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Assessing the adaptability of transit-oriented development indicators and structural-functional pathologies in the central fabric of Zanjan

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Abstract

Transit-oriented development (TOD) in historic urban fabric involves designing and implementing transportation systems that enhance accessibility, reduce traffic congestion, and preserve the cultural and historical identity of old neighborhoods. This approach is crucial in historic cities and traditional urban cores with significant cultural and social value. However, due to poor spatial management and inefficient accessibility-based planning, traffic congestion and unsustainable transportation patterns have resulted in undesirable spatial flows and increased public costs. This study employs an analytical-exploratory method to examine and assess TOD indicators in the central fabric of Zanjan. Data collection was conducted through both library research and field studies. Data analysis employed geographic information system-based methods, specifically the calculation of the Optimal Accessibility Index, inverse distance weighting interpolation, and weighted overlay network analysis in ArcGIS 10.8. The evaluation focused on key indicators such as population density, land use, land use diversity, activity center distribution, and transportation capacity. Based on the spatial mobility index using Euclidean geometry, 31% of the central fabric exhibited a balance between population mobility and activity distribution, allowing residents to access services within short distances due to land use diversity and mixed-use development. However, the central area of Zanjan does not align with TOD principles due to narrow and irregular street networks, uncoordinated intersections, high traffic volumes, and an underdeveloped public transportation system. To enhance TOD compatibility in Zanjan's historic fabric, it is essential to limit private vehicle use, relocate incompatible land uses, encourage walking and cycling, maintain population density, and prevent the conversion of residential areas into commercial or service-oriented spaces.

Keywords: Urban transportation; Physical-spatial development; Central urban fabric; Zanjan city

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1. Introduction

Transit-oriented development (TOD) in historic urban fabric refers to the design and implementation of transportation systems that improve accessibility, reduce traffic congestion, and preserve the cultural and historical identity of old neighborhoods.

This approach is particularly significant in historic cities and traditional urban cores with high cultural and social value. However, poor spatial management and inefficient accessibility-based planning have led to traffic congestion, unsustainable transportation patterns, undesirable spatial flows, and increased public costs (Spears *et al*., 2018).

The rising demand for private vehicle ownership has exacerbated multiple urban challenges, including excessive energy consumption, environmental pollution, traffic congestion, psychological stress caused by traffic delays, and depletion of non-renewable energy resources (Hazel, 2007). In response to these negative impacts, TOD has gained prominence among policymakers and urban planners in the United States since the 1970s (Guerra & Cervero, 2015). In essence, TOD projects are designed to promote the use of public transportation within areas featuring a mix of residential, commercial, and office spaces near key transit nodes, such as bus and metro stations. However, a truly effective TOD initiative extends beyond a single transit station, integrating broader neighborhood functions and fostering sustainable urban development.

Urban centers with a mix of residential, commercial, and service-oriented land uses generate high volumes of vehicular traffic, leading to congestion, noise pollution, and air pollution. Consequently, policymakers have consistently sought strategies to reduce car dependency in urban areas (Duncan, 2017). The TOD framework offers a structured approach to managing urban space and optimizing intra-city travel flows (Hardy, 2018). The concept of transit-oriented urban development has been shaped by North American research and is closely linked to complementary urban planning models such as New Urbanism, Smart Growth, Traditional Neighborhood Development, Infill Development, and Affordable Housing (Ratner & Goetz, 2013). Theories on transportation and land use planning suggest that integrating public transit with land use policies can provide practical and comprehensible solutions for optimizing public transportation systems (Manaugh & Kreider, 2017). However, inefficient governance and fragmented policymaking have increasingly weakened the connection between transportation development plans and land use strategies, ultimately failing to promote economic activity around transit stations and depriving communities of key opportunities for sustainable development (Massachusetts Government, 2019). As a result, urban density has declined in areas further from city centers, leading to increased reliance on private vehicles and worsening road congestion over time (Braswell II, 2013). Transit-oriented urban development is a viable solution for mitigating traffic congestion and achieving sustainable urban mobility. This model enhances environmental quality by fostering vibrant, mixed-use urban areas while reducing pollution. TOD, as part of the Smart Growth and New Urbanism movements, seeks to create economically dynamic and livable communities (Cervero, 2016). This development model is typically centered around public transit hubs, such as bus terminals and metro stations (Reconnecting America's Center for Transit-Oriented Development, 2017). TOD projects emphasize pedestrian-friendly design, urban fabric integration, and mixed land use planning to encourage public transit over car dependency (Atkinson-Palombo & Kuby, 2011). From another perspective, TOD represents a compact urban development strategy focused on pedestrians and cyclists, incorporating open spaces, public services, and residential units adjacent to new or existing mass transit stations (Pojani & Stead, 2014).

Zanjan, with a population of 430,871, is the capital and most populous city of Zanjan province. Structurally, it is classified as a monocentric city, where the central district aligns with the main commercial core. This core is the primary hub for daily urban services, resulting in high commuter flows between residential neighborhoods and the city center. One of the critical transportation challenges in Zanjan is the narrow street network. Due to slow-paced urban renewal, the central district predominantly features an irregular and winding street layout, which evolved organically over time rather than through pre-planned design. While early urban regulations aimed at street widening and expansion, the road infrastructure has remained unchanged for decades, making it insufficient to accommodate modern transportation demands. These factors have collectively contributed to an inefficient and problematic urban transport system, particularly in the city's central area. The only viable solution to address these transportation constraints is the implementation of sustainable mobility strategies in Zanjan. Given the current challenges in transport planning, the inadequacy of existing infrastructure, and the increasing traffic demand surpassing the available urban transport facilities, adopting a TOD-based approach is crucial. This strategy could optimize travel demand, reduce unnecessary trips, and provide practical models for achieving sustainable urban mobility. Given the above considerations, this study seeks to answer the following key question: Is the urban development and spatial planning of Zanjan's central district aligned with a TOD framework?

1.1. Theoretical framework

The earliest TOD projects in the United States emerged as developments surrounding railway lines and suburban areas with car-accessible streets in the late 19th and early 20th centuries. Early railway streetcars, powered by steam engines, offered consistent speeds and reasonable acceleration but required long stop durations. As a result, stations were spaced several miles apart (Litman, 2016). According to Bass Warner (1978), TOD significantly shaped the urban and suburban fabric of the United States. The relationship between transportation, real estate, and suburban development laid the foundation for the decentralization of American cities. Radburn, the Garden City in New Jersey, is a primary example of TOD. Established in 1902, Radburn was a central city with multiple garden suburbs arranged in continuous concentric circles and enclosed by green belts. These well-designed communities were self-sufficient and seamlessly connected by a reliable public transportation system, ultimately achieving an ideal balance between residential, commercial, and agricultural zones (Jushi *et al.*, 2017). Thus, TOD seeks to organize and concentrate diverse land uses at specific locations based on population distribution and land-use diversity. These locations are typically public transit stations, especially metro and light rail stations. The TOD approach aims to align investments in public transportation with current and future land-use patterns (Niles & Nelson, 2011). Shen *et al.* (2023) argue that applying TOD in heritage-rich urban fabrics requires balancing accessibility and land-use integration with cultural preservation. Their geographic information system (GIS)-based study in Nanjing demonstrated the need for adaptive planning strategies to manage density, traffic flows, and heritage constraints simultaneously (Krismawanti & Destiawan, 2025). Uddin *et al.* (2023) developed a framework using nine GIS-based indicators across four dimensions (accessibility, density, diversity, and design) to measure TOD levels in Dhaka's rapid transit system. Their results underscore the value of composite spatial models in transit planning. Jamshidi (2024) introduced a composite index combining employment cores and residential clusters, showing how polycentric TOD can enhance spatial balance and reduce commuter flows in Tehran's metropolitan region. Nutayakul and Weerawat (2025) proposed a "Reverse TOD Index" to evaluate TOD-incompatible areas, such as unplanned metro zones in Bangkok. Their findings highlight that land value, zoning inconsistencies, and governance barriers are critical obstacles to TOD expansion in developing contexts.

In his book *Streetcar Suburbs*, Bass Warner describes TOD as a "dual-city model: a city of work separate from a city of homes" (Braswell II, 2013, p. 3). This division, as observed by Warner, marked the birth of the ideal American suburb. Dittmar & Ohland (2014) categorize TOD types based on functional domains, including downtown centers, urban neighborhoods, suburban centers, suburban neighborhoods, transitional area neighborhoods, and satellite towns. Calthorpe (1993), a leading theorist and pioneer of New Urbanism, introduced a TOD model in 1993, defining it as "a center with high-density mixed-use development, where public transit stations serve as the core" (Calthorpe, 1993, p.45). Calthorpe regarded this model as a neo-traditional guide for designing sustainable communities, viewing cities beyond their built forms. He considered TOD a community design theory that promised to address various social issues by fostering higher levels of human interaction (Calthorpe, 1993). According to Bernick & Cervero (1997), TOD is a compact, mixed-use community centered around a transit station, designed to encourage residents, workers, and shoppers to drive less and use public transportation more. Similarly, White & McDaniel (2009) classify TOD into various geographic contexts, including single-use corridors (administrative or retail), mixed-use corridors, neo-traditional development (focused on traditional villages and historic cities), TOD (high-density, mixed-use development around transit stations), rural areas (emphasizing single-family housing around a central green space or plaza), and peripheral zones.

Belzer & Autler (2012) propose six fundamental components for implementing urban transit-oriented systems:

(i) Place efficiency: The ability to access jobs, amenities, and recreational facilities within walking or cycling distance
(ii) Devaluation: Limited mortgage availability within designated zones, non-ownership housing taxation, and reduced transportation costs
(iii) Livability: Improved air quality, health, safety, economic well-being, accessibility, and reduced congestion
(iv) Financial returns: Higher taxes and costs, increased return on investment
(v) Choice: Variety in housing, transportation modes, retail, and recreation options
(vi) Efficient regional land-use patterns: Roads and land allocation for transportation infrastructure.

1.2. Types of TOD models

Achieving urban spatial development based on a transit-oriented system requires assessing urban needs, identifying challenges and limitations, and recognizing structural-functional potential. Several models have been designed to analyze existing conditions and predict future scenarios. This study examines three fundamental models.

1.2.1. Single-nodal TOD model

In this model, the transportation system is designed around a single transit-oriented neighborhood surrounding major railway stations. This type of development can occur in either urban or suburban settings. The spatial layout extends in a circular pattern around the rail station, with access radii varying based on population density and activity diversity. Pedestrian access radii typically range from 0.5 km (as seen in the United States) to 2–3 km (as observed in the Netherlands for cycling access) (Moore *et al*., 2010).

1.2.2. Multi-nodal TOD model

Similar to the single-nodal TOD, this model extends beyond a single location to form a regional network of transit nodes around metro stations, buses, and bus rapid transit (BRT) systems. These nodes can be circular or semi-circular, following a "beads-on-a-string" pattern. The objective is to ensure equitable access to transit across the entire urban area, minimizing reliance on private cars (Smas *et al*., 2016).

1.2.3. Corridor-based TOD model

This model is designed for urban areas where transit development follows metro, tram, or BRT corridors. The spatial development pattern aligns with transit routes, as nodes (such as tram stops) are closely spaced. Corridor-based TOD is commonly planned for existing urban regions and future city expansion programs. Many cities aim to implement this model as a key urban development strategy (Calthorpe, 2013).

1.3. Experiences of cities based on the TOD system

One of the most essential approaches to examining urban spatial development based on TOD is to analyze the successful experiences of cities in this field.

1.3.1. China

China is often considered an emerging test bed for TOD practices due to its rapid urban growth and the development of mass transit networks. TOD implementation can be strongly influenced by institutional barriers to urban growth. In this context, transportation planning and urban development experts have proposed three types of TOD development in China: (i) regular transit stations serving suburban development, (ii) rail-plus-real estate development at depot stations, and (iii) integrated development at regional transit hub stations.

In contrast to these three models, three key land use management strategies and principles for TOD development have also been proposed and are currently being implemented in the country: (i) having specific floor area ratios and restrictions on development in transit station areas, (ii) transferring station land development rights to transit providers at pre-rail market prices, and (iii) having clear rules for sharing costs and benefits between the public sector and developers (Song *et al*., 2021).

1.3.2. Japan

Japan is one of the pioneers of TOD in urban planning. One of the most significant TOD projects in the country is the Tsukuba Express Project, which aims to integrate urban transportation and housing development. This project connected the entire city through railway lines, trams, and rapid buses, and linked cities within a region by expanding intercity transit systems. Extending three major transit corridors created an integrated metropolitan transit system. The project was based on three core principles: cycling, public buses, and urban rail (Boarnet, 2011).

1.3.3. Brazil

One of the earliest and most successful examples of TOD is Curitiba, Brazil. The goal of urban and transportation planners in Curitiba was to organize the city and its transportation system around BRT corridors (Cervero, 2016). Curitiba's innovation lies in its unique form of participatory urban planning, emphasizing education, discussion, and public consensus. The zoning regulations of this system are based on transit capacity, population density, and land use activities. The number of bus routes is determined by population volume, economic activities, and physical-spatial constraints. Due to the affordability of travel in this system, public participation and engagement of urban managers are exceptionally high (Martinez, 2010).

1.3.4. Hangzhou (China)

Evidence from Hangzhou illustrates that the current land-centered and property-led urban rail transit construction, although contributing to the economic sustainability of "urban development strategy," has led to unaffordable housing prices and has failed to decentralize population away from downtown areas. In this regard, the Hangzhou government requires officials to increase the land value along the metro line within their jurisdiction through land redevelopment and strengthen the funding feedback mechanism of land transfer fees from land commercialization to rail transit development (Su *et al*., 2024).

1.3.5. The Netherlands (Amsterdam)

One of the most successful TOD-based urban design experiences is in Amsterdam, the Netherlands. This city has a dense, multimodal public transport system based on metro, trams, buses, and bicycles. Its urban area is a prime example of successful and even complex mobility control (Smas *et al*., 2016). Amsterdam's transit planners established four primary stations in different parts of the city, which were further connected to 17 secondary stations along four main corridors. Additional transit stations were then distributed based on this framework. Separate metro and tram lines are directly connected to these key stations, while the city center has no bus or metro stations. Instead, it is supported by pedestrian-friendly design, bicycle networks, and limited-access taxis. The main drawback of this system is restricted travel access within the city center. However, this issue is mitigated mainly through traffic control measures (Singh, 2015). Due to Amsterdam's extensive bicycle usage, the standard travel distance to rail stations is significantly higher than in TOD areas of other countries (Smas *et al*., 2016).

2. Literature review

Numerous domestic and international researchers have studied TOD indicators from various geographic and transportation perspectives, analyzing their impact on different aspects of urban development aligned with TOD principles. While it is impossible to cover all findings, the following are some notable studies.

Nutayakul and Weerawat's (2025) study on reverse TOD indicators for unstructured TOD (Bangkok Metro case study) identified barriers to TOD development in urban planning and design. Their findings indicate that land prices are the primary factor influencing reverse TOD expansion. Peng *et al*. (2025) analyzed walkability, parking density, commercial density, and the threshold effects of TOD on housing rents. They provided practical guidance for developing targeted urban development strategies.

Jamshidi (2024) found that multi-centered TODs offer better integration of urban amenities and transportation systems, benefiting from higher accessibility to public and private transit. In addition, spatial synergy between polycentricity and TOD-ness was more potent in multi-centered TODs. Wang *et al*. (2024) revealed that some metro stations in suburban areas play a crucial role in residential suburbanization and mixed-use commercial development within TOD implementation. However, nearly half of Beijing's metro stations do not exhibit TOD characteristics, suggesting that TOD-based urban development requires a diverse, flexible, and context-specific planning approach.

Uddin *et al*. (2023) used GIS analysis of nine indicators across four criteria to show that TOD planning and design must go beyond traditional sustainable transport models to incorporate environmental diversity, renewable energy accessibility, and the creation of a livable urban environment. In addition, Chen et al. (2021) found that public perceptions of local government capacity influence willingness to participate in public transportation, while perceptions of TOD's usefulness and its positive impact on surrounding economies further shape public attitudes toward TOD.

3. Research methodology

This research adopted an applied, descriptive-analytical approach to evaluate TOD indicators within the central urban fabric of Zanjan. Data were collected through two main sources: (i) secondary data from municipal reports, master plans, and transportation statistics, and (ii) primary data through field observations and note-taking. To assess the spatial compatibility of Zanjan's core with TOD principles, this study used GIS-based modeling in ArcGIS 10.8.

3.1. Selection of TOD indicators

Based on urban planning theories and prior research, 12 indicators were selected, including population density, land use diversity, intersection density, commercial land use share, pedestrian and bicycle paths, passenger loads during peak/off-peak hours, safety and facilities at transit stations, and accessibility to services within walking distance. These indicators were localized to the spatial context of Zanjan.

3.2. Data layer preparation

Spatial data layers were prepared for each indicator using GIS-compatible formats (e.g., shapefiles, raster layers). For example, population density was calculated per sqm using census data, and employment/service distribution was mapped from land use records.

3.3. Spatial interpolation

The inverse distance weighting interpolation method was applied to estimate continuous spatial values (e.g., passenger load, accessibility levels). This technique enabled the generation of surface maps reflecting congestion levels and access gaps.

3.4. Standardization and reclassification

Indicator layers were normalized using a standard scale (e.g., 0–1 or 1–5) to ensure comparability. Layers were then reclassified based on TOD standards. For example, pedestrian paths over 400 meters per hectare were classified as "High TOD compliance."

3.5. Weight assignment and overlay analysis

Each indicator was assigned a weight based on its relative impact on TOD performance. Weights were assigned as follows: population density (4.5), economic institutions (4), land use (3.5), traffic volume (5), and others between 1.5 and 4. These values were based on expert judgment and literature benchmarks. The weighted overlay method was then used to create composite TOD suitability maps.

3.6. Network analysis and accessibility modeling

A network dataset was created using the street and transit network of the city. Accessibility indices were calculated using the origin-destination cost matrix tool (ArcGIS Pro, version 3.1). The spatial mobility index (MI) was calculated as the ratio between real travel distance (T_real) and Euclidean distance (T_airline), providing insights into connectivity gaps.

These steps allowed us to generate synthetic maps of TOD compatibility, congestion hotspots, and accessibility levels, providing spatial evidence to assess Zanjan's readiness for TOD-based planning (Figure 1).

4. Results

The city of Zanjan, based on its physical and transportation needs and challenges, has developed specific key capacities for urban transportation to minimize citizens' mobility issues. In this regard, an analysis of Zanjan's urban transportation capacities, particularly in the central fabric – serving as the hub of social and economic activities, the marketplace for goods and services, and the focal point of citizens' spatial identity – reveals that its alignment with TOD standards is insufficient for transit-oriented urban development. As indicated in Table 1, the current situation reflects multiple spatial-physical challenges and transportation deficiencies in accommodating population density and activity levels within this area.

An evaluation of the transportation capacities within the traffic plan zone indicates that this area includes over 43 km of road networks with widths exceeding 25 m, more than 90 km of bus routes with 47 bus stations, and 93 buses (Zanjan Municipality, 2023). The taxi and private vehicle networks also contribute to the overall transportation system. However, since TOD principles emphasize public transit systems (buses, metro, BRT, tram, etc.), pedestrian and cycling infrastructure, and mixed land use (Calthorpe, 2013), the central fabric of Zanjan relies primarily on public buses and taxis, while lacking dedicated cycling lanes and public parking facilities. Therefore, to address the root causes of traffic and transportation issues, it is essential to analyze land use principles and the spatial distribution of population, economic activities, and land use concerning transportation capacities.

This section analyzes Zanjan's central fabric based on TOD indicators, assessing its alignment with global TOD standards through an evaluation table and GIS analysis. A standard table with eight main criteria was used to measure the compatibility of the central transportation system with TOD principles.

The analysis of TOD criteria in the traffic plan zone indicates that the population density in the central fabric of Zanjan is 105 persons per sqm, exceeding the standard threshold. Consequently, only 23% of the area meets the optimal population distribution standards, making excessive population density the primary cause of traffic congestion in the study area. Regarding land use diversity and integration, the distribution of functional land uses is not optimal. As a result, there is a high influx of visitors from other areas of the city and a significant movement of local residents seeking access to services. While commercial and service activities occupy 24% of the area, most commercial and service land uses are concentrated in a compact area from Amir Kabir Square to Enghelab Square and Saadi Crossroads. This non-standard distribution of land use further increases population mobility beyond acceptable levels.

In terms of pedestrian and cycling paths (meters) and intersection density (number of intersections), the findings indicate that despite the pedestrian-oriented nature of the roads, the absence of cycling paths means that only 50% of this criterion is met. According to Figure 2, limited pedestrian and cycling routes have been implemented in the central fabric.

Regarding the density of commercial institutions, municipal tax revenues, and employment levels, findings

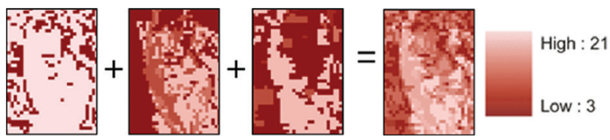

Figure 1. Overlay function in classified raster layers
Source: Image adopted from authors.

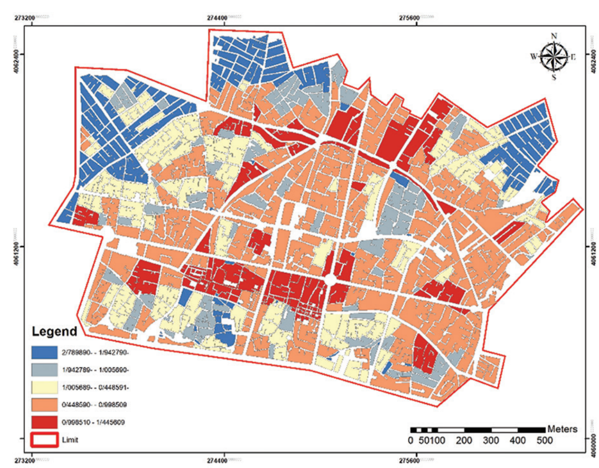

Figure 2. Spatial mobility index of population and activity in the central area of Zanjan
Source: Map by the authors.

Table 1. Compatibility of the current state of Zanjan with transit-oriented development measurement criteria

Status in the city of Zanjan	Regulations	Symbol	Index
Only 23% of the standard has been met (105 persons per sqm)	Urban density is crucial for transit-oriented development (TOD) (25 persons per sqm)		• Population density (persons per sqm)
Land use distribution is uneven and does not align with population capacity and passenger mobility	Land use diversity creates a vibrant and dynamic node		• Land use diversity
In the core of the urban fabric, this indicator has been achieved at only 50%. Although streets are generally pedestrian-oriented, bicycle lanes are largely absent, and pedestrian as well as bicycle paths have been implemented only to a limited extent	Urban space design based on walkability and cyclability is essential for TOD areas		• Mixing residential use with other land uses • Presence of pedestrian and bicycle paths (meters) • Intersection density (number of intersections)
24% of the area's space is designated for activity uses. 19% of the municipality's revenue comes from taxes on these uses. The employment rate in this area is 61%	Greater economic development in an area leads to increased TOD		• Commercial establishment density • Municipal tax revenue • Employment levels
The traffic load of stops in the area exceeds 10 min, so the area's capacities are highly saturated	The transportation system must have free capacity. Saturated capacities cannot attract more passengers		• Passenger load during peak hours • Passenger load during off-peak hours
There are 2 terminals with low safety standards; no kiosks at the stations, and user-friendly facilities are <5%; lack of information display systems at the stations	A user-friendly transportation system is essential to encourage people to use public transit		• Passenger safety at transportation stations • Basic facilities at stations • Presence of information display systems
The presence of multiple intersections and high passenger transfer capacity and route changes; the employment rate in this area is 61%; the access distance to bus stations is <6 min	A node with better access and high accessibility increases the chances of TOD		• Frequency of transportation services • Interchange to different transportation routes • Interchange to other modes of transportation • Access to opportunities within walking distance from the bus station (number of jobs)
Lack of car and bicycle parking in the area	Providing parking for bicycles and cars helps more people use public transportation for their long-distance trips		• Supply-demand for cars (parking) • Supply-demand for bicycles (parking)

Note: The regulation details, symbols, and index information in the table were taken from Singh (2015).

show that 24% of the area is dedicated to commercial and service activities. A significant portion of the city's population commutes daily to this area for work, services, and shopping, contributing to 19% of the municipality's tax revenue. In addition, employment in this zone accounts for 61% of the total employment rate in the area.

The central urban area has two terminals with low safety standards. In addition, most stations lack secure, user-friendly kiosks and do not have an information display system. Furthermore, the absence of high-capacity standard parking facilities around the central area, inadequate infrastructure for non-motorized transportation, such as bicycles, and a non-standard road network (narrow and winding streets) continuously exacerbate transportation issues. Moreover, there is no official public parking in this area. The bicycle lanes and pedestrian paths are limited to the surroundings of Sabzeh Meydan and play a minimal role in passenger mobility. A summary of the area's transportation conditions is presented in Figure 3, while Table 1 compares the current state of the central urban fabric based on the TOD indicators.

As explained in Table 1, some TOD indicators are absent within the traffic plan area, while others face multiple challenges, making them insufficient to meet the actual needs of the population. Consequently, these indicators received very low scores. Using the network analysis algorithm in the GIS environment, the collected indicators were integrated into GIS, converted into spatial layers, and then weighted before being transformed into raster format. Finally, the network analysis was conducted to generate the final output. As illustrated in Figure 4, the layer overlay for the network analysis was performed in ArcGIS.

The analysis of the mismatch between the structural-functional characteristics of the central fabric of Zanjan and TOD indicators, along with the existing traffic and transportation issues in this area, involved an integrated examination of various layers. The results of the traffic map analysis based on peak and off-peak passenger load – identified as traffic hot spots through daily statistics published by the Traffic Control Center and analyzed using the inverse distance weighting technique – indicate that the most congested areas of Zanjan's central fabric align with zones of high-density activity and narrow, predominantly one-way streets (<25 m wide). Therefore, the primary cause of transportation issues in this area lies in spatial-structural deficiencies and street design, which have led to an increasing dependence of other city areas on the central district and a rise in daily commuting. Consequently, the lack of balanced land use distribution across the city, residents' dependency on the central district for social, economic, and cultural services, the city's semi-radial shape with its core positioned in the center of the semicircle, and the subsequent limitation in street distribution contribute to heightened traffic congestion – despite the availability of various public and private transportation services in

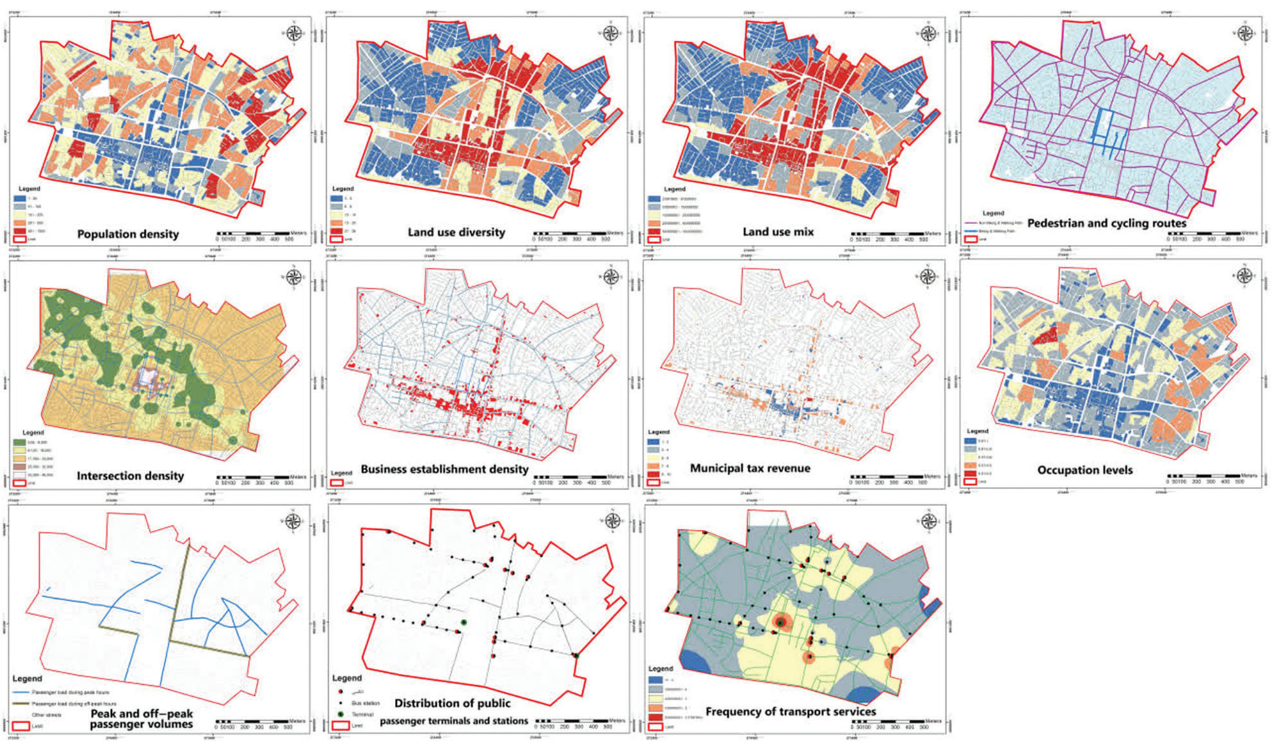

Figure 3. Transportation capacities in the transit-oriented central fabric of Zanjan
Source: Maps by the authors.

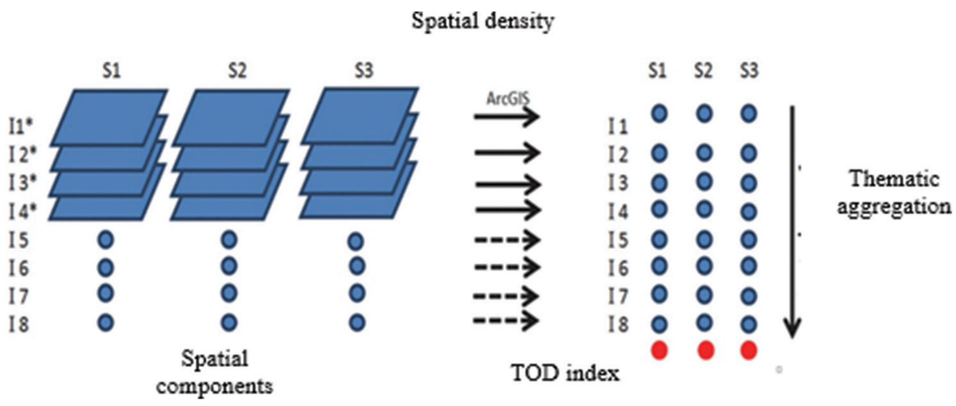

Figure 4. Method of defining layer overlays in network analysis using ArcGIS
Source: Diagram by the authors.
Abbreviation: TOD: Transit-oriented development.

the area. As illustrated in Figure 5, these traffic hot spots are concentrated in Zanjan's central fabric, confirming the results of the analysis.

At this stage, spatial analysis models and accessibility indices were used to illustrate the relationship between urban transport capacity, population density, and activity concentration in the central fabric of Zanjan. The data used in this analysis included street network maps, traffic hot spots, population data, and street widths. To calculate the accessibility index, traffic zone layers at intersections were analyzed, assuming a uniform population distribution within the area. The percentage of individuals with access to the street network within a specified distance was then determined.

In the first step, datasets were prepared in the Arc Catalog environment, considering general traffic rules and assigning weight coefficients to key fields affecting network analysis. Once pixel distances and the flow dynamics between key points were determined through spatial analysis, the accessibility level of activity centers based on transport network capacity was assessed. The findings indicate that in most of the examined areas, accessibility in the central fabric is significantly low. In zones with peak transportation capacity, accessibility decreases further due to high population density and heavy traffic congestion.

Spatial analysis results revealed that the highest accessibility was found in the Saadi Shomali area, extending toward Darvazeh Rasht and Ghaem Boulevard. This region experiences lower movement intensity due to a well-connected street network, fewer commercial and service land uses, and relatively lower public footfall. Consequently, one of the main factors contributing to

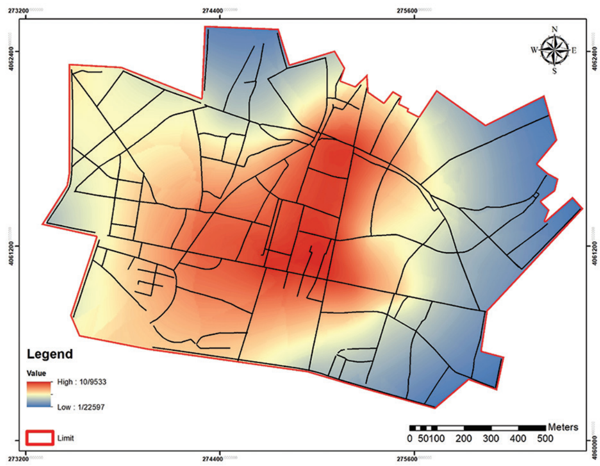

Figure 5. Traffic hot spots in the central fabric of Zanjan
Source: Map by the authors.

traffic congestion and high foot traffic in the central area is the presence of affordable public transportation systems, which encourage residents to conduct their daily activities within this zone. As illustrated in Figure 6, this spatial disparity in accessibility patterns is evident within Zanjan's central fabric.

The spatial MI was determined by examining the alignment of population and activity with a formula structure where the origin score represents population centers and the destination score represents activity centers. Given that immobility limits access to opportunities, improving public access to opportunities requires the implementation of high-quality networks. In this context, mobility is a variable that measures the movement of people and goods within a specific system or area. Essentially, this index compares the existing network structure to an

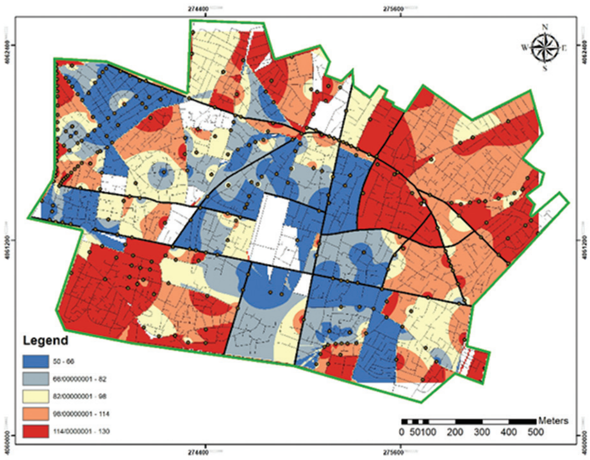

Figure 6. Accessibility in the central fabric of Zanjan
Source: Map by the authors.

ideal network that connects origins and destinations using Euclidean distances.

According to the following formula (Equation I), this index is equal to the ratio of travel time between the origin and destination based on network distance to travel time between the origin and destination based on Euclidean distance:

$$MI = \frac{T_{real}}{T_{airline}} \quad \text{(I)}$$

where T_real and T_airline represent the travel time along the physical route and the travel time along the Euclidean route between the origin and destination, respectively. Since only distance is considered as impedance, direct distance is used instead of time to calculate this index. In addition, the MI compares the distances in the real and Euclidean networks, and the distance between activity and population centers must be calculated directly.

To create the Euclidean network, network analysis in ArcGIS and the origin-destination cost matrix tool were used. The spatial analysis results show that 22% of the area in the study zone falls into the "very high" MI category, while 47% of the area falls within the "high" spatial mobility range. This indicates that many residents in the region are unable to meet their needs locally and need to travel long distances within the central area to access various services, as the diversity of activities is not maintained in some parts of the area.

According to the model's output, only 31% of the study area shows a balance between population mobility and activity distribution, where, due to land use diversity and mix, people travel short distances to access services. This includes 12% of the area with very low spatial mobility, 9% with low mobility, and 10% with moderate mobility. Thus, the main challenge in the central area of Zanjan city lies in the spatial distribution of land uses and creating a balance between population and activity/service uses rather than in transportation itself. This imbalance has increased pendular movement within the city, especially in the study area. As a result, the urban transportation capacity does not adequately address the city's spatial and structural issues.

5. Discussion

The findings of this study highlight a significant mismatch between TOD indicators and the current spatial-structural conditions of Zanjan's historic center. While approximately 31% of the study area shows acceptable spatial mobility aligned with TOD standards, the remainder of the central district remains structurally and functionally incompatible with TOD principles. This outcome echoes Shen *et al.* (2022), who argue that historic urban fabric poses distinct challenges for TOD implementation due to narrow streets, land-use rigidity, and the need to preserve cultural identity. In Zanjan, similar constraints were observed: uncoordinated intersections, irregular road geometry, and the over-concentration of services and employment within a compact area. Consistent with Jamshidi (2024), who highlighted the importance of polycentric development, the results in Zanjan reveal that the monocentric form of the city contributes to excessive daily commuting into the central core. Unlike polycentric models that distribute population and activity across several nodes, Zanjan's current configuration intensifies congestion in one focal area. Moreover, despite the relatively high presence of commercial uses, the area fails to adequately support pedestrian and non-motorized travel infrastructure, aligning with Uddin *et al.* (2023), who emphasized the importance of walkability and design diversity in TOD success. The lack of safe terminals and station-level amenities also undermines public confidence in transit systems, similar to concerns raised in Chen *et al.* (2021). One distinctive aspect in the Zanjan context is the limited flexibility in land use transformation, particularly in the historical zones, where redevelopment faces institutional and conservation-related barriers. This aspect corresponds with findings from Nutayakul and Weerawat (2025), who identified governance limitations and market-driven land constraints as obstacles in similar Asian urban environments. Thus, while GIS-based spatial modeling provides a valuable lens for evaluating TOD readiness, its translation into actionable policy remains constrained by institutional inertia, physical constraints, and the socio-cultural specificity of the context. Any TOD strategy for Zanjan must consider adaptive reuse, functional diversification, and context-sensitive mobility planning.

6. Conclusion

The TOD index status in the historic fabric of Zanjan city clearly highlights serious challenges in the design and performance of the urban transportation system. Over 75% of the area does not meet TOD population density standards due to overconcentration in limited zones. Commercial and service land uses are spatially clustered, generating traffic bottlenecks and intensifying pedestrian pressure. There is a severe lack of cycling infrastructure and designated pedestrian pathways, especially beyond the immediate vicinity of Sabzeh Meydan. Transit facilities (stations, terminals) are inadequately equipped, with poor safety, limited amenities, and no real-time information systems. Accessibility analysis indicates high traffic volumes correlate with weak spatial mobility, especially in narrow, irregular streets.

In addition, the weak public transportation system in Zanjan is one of the key factors contributing to the inefficiency of the TOD index. The absence of regular and reliable public transport lines encourages citizens to use private vehicles, which increases traffic and puts additional pressure on existing infrastructure. The conclusion drawn from this situation indicates that to improve the TOD index in the historic fabric of Zanjan, there is a need to revise and enhance the urban transportation infrastructure and strengthen the public transportation system. These measures could include redesigning streets, creating new public transportation routes, and improving access to urban services and facilities.

A review of experiences from other countries shows that Japan emphasizes cycling, public buses, and urban trains, while Brazil focuses on using BRT lines in the city center. In Amsterdam, Netherlands, like in Zanjan's city center, there are no bus or metro stations, and the transportation mode is primarily through bicycles and specialized taxis. The experience from Amsterdam suggests that to create a transportation-oriented city and control traffic, the primary and secondary terminals should be designed around the central area with hierarchical relationships. The central area should be managed through pedestrian and bicycle-oriented designs, along with special and limited taxis. Furthermore, the analysis of the alignment of transportation capacity and land use patterns with TOD principles showed that Zanjan has not been successful in adhering to standards of pedestrian orientation, distribution of bus and taxi stations, station safety, accessibility, cycling, and spatial distribution of land use in line with population capacity. Previous research findings, such as those by Nutayakul and Weerawat (2025) on land price control, Jamshidi (2024) on spatial synergy and multi-centering, Wang *et al*. (2024) on adopting diverse and flexible planning approaches, Uddin *et al*. (2023) on emphasizing TOD design, and Chen *et al*. (2021) on enhancing citizen awareness of the benefits of TOD, have provided significant insights in this regard.

The overall findings of the study, in comparison with experiences and previous research findings, indicate that the most important spatial development model based on public TOD in the central area of Zanjan is the combination of land use through the redistribution of land uses and necessary public services. The primary issue in transportation is not the lack of transportation infrastructure, but rather how land use management, population, and activity capacities have been handled. The research findings suggest that regarding land use mix, emphasis should be placed on matching population density with economic, transport, and land use capacities. In other words, the population density in the area should be redistributed according to the capacity of the area. The construction of high-rise residential buildings should be limited to prevent the population density from exceeding the area's capacity. In terms of activities, the focus should be on the ratio of employed individuals to the population and the flow of goods and services. For transportation, the accessibility index of transport capacities to land uses and services should be reconsidered.

Based on the findings, this study proposes several recommendations to be considered. First, redistribute land uses to create more balanced mixed-use nodes across the urban fabric, especially by reducing commercial clustering in central corridors. Second, control and regulate population density by limiting high-rise residential developments in areas lacking sufficient transport capacity. Furthermore, the government can upgrade public transit terminals to meet safety and service standards, including installing information systems and designated passenger zones. They could also expand pedestrian and cycling infrastructure across the entire central district, not just in tourist or high-traffic areas. In addition, promote polycentric urban development to alleviate monocentric congestion, inspired by successful examples such as Tehran, Amsterdam, and Curitiba. Finally, adopt adaptive TOD frameworks suitable for heritage zones, focusing on rehabilitation rather than demolition, with respect to Zanjan's historic urban identity.

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