysis process was continued for the street network and then for the medical centers.

Figure 8. Centrality index status in population blocks

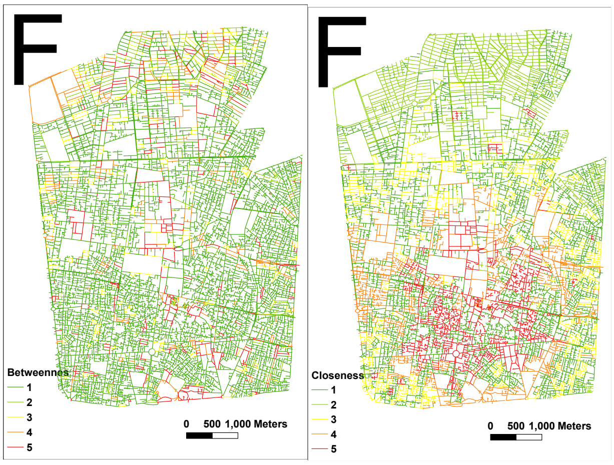


Figure 9. Centrality index status in the street network

4. Results

The results of the centrality analysis for arterial and district street networks are presented in Table 2, which summarizes the length of roads classified by centrality index density and their implications for network reliability and decision-making. As shown in the table, only a very small proportion of the main and secondary streets fall into the high or very high categories for both Closeness (C) and Betweenness (B). Specifically, for Index C, just 0.4% of the main network and 0.1% of the secondary network reach high levels, indicating limited accessibility and network robustness, particularly in districts with dense secondary streets such as 9, 10, 12, 13, 14, and 19. For Index B, 1.3% of main roads and 0.7% of secondary roads rank high, highlighting a small subset of crucial intersections and long arterial roads with significant traffic importance. These findings emphasize both the vulnerability of secondary streets in disaster conditions and the critical role of a limited number of main routes in maintaining overall accessibility and resilience.

Table 2. Length of arterial and district roads based on the index density and description of their status

Index Type	Main Streets	Secondary Streets	Decision-Making
Index C	Among 226000 km of the main street network, only 0.4% (900 km) pertains to the high and very high degree of this index.	0.1% (819 km) is related to the high and very high degree of this index among 819000 km of secondary and district street networks. The high values of the index for the secondary streets indicate the unreliability of these streets in disaster situations.	Districts 19, 12, 9, 10, 13, and 14 have a high index. The main reasons for high index include dense secondary streets, fine passages, the number of injuries, and reduced network resistance. In districts 9, 10, and 13, high indexes are caused by high-density streets, and this is related to the number of injured people, casualties, and reduced network resistance in these districts.
Index B	Of 226000 km of the main street network, only 1.3% (2938 km) accounts for the high and very high degree of this index.	Among 819000 km of the secondary and district street networks, 0.7% (5733 km) pertains to high and very high degree of this index. The high values of the index for the secondary streets represent the unreliability of these streets in disaster situations.	High index values represent the high potential of traffic. This index reveals the crucial intersections more than any other indices. The long straight roads, as well as streets with high traffic performance, resulted from this index. Selecting the servicing places is regarded as one of the options of the decision-making managers for critical conditions. An increase of this index in districts 9, 13, and 14 is due to the injuries in districts 25, 26, and 27, 31, and 28 due to the straight and long streets.

Figure 10 illustrates the distribution of main and secondary street densities in relation to the severity of centrality indices, while Figure 11 highlights the clustering patterns of medical centers and their convergence rates with each index. Table 3 complements these visuals by classifying medical centers into three clusters: those associated with Closeness (C) show that 40% of total hospital beds are concentrated in facilities located within older and less accessible urban textures, whereas Betweenness (B) accounts for only 16% of beds, reflecting that many medical centers are situated away from high-flow routes and lack direct accessibility. Moreover, medical centers positioned near high-traffic regions are expected to face significant demand during post-earthquake emergencies. Figure 11 also demonstrates how districts with low centrality adjacent to hospitals with similarly low indices paradoxically enjoy relatively higher access, while districts with higher centrality indices aligned with low-access hospitals face accessibility challenges. Together, these findings emphasize a spatial mismatch between hospital distribution, traffic flow, and network centrality, underscoring the need for improved urban health infrastructure planning.

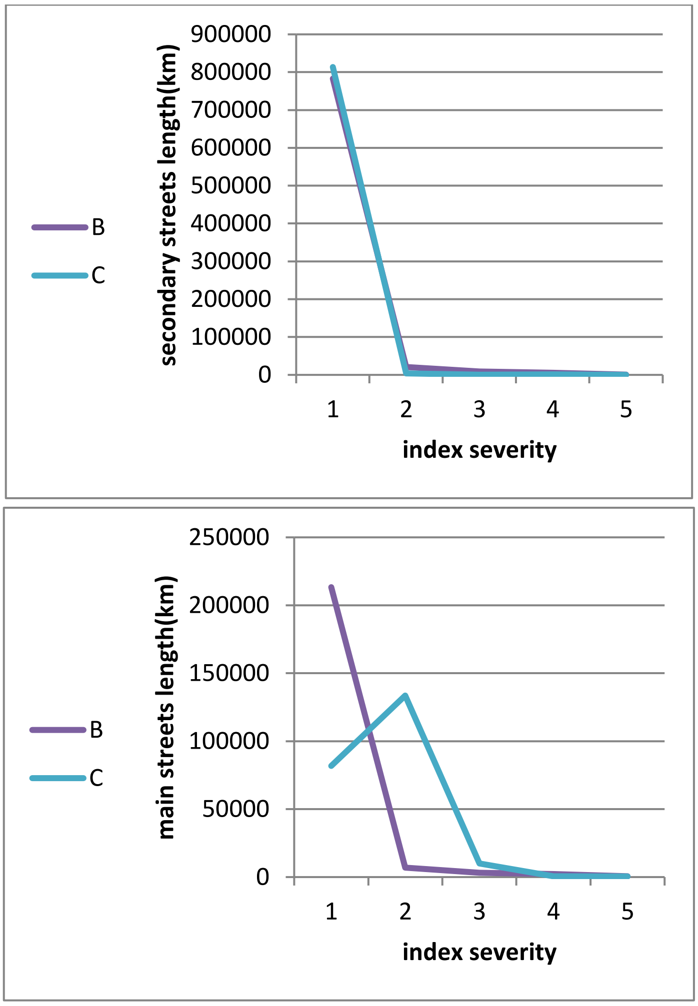


Figure 10. Relationship between street network and centrality index density

Table 3. Results of centrality index density with medical centers and districts

No.	Type Index	Number of the Medical Center
1	C	This index was used in medical centers 3, 4, 8, 9, 10, and 17 with a very high degree, and 6, 7, 16,

		15, 19, 18, and 22 with a high degree and a total of 1702 beds (40% of the total beds in the medical centers of the area). Accessing these centers is difficult due to the old texture.
2	B	This index was used in medical centers 4, 17, and 23 with a very high degree, and 3, 26, 27, and 45 with a high degree, and a total of 688 beds (16% of the total beds in the medical centers of the area). The lowest centrality is related to this index; therefore, most medical centers are located away from direct and straightforward places.

Figure 11. Density status of the centrality indexes and medical centers

5. Discussion and Conclusion

The location of most medical centers in areas with low centrality indicates that medical centers in Tehran are self-developed rather than planned, and this is not sufficient, especially in older and worn-out districts that are more vulnerable to accidents. A participatory management approach at the neighborhood level, which relies on the active involvement of residents, performs more effectively in addressing both normal and critical conditions and contributes to greater resilience. Therefore, evaluating each neighborhood's access to service centers with respect to travel costs and centrality indicators represents a logical and practical strategy.

Furthermore, the application of spatial analysis provides extensive capabilities for assessing urban road networks and serves as a valuable decision-making and planning tool for managers at both macro and local levels. This approach makes it possible to identify key rescue routes, critical traffic nodes, and optimal locations for service centers based on neighborhood needs and the responsiveness of the existing road network. It should also be noted that this study considered traffic flow speed based on travel time during the morning peak hour, reflecting real-world conditions of accessibility. While the centrality index has been less emphasized in earlier research, its growing use highlights its potential as a robust tool not only for crisis management but also for long-term infrastructure and service planning. This tool is especially effective in identifying suitable sites for new service centers and in proposing improvements for existing high-demand centers.

Overall, the findings of this study highlight the mismatch between the current distribution of medical centers and the centrality of Tehran's road network. Only a small proportion of arterial and secondary streets achieve high centrality values, which underscores the vulnerability of the urban fabric in disaster scenarios. District-level analysis demonstrated that high-density secondary streets, fine passages, and the concentration of injuries contribute significantly to reduced network resilience. By applying centrality measures in a GIS environment, this research provides a framework for integrating accessibility, resilience, and community needs into urban planning and disaster management policies.

This study is not without limitations. First, the analysis focused primarily on spatial and network-based measures without incorporating dynamic traffic conditions across different times of day or seasons, which may influence accessibility outcomes. Second, the study emphasized structural indicators and did not include social vulnerability factors such as population demographics, socioeconomic conditions, or health service capacity. Finally, the reliance on available GIS data may limit the accuracy of results in areas with incomplete or outdated street network information.

Future research should build upon these findings by incorporating real-time traffic data, multi-hazard scenarios, and advanced simulation models to capture the complexity of urban disaster responses. Expanding the analysis to include social vulnerability indicators and integrating community-based data could also provide a more holistic understanding of resilience at the neighborhood level. Moreover, comparative studies across different metropolitan areas would help evaluate the generalizability of the proposed approach and identify context-specific strategies for enhancing urban resilience.

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