

Article

Sustainable Urban Renewal: Planning Transit-Oriented Development (TOD) in Riyadh

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Abstract: Rapid urbanization and car dependency have transformed Riyadh into a sprawling metropolis, straining mobility, sustainability, and land use efficiency. Investments in metro and Bus Rapid Transit (BRT) systems present an opportunity to shift toward transit-oriented development (TOD), making strategic urban planning essential. This study assesses Riyadh's TOD potential by analyzing its urban structure, transport accessibility, and regulatory framework while drawing lessons from successful global models. This study applies GIS-based spatial analysis, policy review, and AI-driven clustering techniques (e.g., DBSCAN, K-Means) to evaluate TOD readiness and inform actionable strategies for Riyadh. The findings indicate that transit investments alone are insufficient due to gaps in zoning policies, pedestrian connectivity, and urban density. Enhancing compact, mixed-use developments, improving first- and last-mile accessibility, and leveraging AI-driven planning can reshape the city's mobility ecosystem and foster sustainable urban growth. Vision 2030 provides a pivotal opportunity to align infrastructure investments with urban planning policies, ensuring Riyadh evolves into a modern, efficient, and transit-friendly city.

Keywords: transit-oriented development (TOD); urban mobility; sustainable urban planning; Riyadh Metro; bus rapid transit (BRT); mixed-use development; pedestrian accessibility; zoning policies



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1. Introduction

Urbanization has transformed cities worldwide, shaping their growth patterns, infrastructure, and mobility systems [1]. Many metropolitan regions have embraced transit-oriented development (TOD) as a strategy to address congestion, enhance sustainability, and promote efficient land use [2]. TOD principles encourage high-density, mixed-use developments centered around transit hubs, fostering walkable environments and reducing dependence on private vehicles [3]. Successful TOD implementation has improved urban efficiency, environmental performance, and economic vitality, demonstrating its potential as a sustainable planning approach [4].

Despite these global advancements, many cities continue to struggle with car dependency, urban sprawl, and fragmented transit networks [5]. Auto-centric development has led to increasing congestion, inefficient land use, and environmental degradation, prompting urban planners to seek solutions that integrate land use and transport planning [6]. TODs offer a viable framework to restructure urban mobility [7–10], ensuring that cities grow in a more sustainable and accessible manner [11].

Riyadh, one of the fastest-growing cities in the Middle East, reflects many of these challenges [12–14]. Decades of rapid expansion, coupled with a road-centric urban model, have resulted in widespread car dependency, traffic congestion, and limited walkability [15]. The city's urban structure is characterized by low-density development and isolated land uses, making public transportation less effective [16]. While major investments have been made in transit infrastructure, including the Riyadh Metro and Bus Rapid Transit (BRT) system, these projects alone are insufficient to shift mobility patterns unless they are supported by a well-planned urban framework [17] (Figure 1).

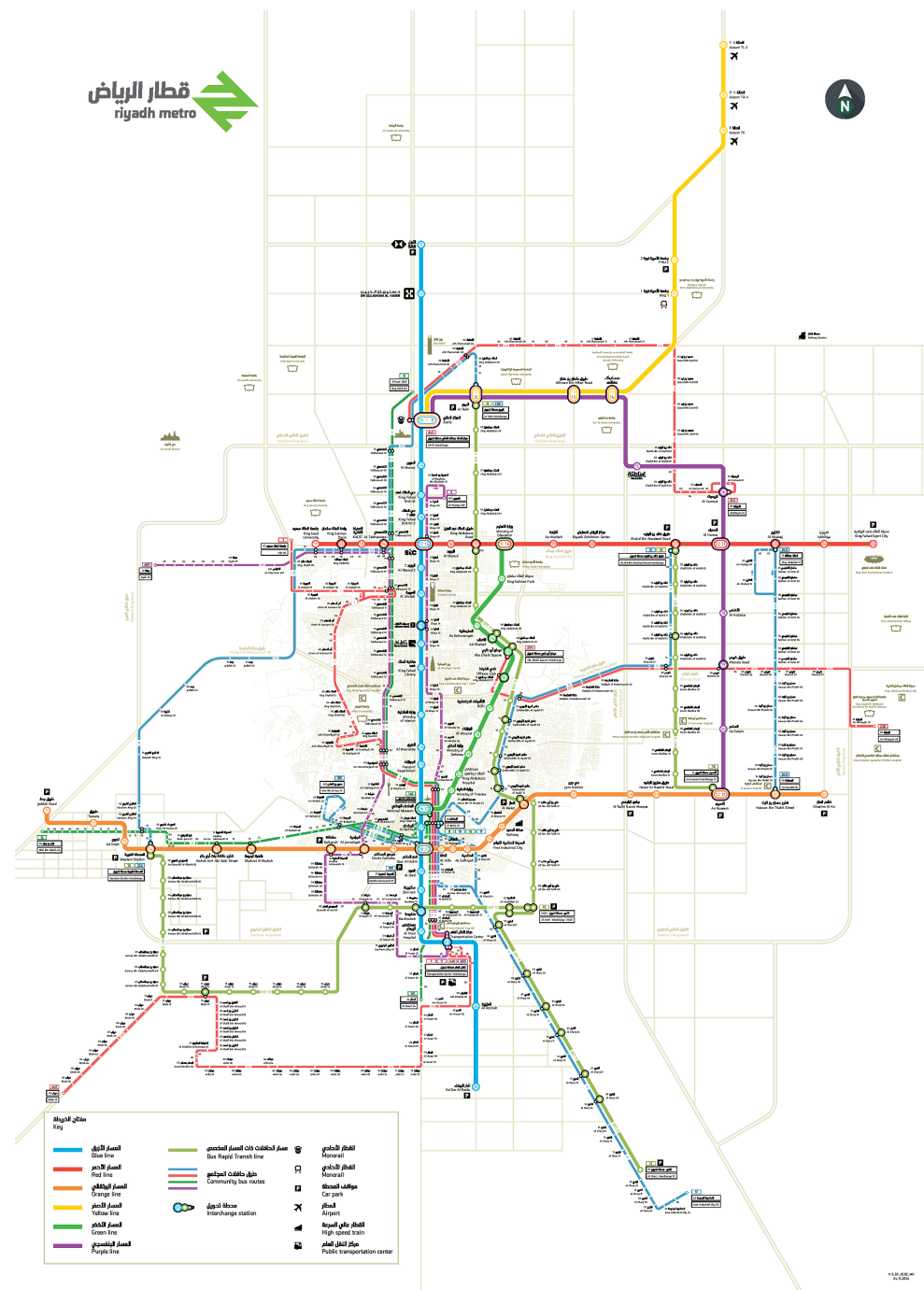


Figure 1. Map for Riyadh city with the metro and BRT lines (credit: Royal Commission for Riyadh City, Credit: <https://old.rcrc.gov.sa/en/projects/king-abdulaziz-project-for-riyadh-public-transport/>, accessed on 5 May 2025).

Saudi Vision 2030 presents an opportunity to reshape Riyadh's urban landscape through TOD-focused planning [18]. The introduction of metro and BRT systems establishes the groundwork for integrating transit with land use, promoting compact, pedestrian-friendly developments. However, the successful implementation of TOD requires overcoming challenges related to zoning regulations, urban design, and behavioral shifts [19]. Riyadh's existing infrastructure favors private vehicles, and a lack of mixed-use developments around transit stations limits the full potential of public transportation investments [20].

Three central research questions have been formulated to guide this study. The aim is to frame the analytical approach and ensure relevance to Riyadh's urban transformation goals. First, what are the primary barriers and opportunities associated with implementing transit-oriented development (TOD) in Riyadh, particularly in the context of the Kingdom's Vision 2030 agenda? This question addresses the practical and institutional challenges that must be overcome to align TOD strategies with national development goals. Second, how does Riyadh's current urban structure, mobility infrastructure, and policy environment compare to globally established TOD cities such as Tokyo, Singapore, and Copenhagen? This comparative lens enables a critical examination of Riyadh's readiness and identifies transferable best practices. Third, what spatial, regulatory, and design interventions are necessary to accelerate TOD adoption and promote inclusive, sustainable urban mobility in Riyadh? This question allows for building scenarios and actionable recommendations that align local conditions with international standards. Together, these questions define the scope of this research and provide a roadmap for analysis and evaluation. This study examines Riyadh's TOD potential, analyzing current infrastructure, regulatory frameworks, and socio-economic factors influencing TOD implementation. It identifies barriers to effective TOD and proposes strategic solutions to optimize Riyadh's urban growth, enhance transit accessibility, and improve sustainability.

This study contributes to the existing TOD literature by offering a Riyadh-specific spatial and policy assessment utilizing AI and GIS tools, which are currently underexplored in this context. It identifies concrete spatial mismatches in transit access and zoning patterns, proposing an integrated planning approach that is responsive to Riyadh's socio-economic and environmental realities. Moreover, the research fills a critical gap in TOD studies for Gulf cities by bridging established global models with hyper-local conditions, thereby enriching the discourse on sustainable urban development in the region.

By highlighting the unique challenges faced by Riyadh, this study sets the stage for future research that can build on these findings, exploring additional dimensions such as community engagement, economic implications, and environmental impacts. This comprehensive approach not only advances academic understanding but also provides practical frameworks for urban planners and policymakers aiming to implement effective TOD solutions. The remainder of this paper is structured into five sections to provide a comprehensive exploration of the topic. Section 2 reviews the existing TOD literature and global best practices, establishing a theoretical foundation for the analysis. Section 3 outlines the methodology employed in the study, detailing the analytical techniques used to assess TOD readiness. Section 4 presents empirical results derived from the data analysis, highlighting key findings and insights that inform the subsequent discussions. Section 5 offers discussions and implications based on these results, providing a critical evaluation of the findings in the context of Riyadh's urban landscape. Finally, Section 6 concludes with recommendations that are closely aligned with the goals outlined in Vision 2030, ensuring that the proposed strategies are not only actionable but also relevant to the city's long-term development vision.

2. Literature Review

2.1. Conceptualizing Transit-Oriented Development (TOD)

TOD is an urban planning approach that integrates land use and transportation to create compact, walkable, and high-density communities centered around public transit [21]. This concept aims to reduce automobile dependency, enhance urban livability, and support sustainable mobility. Scholars and urban planners emphasize that TOD is an effective strategy for mitigating urban sprawl while fostering mixed-use environments that blend residential, commercial, and recreational spaces [22,23]. The fundamental idea is to position urban development around transit nodes, ensuring that people live, work, and socialize within walkable distances from public transport.

The core principles of TOD revolve around six essential elements that determine the success of such developments. Diversity in land use allows different functions, such as housing, retail, offices, and cultural amenities, to coexist within the same urban setting [24]. Density significantly contributes in supporting transit infrastructure, as higher population concentrations near transit hubs increase ridership and reduce per capita transportation costs [25]. Design considerations focus on pedestrian-friendly environments, ensuring accessibility, safety, and an engaging public realm [26]. Distance to transit determines how seamlessly residents and workers can integrate transit into their daily routines [27]. Destination accessibility ensures that key locations such as employment centers, educational institutions, and healthcare facilities are well connected within the transit network [28]. Demand management strategies, such as limiting parking spaces and promoting non-motorized transport, help reduce car dependency and create more efficient urban mobility patterns [29].

TOD plays a transformative role in reshaping urban mobility and environmental sustainability. Cities can decrease congestion, lower greenhouse gas emissions, and optimize land use by prioritizing transit infrastructure over car-centric development [30]. Urban areas designed around TOD principles tend to foster active modes of transport, including walking and cycling, which contribute to public health and social well-being [31]. Additionally, TOD is associated with economic benefits such as increased land values near transit stations, job creation, and higher commercial activity due to the accessibility of businesses [32]. The concept has gained traction globally, leading many cities to rethink their urban planning strategies in response to climate change, urbanization pressures, and economic diversification goals.

2.2. Global TOD Best Practices

TOD has been successfully implemented in various cities worldwide, providing valuable insights into how Riyadh can enhance its transit infrastructure and urban development strategy. Cities that have effectively integrated TOD principles have demonstrated significant reductions in automobile dependency, increased transit ridership, and improved urban efficiency [33]. These experiences highlight the importance of coordinated policies, transit investments, and spatial planning in shaping urban environments.

The selection of Tokyo, Singapore, and Copenhagen as comparative case studies is intentional, reflecting a diversity of transit-oriented development models that differ in governance, planning strategies, and socio-spatial outcomes. Tokyo represents a market-driven, private sector-led TOD system where real estate and transit infrastructure are tightly integrated through railway corporations that both build and operate urban services. In contrast, Singapore showcases a centralized, government-led model, where urban planning and transport policy are meticulously synchronized to achieve high transit ridership and compact development. Copenhagen offers a hybrid example where public planning initiatives such as the Finger Plan promote balanced growth along transit corridors while

also incorporating non-motorized modes like cycling into the TOD framework. Each city exemplifies distinct trajectories of TOD implementation, offering Riyadh a spectrum of lessons applicable to different stages of urban maturity and mobility challenges. Their selection also ensures a balanced geographical and policy-oriented comparison that highlights institutional adaptability. In addition to these established cases, broader TOD typologies and frameworks provide a valuable lens for comparative analysis. Researchers [34] have proposed a typology that differentiates TOD contexts based on governance, land use, and transport integration, helping to frame how lessons from global cities can be adapted to emerging urban contexts such as Riyadh. Tokyo's corporatized railway-driven TOD model has also been explored in terms of unplanned suburban growth and the unique role of private rail companies in shaping urban expansion [35]. Meanwhile, Singapore's value capture mechanisms offer replicable tools for financing TOD in cities undergoing rapid growth. Copenhagen's approach aligns with broader sustainability principles, where urban form, density, and mobility behavior are closely interlinked [36]. Together, these perspectives facilitate deep insight into TOD as both a spatial and institutional strategy, reinforcing the relevance of the selected case studies.

Tokyo is a prime example of a city that has developed around its extensive railway system [37]. The transit network has played a fundamental role in shaping urban growth, with high-density developments clustered around train stations [38]. The success of TOD in Tokyo is largely attributed to the seamless integration of public transit with land use policies that encourage mixed-use development [39]. Rail companies have actively participated in real estate development, ensuring that commercial, residential, and office spaces are optimally placed around transit hubs. As a result, Tokyo's urban fabric is characterized by walkability, vibrant street life, and high levels of transit accessibility [40]. The emphasis on vertical integration has allowed the city to accommodate a growing population without expanding outward, preventing the urban sprawl that is common in car-dependent cities.

Singapore offers another well-structured TOD model, where government-led planning has ensured a systematic approach to urban growth. The Mass Rapid Transit (MRT) system has served as the backbone of urban mobility, with high-density developments and commercial districts concentrated along transit corridors [41]. Singapore's planning authorities have implemented strict zoning regulations to ensure that new developments align with public transit infrastructure. Policies such as limited parking availability, congestion pricing, and pedestrian-friendly urban design have successfully encouraged public transport use over private vehicles [42,43]. In addition to transit accessibility, Singapore has focused on creating self-sustaining urban hubs that combine housing, workplaces, and recreational spaces within transit-oriented districts [44]. The effectiveness of this approach is evident in the city's high transit ridership and reduced traffic congestion.

Copenhagen represents a hybrid approach to TOD, integrating transit-oriented and cycling-oriented development within its urban planning framework [45,46]. The city's growth has been guided by the Finger Plan, which concentrates development along radial transit corridors extending from the city center [47]. High levels of connectivity between rail services, cycling networks, and pedestrian pathways have created an efficient and sustainable urban mobility system. The city has invested heavily in cycling infrastructure, complementing its public transport system and reducing reliance on automobiles. Transit stations are surrounded by mixed-use developments, ensuring that essential services, workplaces, and residential areas are within close proximity. The result is an urban environment that prioritizes accessibility, sustainability, and livability.

Although Tokyo, Singapore, and Copenhagen did not originate from the same level of automobile dependence as Riyadh, each has experienced significant transitions in urban mobility paradigms that reflect transformative shifts toward TOD principles. Tokyo, for instance,

underwent rapid post-war urban growth and consciously structured development around rail infrastructure, preventing the kind of sprawl seen in many Western cities. Singapore actively discouraged car ownership through policies like high registration taxes and congestion pricing, while simultaneously building an efficient Mass Rapid Transit (MRT) system that anchors dense, mixed-use development. Copenhagen, while never fully car-dependent, shifted from a more automobile-focused mid-century planning model to one centered on sustainable transit and cycling, leveraging strategic land use policies to promote radial development. These cities demonstrate that even established urban patterns can be reoriented toward sustainable, transit-based models, making them relevant precedents for Riyadh's current efforts to pivot away from car-centric growth. While the comparative review of global transit-oriented development (TOD) models provides foundational insights, it is crucial to emphasize that Riyadh's TOD transition is deeply rooted in a unique socio-spatial context that diverges significantly from the studied cities. The current regulatory framework, shaped by historical planning paradigms, tends to favor car-oriented development [48], posing challenges for the implementation of more flexible and innovative urban strategies [49]. Furthermore, Riyadh's harsh climatic conditions—characterized by extreme heat and arid landscapes—pose unique challenges for outdoor mobility and pedestrian accessibility. Such environmental factors make it imperative to design urban spaces that not only accommodate but also encourage pedestrian movement and public transport use. Societal preferences for private car use, shaped by long-standing mobility patterns, present unique challenges for increasing public transport adoption [50]. This reliance on automobiles is deeply ingrained in social behavior, where car ownership is associated with status and convenience. Moreover, the coordination of multiple institutional stakeholders presents a complex landscape, requiring enhanced collaboration to support cohesive TOD implementation. Various stakeholders—including government agencies, private developers, and community organizations—often have differing priorities and objectives, leading to a lack of coordinated action. Therefore, rather than applying best practices from other cities wholesale, this paper repositions these global models as adaptable frameworks tailored specifically to stimulate policy reflection, urban design adaptation, and institutional learning in Riyadh [15]. The subsequent sections will shift focus to the city's distinct challenges and opportunities, underscoring the need for context-sensitive approaches that respect local conditions while aiming for sustainable urban growth.

2.3. TOD in Riyadh: Challenges and Opportunities

Riyadh has historically been shaped by an automobile-centric urban model, and unlike transit-oriented cities that prioritize high-density development near transport nodes, Riyadh has experienced decentralized growth patterns, leading to longer commuting distances and increased traffic congestion [51,52]. However, with the ongoing development of the Riyadh Metro and BRT network, there is a growing opportunity to transition toward a TOD framework that aligns with sustainable urban development goals.

One of the key challenges facing Riyadh in implementing TOD is the existing urban fabric, which is predominantly characterized by low-density development [15]. The traditional zoning system has separated residential, commercial, and industrial zones, making it difficult to establish mixed-use transit-oriented districts [19]. The lack of pedestrian infrastructure further exacerbates this issue, as many areas are not designed for walking or cycling, limiting the effectiveness of transit integration [53,54].

Despite these challenges, Riyadh's investment in public transit infrastructure provides a significant opportunity to reshape its urban development approach. The introduction of six metro lines and an extensive BRT system creates a framework for densification around transit hubs [48]. Integrating residential and commercial developments within walking distance of transit stations can enhance accessibility and encourage public transport use.

Additionally, improving public spaces, sidewalks, and cycling infrastructure can make transit-oriented districts more attractive and functional. Policy reforms, such as updating zoning regulations to allow for higher density and mixed-use developments, can further support the TOD transition.

The success of TOD depends on the integration of transport infrastructure with land use planning, ensuring that transit investments are complemented by supportive urban policies.

The challenges of implementing TOD in Riyadh extend beyond spatial and infrastructural limitations, encompassing deeply rooted socio-cultural, regulatory, and behavioral dimensions. The city's zoning codes have traditionally enforced land use segregation, creating spatial mismatches between housing, employment, and services that undermine the effectiveness of public transport. Furthermore, private car use is often linked with perceptions of convenience and privacy, which may influence the pace of transition toward public mobility modes. Institutional fragmentation also presents a barrier: various planning and transport agencies operate in silos, slowing progress on integrated TOD initiatives. Additionally, the urban environment presents significant challenges for pedestrians and cyclists, particularly in terms of infrastructure continuity and climate adaptation, with high summer temperatures exacerbating discomfort in the absence of shaded routes or green corridors. Without addressing these interconnected layers—regulatory rigidity, cultural attitudes, inter-agency coordination, and climate-responsive design—Riyadh's transition to a transit-oriented model risks being partial and unsustainable. Finally, cultural preferences for privacy and climate-controlled mobility further complicate behavioral shifts toward public transport. In Riyadh, the social fabric is interwoven with a strong emphasis on individualism and personal space, which can hinder the acceptance of communal transportation systems. These aspects reinforce the need for localized TOD solutions that respect socio-cultural expectations while encouraging gradual transitions toward more sustainable mobility modes. Understanding these socio-cultural nuances is vital for crafting effective urban policies and designing infrastructure that resonates with the community's values. Engaging local stakeholders in the planning process can foster greater acceptance and facilitate behavioral change, ultimately contributing to the success of TOD initiatives in Riyadh. This engagement can take the form of workshops, public forums, and interactive design sessions that invite feedback and suggestions from community members. By involving residents in the decision-making process, urban planners can not only address concerns but also cultivate a sense of ownership over the new developments, which is essential for long-term sustainability.

2.4. Comparative Analysis of TOD Features in Riyadh vs. Global Cities

The experiences of Tokyo, Singapore, and Copenhagen offer valuable insights into how Riyadh can refine its TOD strategy. A comparative analysis based on the papers reviewed in this study reveals key differences in transit accessibility, urban density, and land use integration. While global TOD cities prioritize high-density, mixed-use developments, Riyadh's urban structure remains largely decentralized. Table 1 summarizes the comparison. Public transit ridership in Riyadh is significantly lower compared to that in established TOD cities, highlighting the need for policies that encourage transit-oriented growth. Walkability and cycling infrastructure are also underdeveloped in Riyadh, whereas cities such as Copenhagen have successfully integrated active mobility within their transit systems. It is important to acknowledge that Copenhagen's trajectory toward TOD differs significantly from Riyadh due to its longstanding tradition of integrated urban planning and sustainable mobility. The Danish capital's spatial development has been guided since 1947 by the Finger Plan, which deliberately concentrated growth along five "fingers" radiating from the city center, each aligned with commuter rail lines and interspersed with

green wedges. This structured growth facilitated transit-oriented urbanization decades before the TOD concept became globally mainstream. Furthermore, Copenhagen’s deeply embedded cycling culture and early investments in pedestrian infrastructure created a mobility ecosystem where public and non-motorized transport modes dominate. By contrast, Riyadh has evolved under a car-centric paradigm, with low-density zoning, wide arterial roads, and minimal walkability. Therefore, while Copenhagen provides useful benchmarks in terms of transit integration and multimodal design, its unique historical and cultural context requires careful consideration before applying its model wholesale to Riyadh’s very different urban fabric. A strategic shift toward TOD in Riyadh requires policy adjustments, urban design improvements, and behavioral shifts toward public transport usage. The implementation of TOD principles can help Riyadh achieve sustainable urban growth while addressing challenges related to congestion, air pollution, and land consumption.

Table 1. Comparison of TOD features in Riyadh vs. Tokyo, Singapore, and Copenhagen (source: authors).

Feature	Riyadh	Tokyo	Singapore	Copenhagen
Urban Density	Low-density, urban sprawl	High-density, transit-centric	High-density, compact urban form	Medium-density, transit and cycling integration
Mixed-Use Development	Limited, zoning laws restrict mixed-use areas	Extensive, well-integrated residential and commercial spaces	Government-led mixed-use planning	Integrated land use and transport planning
Public Transit Ridership	Low, currently developing Metro and BRT	Very high (~80%)	High (~60%)	Medium (~40%)
Car Dependency	High, car-oriented culture	Low, highly transit-oriented	Low, strict car ownership policies	Low, cycling- and transit-oriented
Walkability and Cycling Infrastructure	Limited pedestrian and cycling infrastructure	Moderate, pedestrian-friendly streets	Moderate, well-designed pedestrian and cycling infrastructure	Extensive, strong cycling infrastructure
Land Use Planning	Fragmented, car-dependent urban planning	Integrated land use and transport planning	Government-driven transit-integrated planning	Transit-centered, Finger Plan development strategy
Private Sector Involvement in TOD	Limited, mostly government-driven development	Strong, rail companies invest in TOD	Moderate, state partnerships for urban planning	Moderate, private–public collaboration
Public Transport Network Integration	Developing Metro and BRT, limited integration	Comprehensive rail, subway, and bus network	Highly integrated MRT and bus networks	S-train, metro, and bus systems well integrated
Government Policies Supporting TOD	Zoning reforms and TOD-focused planning emerging	Longstanding transit-oriented land policies	Strong regulatory support for TOD	Sustainable mobility and urban design policies
Green Space Integration in TOD	Emerging focus (e.g., Green Riyadh initiative), currently limited in transit corridors	Incorporated into station design and urban streetscapes	Incorporated into station design and urban streetscapes	Core element of planning, green wedges and urban parks linked to transit

Congestion and air pollution are pressing concerns in Riyadh. According to the World Air Quality Index, Riyadh consistently records PM_{2.5} levels exceeding WHO guidelines, largely due to vehicular emissions. Additionally, average commute times in the city surpass 45 min, reflecting high congestion levels on arterial roads. These factors underline the urgency of implementing TOD to reduce vehicle kilometers traveled and improve urban air quality. The severity of congestion and pollution in Riyadh underscores the urgency of implementing TOD as a sustainable alternative to current urban growth patterns. According to global air quality monitoring platforms, Riyadh frequently ranks among the most polluted cities in the Middle East, with average PM_{2.5} concentrations often exceeding 50 µg/m³—well above WHO-recommended thresholds. Vehicular emissions are a primary contributor, with transport accounting for over 40% of the city’s total greenhouse gas output. In parallel, traffic congestion has become a daily burden for residents, with average commute times exceeding 50 min in peak hours, particularly on major routes such as King Fahd Road and the Northern Ring Road. Traffic delays and prolonged commute times in Riyadh have tangible economic impacts, including productivity losses, elevated fuel

expenditures, and increased healthcare costs associated with pollution-induced illnesses. Congestion levels remain high, with commuters experiencing significant travel delays during peak periods. These inefficiencies highlight the urgency of adopting transit-oriented development strategies aimed at reducing vehicle dependency, improving public health outcomes, and enhancing urban air quality. Such measures align with the sustainability and mobility goals outlined in Saudi Arabia's Vision 2030 agenda.

In addition to reducing congestion and pollution, the integration of greenery within TOD zones plays a critical role in enhancing the livability and attractiveness of public transit environments. The presence of green spaces near transit lines contributes to multiple TOD objectives, including improved pedestrian comfort, reduced urban heat island effects, and increased physical and mental well-being for users. Global TOD cities like Singapore and Copenhagen have long recognized the role of green infrastructure in encouraging active mobility and transit use by creating more appealing and human-scaled urban environments. In the context of Riyadh—where high temperatures and limited shading discourage walking—assessing the presence of greenery along transit corridors is particularly relevant. Green space coverage is increasingly recognized as essential to TOD success—especially in arid urban contexts. The inclusion of greenery in this study is not arbitrary but grounded in its role as a climate adaptation strategy that intersects with TOD goals. In Riyadh, where temperatures can exceed 45 °C in summer, the lack of shaded or vegetated pathways can significantly reduce pedestrian traffic and discourage public transit usage. Studies in environmental psychology and urban design consistently emphasize that people are more likely to walk and wait for transit in shaded, thermally comfortable environments. Moreover, the Green Riyadh initiative explicitly links urban greening with mobility and livability objectives. Therefore, including vegetation coverage in the spatial analysis enhances overall comprehension of the urban conditions that facilitate or inhibit TOD implementation and underscores the need for integrated planning that includes both infrastructure and environmental resilience.

Learning from global best practices and adapting them to the local context will be essential in ensuring that Riyadh's urban transformation is aligned with future mobility needs.

3. Methodology

A comprehensive approach is essential to assess the potential for transit-oriented development (TOD) in Riyadh. This study integrates multiple analytical components to ensure a structured evaluation, as can be seen in Figure 2. Data collection forms the core, providing insights into urban structure, transport accessibility, and land use patterns. Spatial analysis examines density distribution, pedestrian infrastructure, and transit connectivity. Policy review assesses regulatory frameworks shaping urban development and transit planning. The analytical framework synthesizes these findings, guiding scenario modeling to evaluate TOD implementation strategies. This interconnected methodology promotes a thorough grasp of Riyadh's TOD potential. The methodological design of this study integrates spatial data analysis, AI-based clustering, and qualitative policy review to create a robust evaluation of TOD potential in Riyadh. Spatial datasets were sourced from official repositories and processed using GIS software version 10.8.2 to assess land use, transit network coverage, and pedestrian accessibility. Clustering algorithms such as DBSCAN and K-Means were applied to determine potential TOD zones based on proximity, transit density, and infrastructural characteristics. Additionally, content analysis of policy documents, including Vision 2030 and municipal zoning laws, was conducted to evaluate institutional readiness. This mixed-methods approach ensures methodological rigor and supports the multi-scalar nature of TOD assessment.

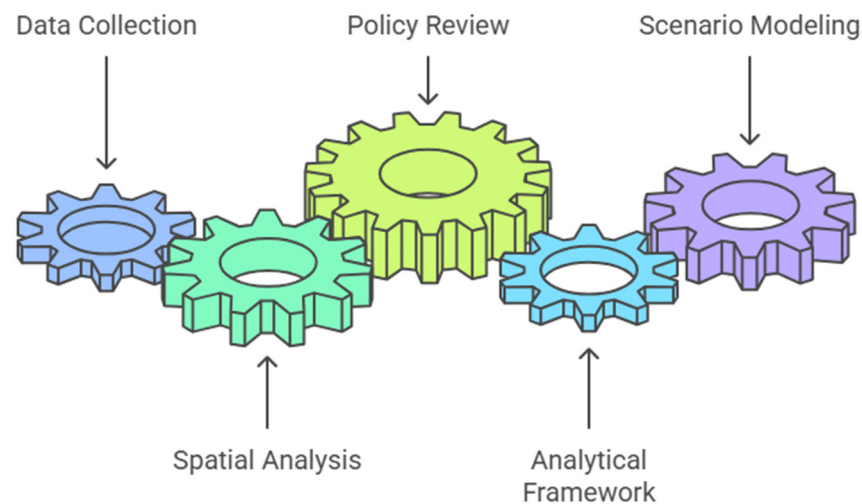


Figure 2. Methodological framework for assessing transit-oriented development (TOD) (source: authors, adapted from standard TOD planning models).

3.1. Data Collection

A multi-faceted approach was employed to collect and analyze data, ensuring a comprehensive evaluation of TOD potential in Riyadh. Given the complexity of urban development and transportation planning, a combination of geospatial data analysis, policy review, and qualitative stakeholder insights is used to assess existing conditions and future prospects. Data were obtained from historical and current sources, primarily from the NEXTGIS website [55], and processed using GeoPackage version 1.3.0, JSON RFC 8259, and Python version 3.10.6 for spatial analysis and mapping.

GIS-based analysis [56] is essential in evaluating land use patterns, transport networks, and urban expansion. This study incorporates data on the Riyadh Metro and BRT network, transit station locations, road infrastructure, population density, and zoning regulations. Through GIS-based mapping, TOD potential zones are identified by overlaying multiple datasets, such as urban expansion trends, proximity to public transport hubs, and land use intensity. This integration of GIS with spatial analytics enables policymakers to recognize areas where TOD principles can be effectively applied, ensuring data-driven decision making [57].

3.2. Spatial Analysis

Spatial analysis is critical in assessing Riyadh's urban morphology, transit accessibility, and pedestrian infrastructure to establish a baseline for TOD evaluation. GIS-based mapping techniques were applied to analyze the spatial relationships between transit corridors and surrounding land uses, identifying areas with high potential for TOD interventions. This analysis involved examining Riyadh's urban density gradient, identifying high-potential zones for compact development, and assessing transit accessibility gaps. Understanding these spatial elements is crucial in determining the feasibility of TOD interventions and optimizing urban growth strategies.

An in-depth evaluation of pedestrian infrastructure was conducted to assess walkability and non-motorized transport integration. This analysis included an assessment of sidewalk availability, cycling infrastructure, and the distribution of pedestrian crossings across different urban zones. Walkability is a fundamental component of TOD, and this study aimed to determine the extent to which Riyadh's built environment supports pedestrian movement and transit accessibility. The spatial analysis also identified barriers that may hinder seamless connectivity between residential areas, commercial districts,

and transit hubs, providing valuable insights into where urban design improvements are needed.

Furthermore, a comparative assessment of Riyadh's transit network and urban expansion trends was carried out to determine whether public transport investments align with population growth patterns. This involved overlaying historical urban expansion data with planned metro and BRT corridors to assess whether transit infrastructure is effectively serving high-density areas. Additionally, lessons from global TOD case studies, including those in Tokyo, Singapore, and Copenhagen, were incorporated into the analysis to benchmark Riyadh's spatial characteristics against successful transit-oriented urban models.

3.3. Policy Review

Understanding the regulatory landscape is essential for evaluating the feasibility of TOD implementation. This study includes a comprehensive review of national and municipal policies that influence urban development and public transportation in Riyadh. Key documents analyzed include Saudi Vision 2030, the Riyadh Metro Master Plan, and municipal zoning codes that govern land use and transit planning. The policy review assesses how these regulations facilitate or hinder the integration of TOD principles into Riyadh's urban framework.

The analysis focuses on zoning and land use regulations, evaluating whether existing zoning laws permit high-density, mixed-use developments around transit hubs. TOD relies on a regulatory framework that encourages compact urban growth, reduces car dependency, and integrates residential, commercial, and recreational spaces. Examining current zoning laws provides insight into potential policy adjustments that could enhance TOD adoption. Additionally, the review considers public transport policies, assessing the government's strategies for transit investment, fare integration, and incentives for non-motorized transport.

Beyond zoning and transport policies, this study examines governance and institutional barriers to TOD implementation. This includes analyzing land ownership constraints, the role of private sector investment, and community perceptions of TOD. The findings highlight the need for regulatory reforms that support mixed-use developments, promote walkability, and ensure that public transport infrastructure is complemented by land use planning strategies. Addressing these policy gaps is essential for Riyadh to achieve a seamless transition toward a more transit-oriented urban structure.

3.4. Analytical Framework

An analytical framework was developed to integrate the findings from spatial analysis and policy review into a systematic evaluation of TOD readiness in Riyadh. This framework combines geospatial analysis, urban growth trends, and transportation planning principles to assess the suitability of different urban areas for TOD interventions. A structured multi-step approach ensures that transit accessibility, land use compatibility, and governance feasibility are considered in the TOD evaluation process.

The framework includes an assessment of transit accessibility, measuring how well public transport nodes serve high-density urban areas. Land use suitability analysis determines locations where mixed-use developments can be effectively integrated into transit corridors. Additionally, governance and policy feasibility are examined to identify institutional constraints and opportunities for TOD implementation. Synthesizing these analytical components provides a data-driven, policy-informed approach to assessing TOD potential in Riyadh.

3.5. Scenario Modeling

Scenario modeling was used to explore various urban planning interventions and policy reforms that could enhance TOD adoption in Riyadh. Different development scenarios were tested to evaluate the impact of high-density urbanization, mixed-use integration, and transit accessibility enhancements on public transport ridership and urban sustainability. The objective of this GIS-based mapping modeling was to determine the most effective planning strategies for optimizing TOD potential.

The scenarios included high-density TOD expansion, simulating the effects of increased population concentration around metro and BRT corridors. Mixed-use integration was assessed to determine how rezoning land around transit stations could create vibrant, transit-friendly districts. Additionally, first-mile and last-mile enhancements were modeled to examine how improved pedestrian and cycling infrastructure could increase public transport use. This study also explored the impact of car demand management policies, such as reduced parking availability and congestion pricing, on shifting mobility patterns toward public transit.

4. Results

4.1. Transit-Oriented Development and Mobility Transformation in Riyadh

Riyadh has undergone rapid urban expansion, significantly altering its spatial structure and transportation demands. Figure 3 illustrates the city's growth from 1940 to 2016, showing the shift from a compact urban form to a sprawling, car-dependent metropolis. This pattern has resulted in increased congestion, inefficient land use, and a lack of sustainable transport options. The introduction of the TOD strategy is intended to address these challenges by integrating high-capacity public transport with mixed-use, pedestrian-friendly urban centers.

As of November 2024, the Riyadh Metro was officially inaugurated, marking a milestone in the city's transport infrastructure. However, most lines remain in early operational stages, with phased rollouts expected through 2025. Ridership data are limited but early reports suggest lower-than-expected daily usage due to incomplete last-mile connections and limited public familiarity. The BRT network is under development, with select corridors piloting operations but not yet citywide. As of November 2024, the Riyadh Metro was officially inaugurated, marking a critical milestone in the city's long-term transit modernization plans. However, the metro system remains in phased deployment. Only a few lines have entered partial operation, with sometimes limited service hours and restricted access in place for system calibration and gradual user adaptation. Initial reports from the Royal Commission for Riyadh City (RCRC) suggest that ridership uptake is still below projected capacity, in part due to incomplete feeder services and low public awareness. Likewise, the BRT system, while structurally outlined and partially implemented along corridors such as King Abdulaziz Road, remains in early rollout phases, with full functionality expected over the next two years. Comprehensive usage statistics are not yet publicly available, but pilot data indicate modest adoption, hindered by limited last-mile integration. These developments suggest that while significant progress has been made in transit infrastructure, complementary policies and services are necessary to fully leverage these investments.

The Riyadh Metro, a six-line network covering 176 km with 85 stations, is designed to serve as the core of this strategy. With an expected daily capacity of 3.6 million passengers, the metro system aims to reduce reliance on private vehicles while enhancing connectivity between key urban areas. The network spans the city with lines serving major residential, commercial, and administrative districts, including connections to King Khalid International Airport and emerging financial hubs. Figure 4 outlines a proposed TOD

framework, highlighting the integration of metro corridors with strategic urban nodes to support high-density, mixed-use developments.

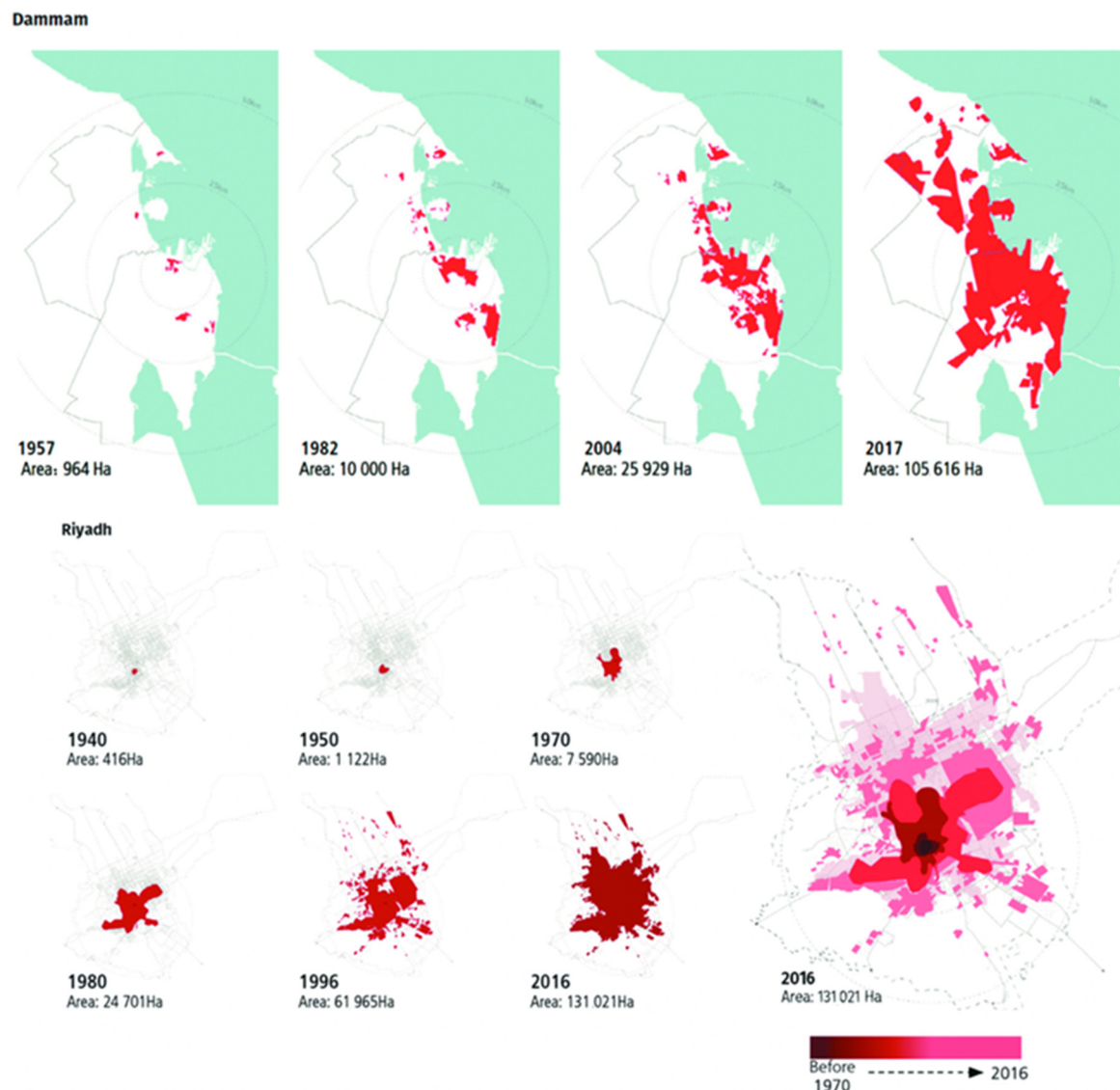


Figure 3. Urban expansion of Riyadh from 1940 to 2016, demonstrating the city’s rapid growth and increasing land consumption [58].

In parallel with the metro, the city is developing a Bus Rapid Transit (BRT) system to expand transit accessibility. The BRT network includes dedicated corridors, feeder buses, and intelligent transport systems to improve efficiency and coverage. Key corridors such as King Abdulaziz Road and Khalid Ibn Alwaleed Route extend transit services to suburban areas, ensuring a broader reach beyond the metro stations. Micro-mobility solutions, including e-scooters and shared bicycles, are being introduced to improve first-mile and last-mile connectivity, further supporting a shift toward sustainable urban mobility.

Despite these investments, pedestrian and cycling infrastructure remains underdeveloped. Riyadh’s urban design has historically prioritized automobiles, resulting in discontinuous pedestrian pathways, unsafe crossings, and limited cycling facilities. The Green Riyadh initiative aims to address these gaps by integrating shaded walkways [59,60], improved pedestrian crossings, and cycling infrastructure, particularly around TOD zones [61]. However, the effectiveness of these interventions will depend on governance, enforcement, and public acceptance.

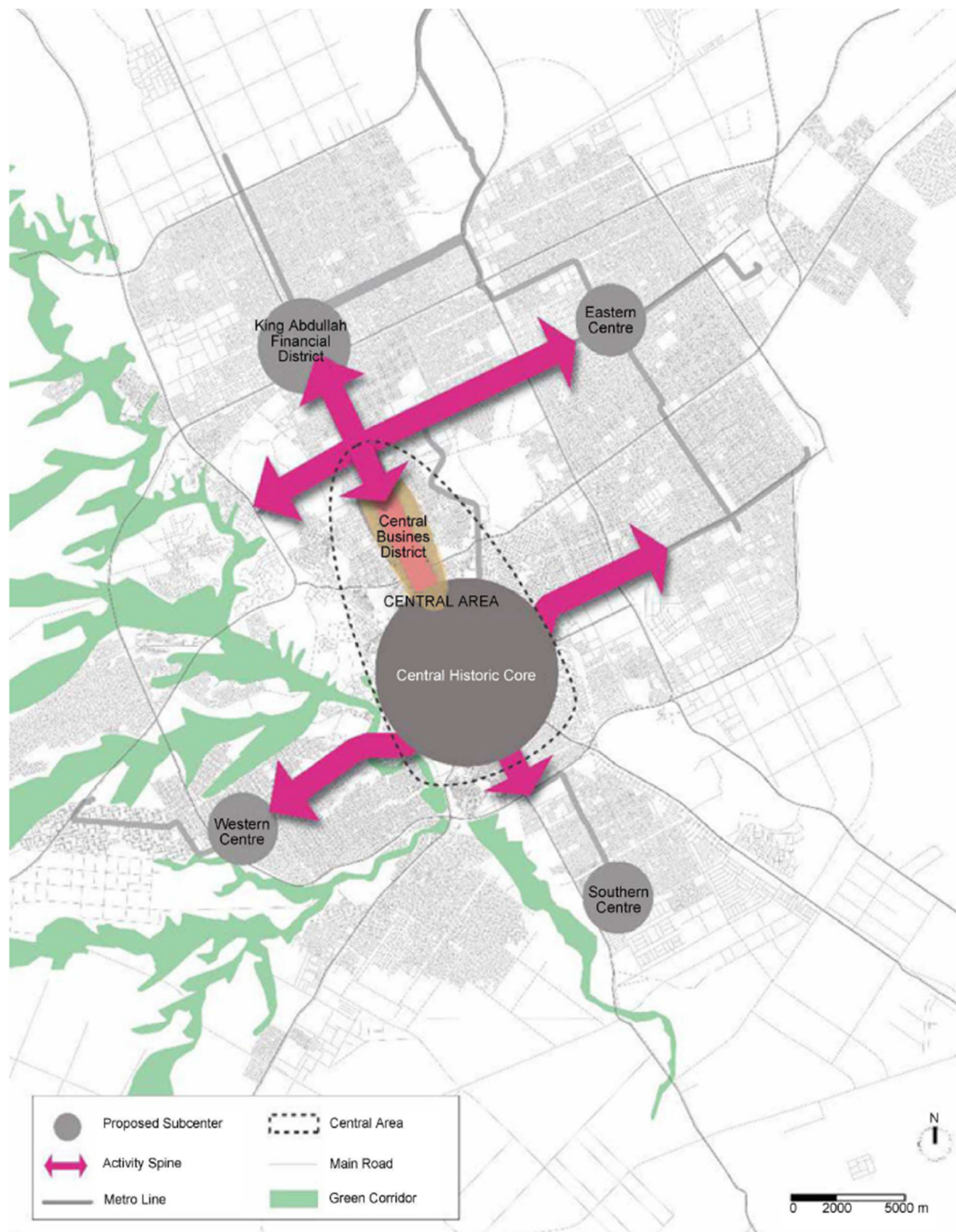


Figure 4. Proposed transit-oriented development strategy for Riyadh, highlighting key metro lines, green corridors, and gray major development hubs in Riyadh (credit: [60]).

Strategic locations for TOD implementation have been identified around key metro stations, including King Abdullah Financial District (KAFD), Qasr Al-Hukm Station, Western Station, and Olaya Station (Figure 5).

These locations present opportunities for high-density development, commercial expansion, and improved urban vibrancy. Figure 6 provides a spatial overview of Riyadh, illustrating its urban form and transportation network, which provides a basis for TOD planning.



Figure 5. Map of Riyadh (credit: authors, https://www.mapz.com/map?zoom=16&lon=46.71601032592279&lat=24.638915976298634&layers=mapz_multicolor_base#next=/export/create?view=download&with_layers=true, accessed on 5 May 2025).

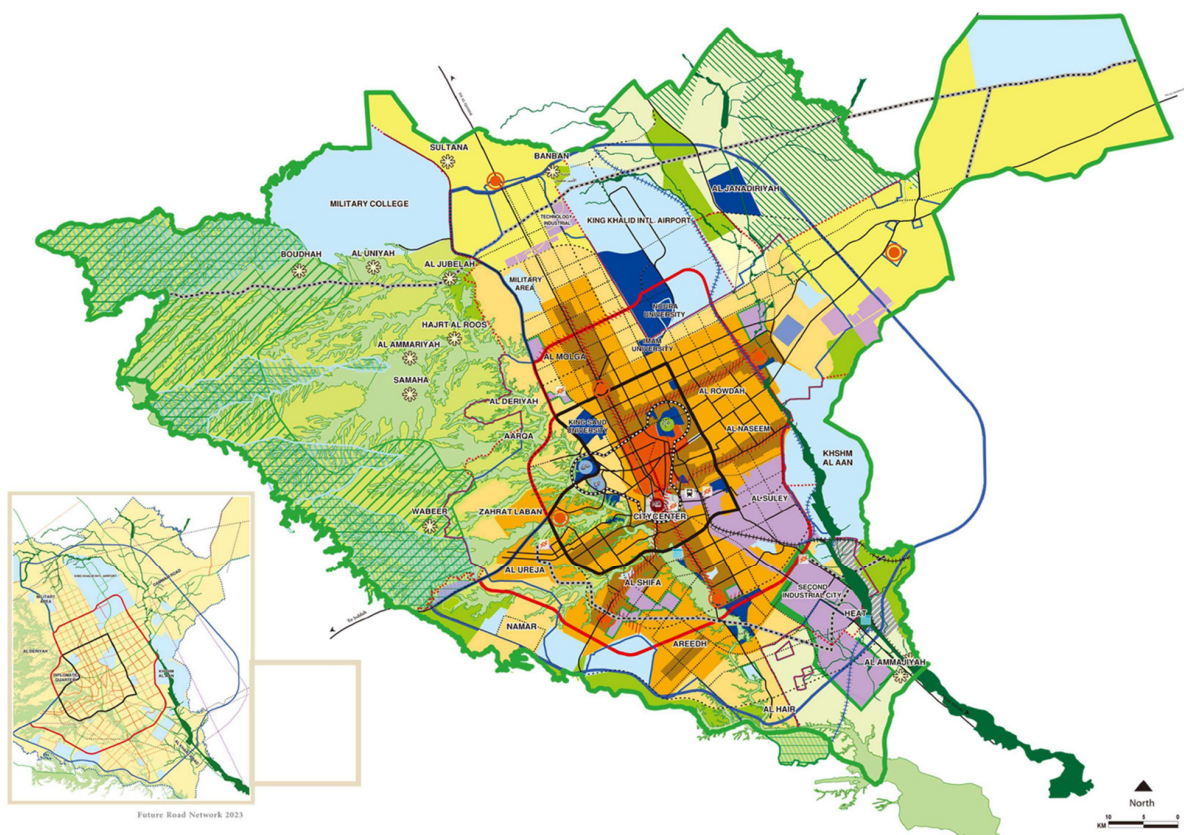


Figure 6. Riyadh-MEDSTAR illustrating the city's urban structure and road network and structure plan 2030. This map represents the MEDSTAR Project (Metropolitan Development Strategy for Arriyadh),

launched by the Arriyadh Development Authority (ADA) in 1996 to manage the city's rapid growth. With Riyadh's population projected to reach 10 million by 2020, the plan covers 4900 km² and proposes a fifty-year vision for structured urban development. The MEDSTAR plan introduces a multi-center city model, balancing growth with accessibility and sustainability. Legend highlights: Red circles—Five new metropolitan sub-centers to serve expanding residential zones. Brown—Activity spines linking sub-centers with the historic core. Gray area—Historic city with key civic and financial institutions. Red area—Central area, including the Royal Court and future central park. Orange zones—New suburban cities, each planned for 1 million residents. Red lines—Public transport corridors, forming the backbone of the urban structure (credits: [58]).

The transition to a transit-oriented urban model presents several challenges, including governance coordination, financial feasibility, and behavioral adaptation among residents. While the metro and BRT systems form the core, complementary measures such as improved pedestrian infrastructure, regulatory incentives for mixed-use developments, and public engagement strategies are necessary to ensure long-term success. The ongoing transformation of Riyadh's mobility landscape marks a critical step toward achieving the sustainability goals outlined in Vision 2030, yet its success will depend on the integration of transport investments with broader urban development policies.

4.2. Spatial Analysis of Transit-Oriented Development and Pedestrian Accessibility in Riyadh

The distribution of highway crossings is a key determinant of pedestrian accessibility, particularly in transit-oriented development (TOD) zones. A density analysis reveals that crossings are highly concentrated in the central parts of the city, particularly in areas with a high volume of commercial and administrative activities. This pattern suggests that pedestrian infrastructure has primarily developed in response to urban demand, yet peripheral areas remain underserved. Figure 7 illustrates these variations, where red zones indicate areas of high crossing density, while lighter shades signify lower pedestrian infrastructure availability. The analysis indicates a moderate alignment between areas of high crossing density, as seen in the overlap between lower pedestrian infrastructure availability. However, a closer spatial overlay reveals several densely populated residential districts—particularly in the southern and eastern parts of the city—that lie beyond the effective availability of pedestrian infrastructure availability. Thus, while there is a visual correlation, it is possible to observe a “spatial imbalance” that specifically highlights these underserved areas where pedestrian movement and access is most needed but currently lacking. The concept of spatial imbalance, in this context, refers to a misalignment between the presence of infrastructure and the spatial distribution of potential user activity. In Figure 7, the heatmap in the left panel represents areas with concentrated spatial movement or demand. These zones signify a latent need for safe and accessible crossings. The blue points represent the current infrastructure, which reflects how this need has been addressed. The imbalance arises where this need remains unfulfilled. In the zoomed-in panel, we show an area where the density of expected movement is high, yet the number of crossings is relatively low. This disconnect suggests that the infrastructure does not correspond to the emerging spatial behavior of users.

Such a mismatch is more than a technical issue. It points to a deeper challenge in spatial planning, the need to understand infrastructure as a response to human presence and movement. When demand and provision drift apart, the urban form becomes fragmented, and user experience is compromised. Resolving this imbalance calls for both targeted infrastructure investments and regulatory reforms to enable urban demand specifically in unserved areas.

This spatial imbalance poses a challenge for transit-oriented planning, as efficient public transport relies on seamless pedestrian integration.

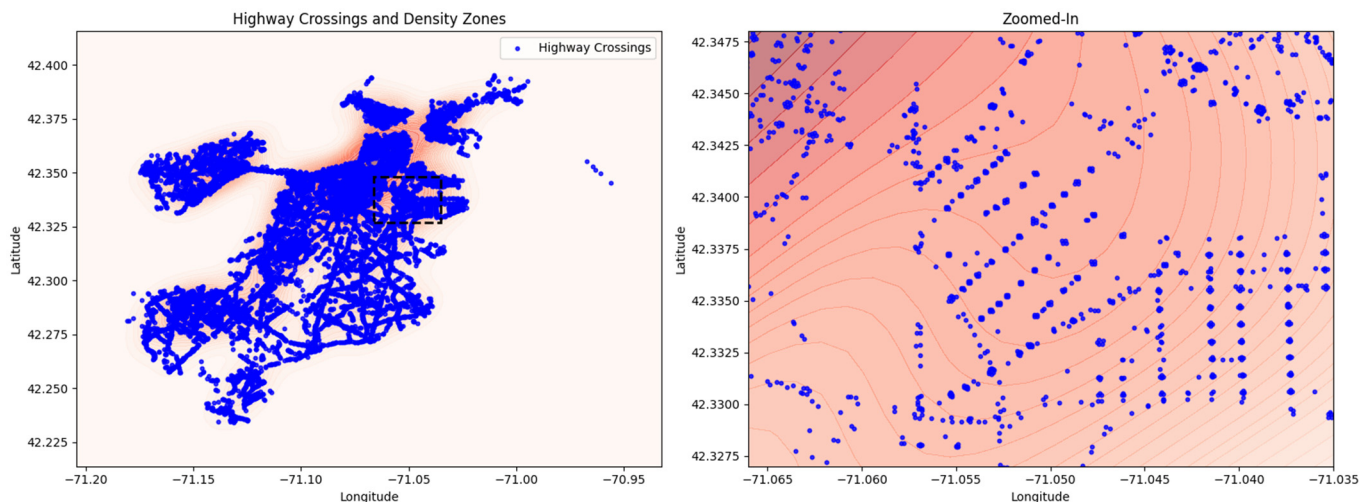


Figure 7. Density of highway crossings in Riyadh, highlighting areas with high pedestrian movement concentration. The blue zones indicate pedestrian concentration, red zones indicate high crossing density, and lighter shades signify lower pedestrian infrastructure availability. The left heatmap highlights zones of concentrated spatial movement (orange-red), indicating unmet demand for safe crossings. Blue points mark existing infrastructure. The zoomed-in figure on the right shows a mismatch between high movement density and low crossing provision, revealing a gap in infrastructure planning that affects connectivity and user experience.

To further assess pedestrian risk zones, a clustering analysis using the DBSCAN algorithm [62] was conducted to identify areas where highway crossings are highly concentrated and locations where crossings appear isolated. The clustering approach segments the dataset into groups based on spatial proximity, revealing distinct clusters of high pedestrian activity. Figure 8 presents these results, where different colors represent separate clusters of crossings, each corresponding to a specific urban zone. The blue cluster encompasses the majority of crossings, indicating a well-connected pedestrian network. The green and purple clusters represent smaller, distinct zones with moderate connectivity, possibly serving localized pedestrian flows within specific districts. In contrast, red points represent outliers, signifying isolated crossings that do not belong to any cluster. These outliers highlight potential pedestrian accessibility challenges, as they are disconnected from the main network. The existence of such isolated crossings suggests areas where pedestrian safety may be compromised due to limited connectivity, requiring targeted interventions such as additional crossings, improved pedestrian pathways, or redesigned urban infrastructure to enhance accessibility and minimize risk.

To test the robustness of the DBSCAN clustering results, a sensitivity analysis was conducted by varying the `eps` and `min_samples` parameters across a range of values. The results indicate that while the core clusters remained stable, the number of outliers fluctuated, particularly in peripheral districts. This variability reinforces the importance of contextual calibration in urban spatial analytics and validates the spatial consistency of high-risk pedestrian zones identified throughout this study. By understanding how different parameter settings affect clustering outcomes, urban planners can make more informed decisions regarding the prioritization of interventions in high-risk areas. Moreover, this sensitivity analysis can serve as a model for future studies wishing to employ similar clustering techniques, ensuring that their findings are robust and applicable across various contexts. This methodological transparency not only enhances the credibility of the research but also provides a framework for other cities facing similar challenges.

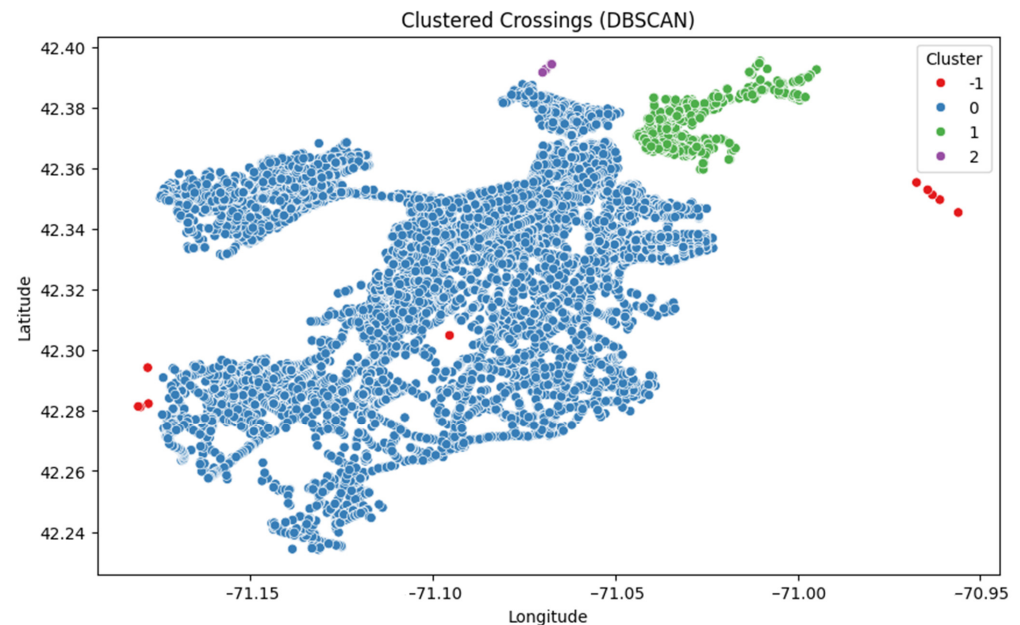


Figure 8. Clustering analysis of highway crossings using DBSCAN, identifying distinct pedestrian activity zones. Clustered areas indicate well-connected pedestrian crossings, while red-marked outliers highlight isolated crossings that may present accessibility challenges.

An expanded analysis of the pedestrian network structure complements the clustering results. Figure 9 presents the connectivity of highway crossings across Riyadh, integrating elevation as a critical spatial variable. The network visualization reveals that central districts benefit from a dense and cohesive structure of crossings, while peripheral areas display both fragmented pedestrian access and elevated terrain. This spatial arrangement suggests that physical barriers such as elevation further compound infrastructural fragmentation, creating dual impediments to pedestrian movement. Such compounded barriers severely limit the viability of transit-oriented development strategies, as pedestrians in fragmented and elevated zones face diminished accessibility to public transport nodes.

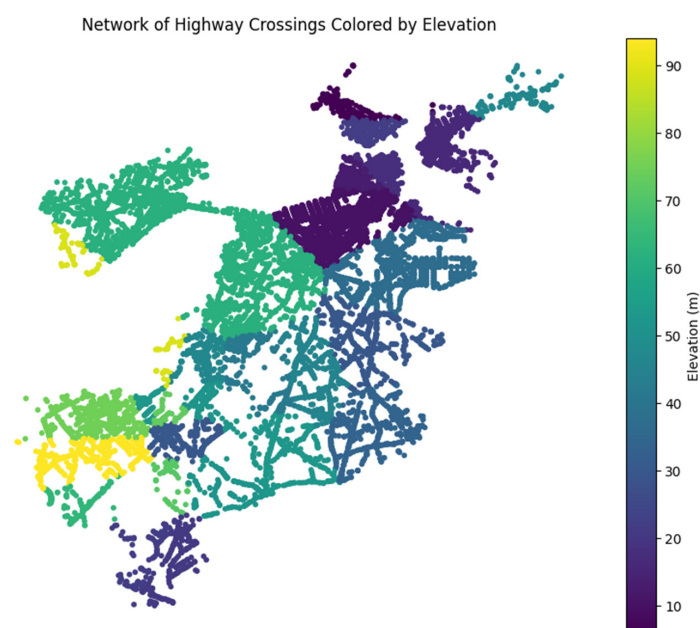


Figure 9. Network representation of highway crossings colored by elevation. The figure illustrates the hierarchical structure of crossings, the fragmentation of peripheral pedestrian networks, and the additional accessibility challenges introduced through elevation gradients.

Although isolated pockets of connectivity exist, their impact is undermined where pedestrian infrastructure remains inadequate. Addressing connectivity gaps must therefore be coupled with sensitivity to topographical constraints to ensure that urban mobility interventions are both spatially and physically equitable. Figure 9 emphasizes the necessity of a dual-focus approach that targets both infrastructural enhancement and terrain-responsive planning. This integrated perspective provides a robust foundation for urban policymakers aiming to promote sustainable and inclusive transit-oriented growth.

Building upon the clustering analysis, a detailed examination of transit node density provides further insights into the spatial structure of public transport accessibility. The density mapping approach reveals critical variations in network intensity between central and peripheral districts, emphasizing key areas requiring targeted interventions.

Transit accessibility in Riyadh is further analyzed through the density distribution of public transport points, including metro stations and BRT stops. The enhanced density map in Figure 10 demonstrates that public transport nodes are highly concentrated in the central regions, while peripheral neighborhoods exhibit significantly lower densities. The addition of a magnitude scale clarifies the intensity of this disparity, offering a more nuanced understanding of accessibility gaps across the urban landscape. This distribution pattern aligns with the broader urban development model of Riyadh, where high-density zones receive priority in infrastructure investments. However, the uneven availability of public transport stations, particularly in outlying districts, suggests a need for expanded feeder networks to ensure that all residents can effectively access high-capacity transit corridors. Limited station density in peripheral areas presents a critical barrier to achieving the modal shift necessary for sustainable urban mobility, reinforcing the urgency of first-mile and last-mile connectivity solutions.

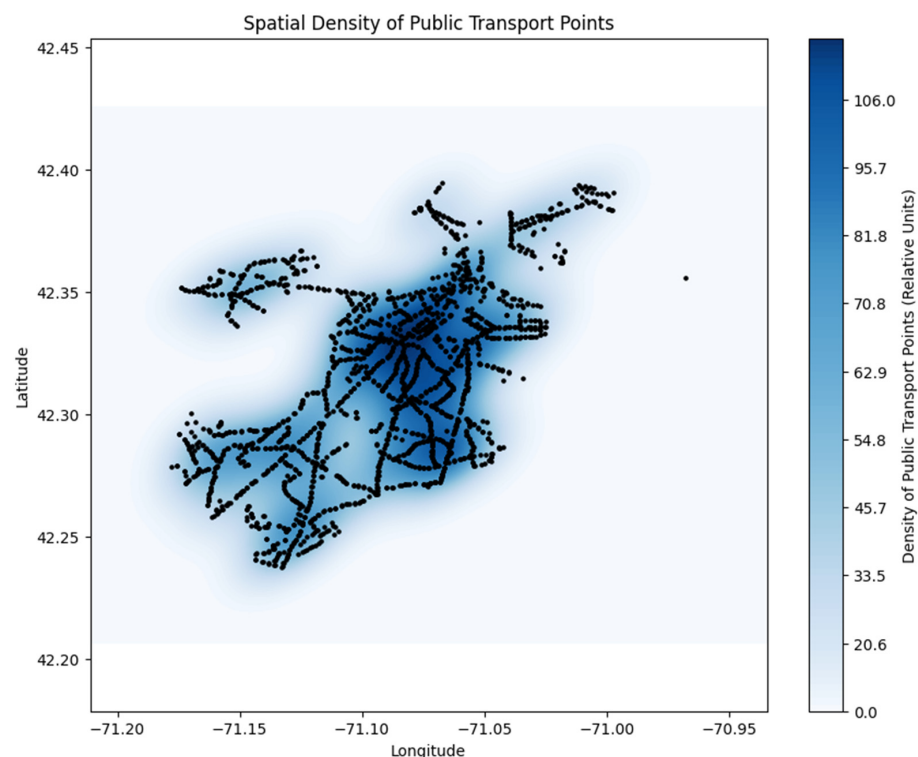


Figure 10. Kernel density estimation (KDE) of public transport points in Riyadh. Black dots represent individual metro stations and BRT stops. The blue color gradient indicates the relative density of transport nodes, with darker shades corresponding to higher concentrations. The legend clarifies the magnitude of density variations between central and peripheral districts, highlighting spatial imbalances in public transport accessibility.

To further evaluate the efficiency of the public transport system, a network analysis was conducted to assess the structural connectivity of metro and BRT stations. In this approach, each transport node is modeled as a graph component, with edges representing potential travel connections between them. The density distribution, now supplemented with a magnitude legend, highlights both the spatial centralization of transit infrastructure and the varying intensity of accessibility across the city. Central areas display dense, interconnected clusters, whereas peripheral districts are characterized by sparse or isolated points, reflecting a much lower magnitude of access. This sharp contrast emphasizes the structural inequities between the urban core and the periphery, where residents face compounded challenges in reaching high-capacity transit options. Figure 10 is intended to illustrate both the distribution and the degree of transit access, strengthening the argument for expanding feeder networks and improving service coverage in underserved zones.

4.3. Land Use and Vegetation Coverage near Transit Corridors

The spatial distribution of land use near metro corridors is mapped in Figure 8, revealing a fragmented pattern of urban development along transit corridors. The analysis shows that built-up areas are concentrated around key transport nodes, yet land use intensity varies significantly across different metro corridors. High-density urban development is visible in certain zones, reflecting areas where TOD principles have been partially adopted. However, large portions of land remain underutilized, with scattered low-density development and vacant parcels. These gaps in urban density can present challenges for achieving compact, pedestrian-friendly environments around transit stations. The findings suggest a need for urban infill strategies that enhance the connectivity between transit infrastructure and surrounding land uses, ensuring that metro corridors serve as catalysts for sustainable development rather than isolated transit corridors.

The presence of vegetation coverage in TOD zones is another crucial factor in enhancing urban livability and environmental quality. Figure 11 illustrates the distribution of green spaces within the study area, showing a relatively limited presence of vegetation near metro corridors. While certain patches of greenery are evident, their spatial distribution remains fragmented, with large sections of transit-oriented zones lacking adequate green infrastructure. The scarcity of vegetation in these areas can have direct implications for pedestrian comfort, particularly in arid climates where shaded pathways and tree-lined streets play a vital role in promoting walkability. The lack of integrated green infrastructure suggests potential misalignment between TOD planning and urban sustainability goals, emphasizing the need for enhanced landscape strategies to improve environmental resilience and pedestrian-friendly urban design.

The results indicate that effective land use planning and green infrastructure integration are essential for maximizing the benefits of transit-oriented development in Riyadh. While certain metro corridors demonstrate high-density urban development, others remain underutilized, potentially limiting their ability to support transit-oriented growth. Similarly, the fragmented distribution of green spaces highlights the need for better coordination between transport planning and urban greening initiatives (Figure 12). The rationale for including greenery as a variable in TOD analysis stems from Riyadh's climatic conditions, where extreme heat, especially in the summer months, significantly affects walkability. Shaded areas, vegetated corridors, and urban green pockets contribute to thermal comfort and pedestrian safety, which are crucial elements in making TOD zones attractive and usable. In cities like Singapore and Copenhagen, green infrastructure is a key element in promoting sustainable mobility. While it may seem initially peripheral, green space availability directly affects user behavior, station area vibrancy, and overall transit corridor quality. In Riyadh's climatic context, where summer temperatures frequently exceed 45 °C,

the presence of shaded green corridors is not merely an esthetic addition but a functional necessity for supporting pedestrian mobility. Vegetated routes enhance thermal comfort, enabling longer walking trips to and from transit stations, especially during peak heat periods. Integrating green infrastructure into TOD evaluation therefore provides a more realistic assessment of pedestrian accessibility and highlights the critical intersection between climate adaptation strategies and transit-oriented planning.

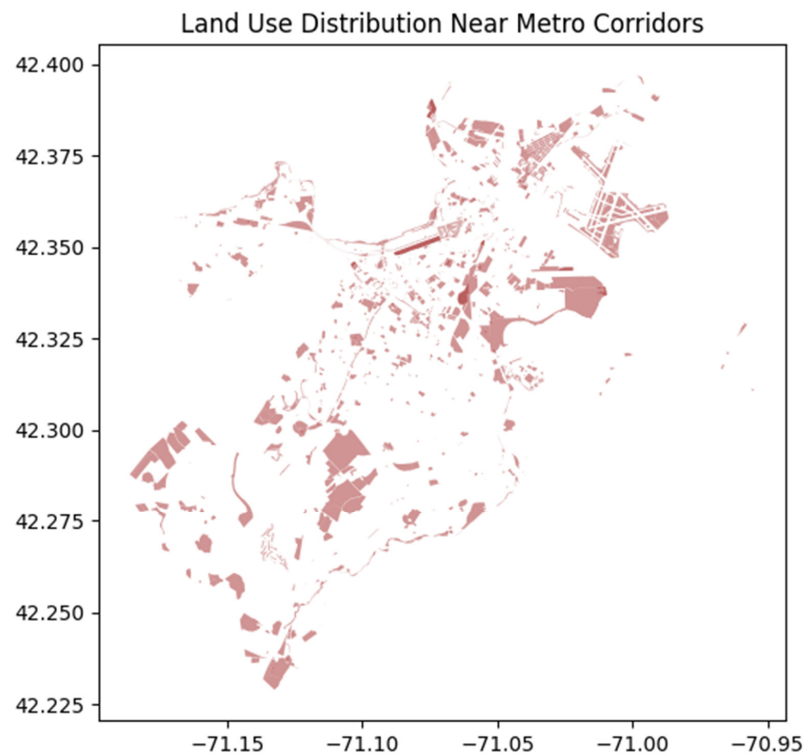


Figure 11. Land use distribution near metro corridors using DBSCAN, illustrating varying densities of urban development.

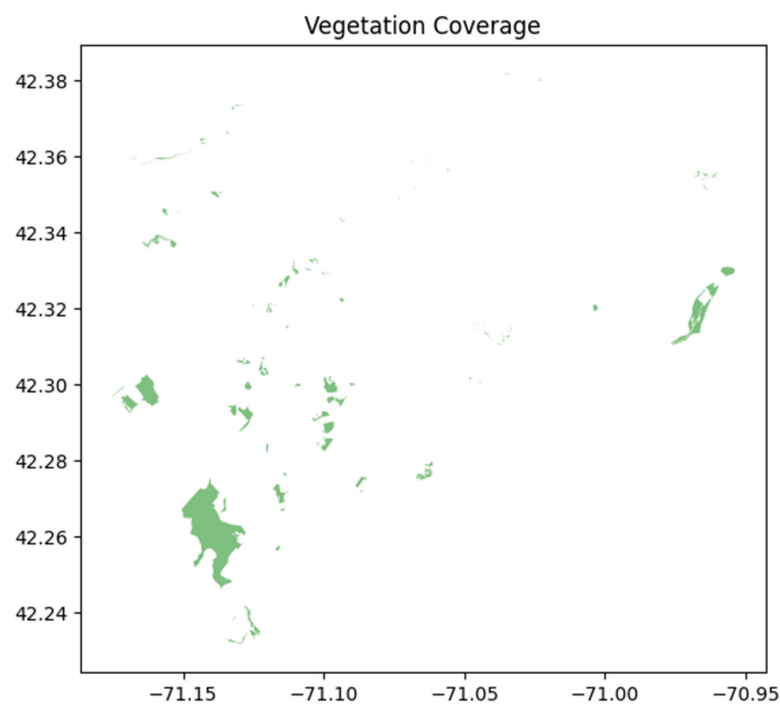


Figure 12. Vegetation coverage in transit-oriented zones using DBSCAN, showing the spatial distribution of green spaces mainly fragmented in the peripheral areas.

Addressing these gaps will require targeted land use policies that encourage mixed-use development, promote higher densities near transit hubs, and incorporate green infrastructure as a fundamental component of TOD planning.

4.4. Transit Accessibility and Urban Connectivity

In Riyadh, assessing transit accessibility requires an examination of pedestrian connectivity, urban density in relation to transport infrastructure, and the spatial distribution of transit services. The findings in this section reveal significant variations in transit accessibility, the interaction between pedestrian crossings and traffic congestion, and potential equity concerns in the distribution of mobility services.

The spatial distribution of high-risk pedestrian areas, as shown in Figure 13, identifies zones where pedestrian movement is heavily concentrated in proximity to major roadways. The density analysis highlights specific locations where pedestrian crossings interact with high-traffic roads, creating potential conflict points. While these areas exhibit high pedestrian activity, the underlying infrastructure may not adequately support safe pedestrian movement, particularly in regions where crossings are unsignalized or lack pedestrian prioritization measures. The results indicate that improvements in pedestrian safety infrastructure, such as the implementation of dedicated pedestrian bridges, signalized crosswalks, and traffic calming measures, are required to mitigate risks in high-exposure areas.

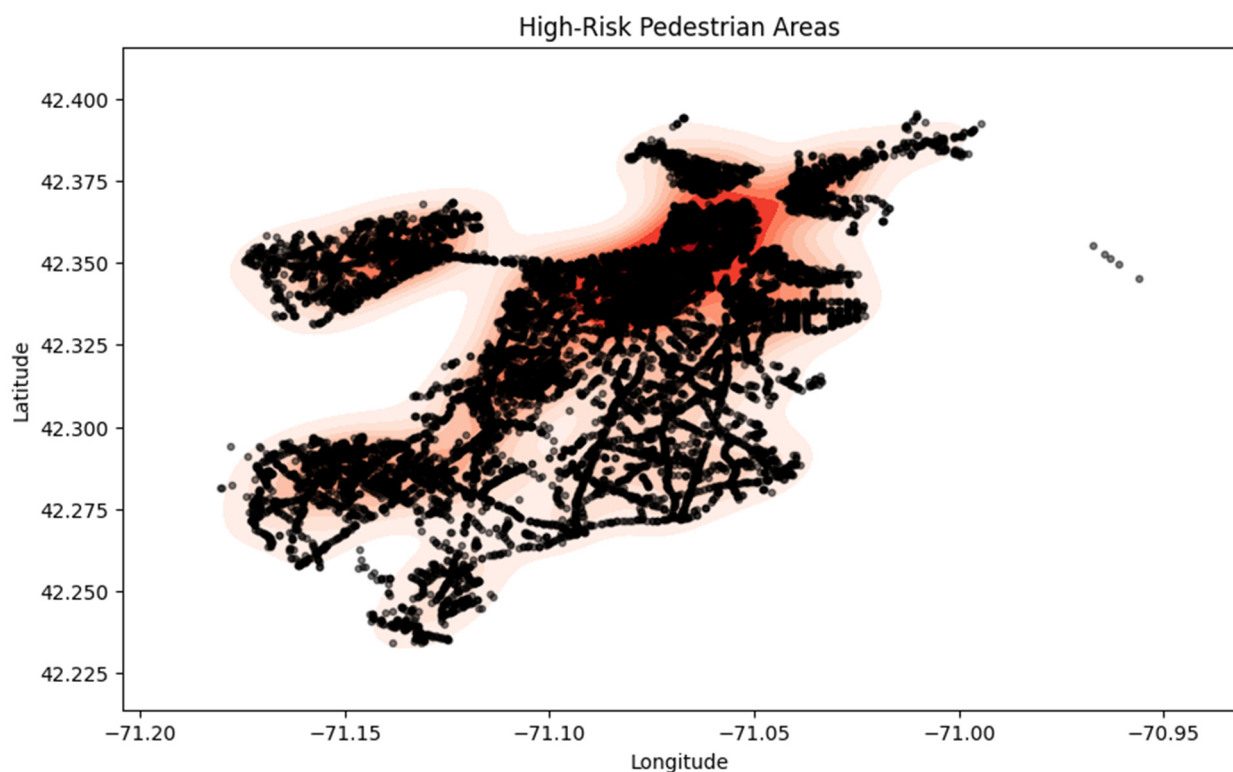


Figure 13. In Red high-risk pedestrian areas identified through density analysis using DBSCAN, highlighting locations with concentrated pedestrian movement and potential safety concerns.

Further spatial analysis of urban density in relation to transit network coverage, presented in Figure 14, reveals the extent to which transit services align with population distribution patterns. The visualization maps transit stations against the spatial distribution of buildings, providing insights into the connectivity between built environments and transport infrastructure. The results indicate that while transit stations are concentrated along key corridors, several high-density urban areas remain underserved by the transit network. This misalignment between transit supply and population distribution suggests

inefficiencies in transport accessibility, with certain urban zones lacking convenient access to public transport.

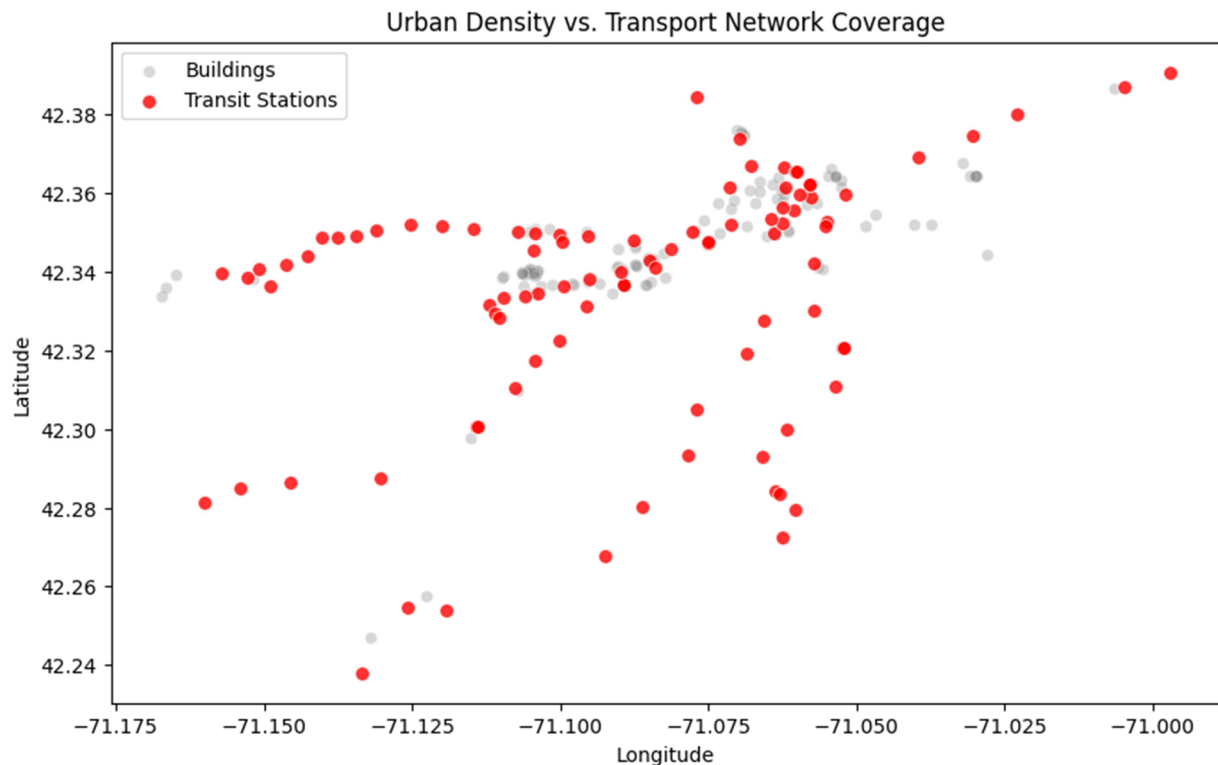


Figure 14. Urban density versus transit network coverage using DBSCAN, illustrating the spatial relationship between built-up areas and transit station locations.

At first glance, Figure 14 suggests a reasonable degree of alignment between transit nodes and high-density urban areas, indicated by overlapping areas of dark shading (built-up density) and red markers (transit stations). However, a more detailed spatial overlay reveals several dense residential districts—particularly in the south and east of the city—that fall outside the effective catchment areas of metro and BRT lines. These underserved areas are not within the typical TOD walking radius of 400 to 800 m from a station, thus failing to benefit from the proximity advantages that characterize successful TOD environments. Moreover, the city’s regulatory constraints prevent vertical densification in key corridors, limiting the expansion of density within walkable distances to transit. Therefore, while visually there is a general correlation, a “spatial imbalance” refers specifically to these critical gaps where the need for transit access is highest, yet the infrastructure does not extend. Addressing this imbalance requires both infrastructural investment and regulatory reform to support transit-accessible densification. A deeper analysis of first-mile and last-mile accessibility gaps is shown in Figure 15, where blue points represent pedestrian crossings overlaid on a density heatmap. The results reveal that while pedestrian pathways are present, there are clear spatial discontinuities that hinder seamless connectivity to transit nodes. Many areas with high pedestrian movement remain beyond convenient walking distances to public transport, limiting ridership potential. These gaps refer to the difficulty commuters face in reaching a transit station from their origin (first mile) or traveling from the transit stop to their final destination (last mile). Poor connectivity in these segments discourages public transit use, as individuals may find the journey to and from transit hubs inconvenient, unsafe, or time-consuming. This fragmentation in accessibility reinforces the need for improved pedestrian infrastructure, such as well-integrated sidewalks, shaded pathways, and urban design elements that encourage walkability within TOD zones. Without addressing these

first-mile and last-mile challenges, transit networks risk being underutilized despite significant investments in public transport infrastructure.

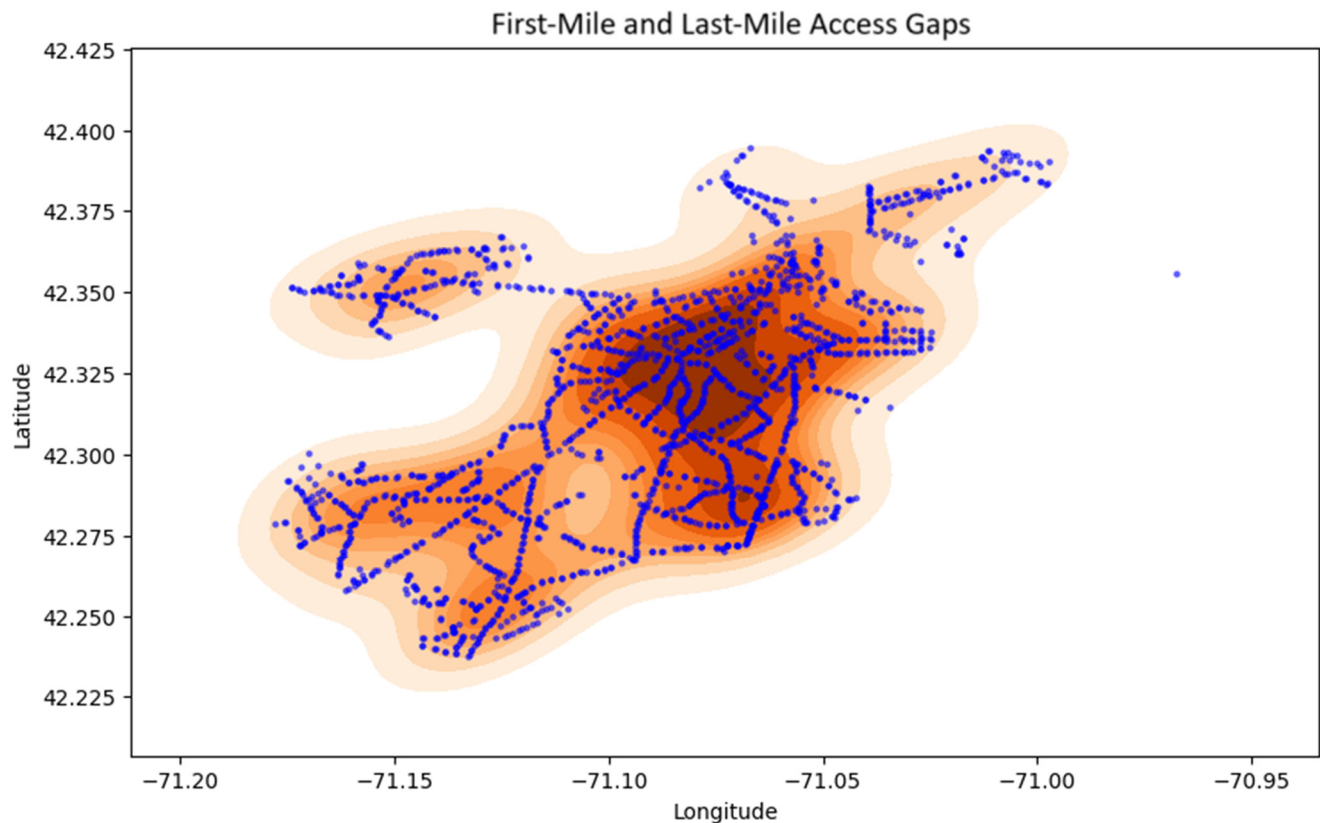


Figure 15. First-mile and last-mile access gaps using DBSCAN, visualizing pedestrian crossings and their connectivity to transit nodes, revealing discontinuities in accessibility. Dark red means more connectivity and light orange means less connectivity.

While Figure 15 highlights visual discontinuities in pedestrian connectivity to transit stations using blue point clusters and heatmaps, it does not quantify the extent of the issue in terms of population impact or ridership potential. To strengthen this analysis, additional data were extracted from GIS overlays that estimate population densities in TOD catchment zones. The results indicate that approximately 35–40% of Riyadh’s population lives outside the 800 m walking threshold to a transit station, which is widely accepted as the maximum convenient walking distance in TOD models. These gaps disproportionately affect peripheral districts and low-income areas where car ownership is lower, thereby exacerbating mobility inequities. Furthermore, surveys conducted by the Riyadh Development Authority report that the lack of safe and continuous sidewalks is among the top deterrents to public transport use. This evidences that first-mile and last-mile challenges are not only spatial but experiential, directly affecting transit adoption rates. Addressing these issues through strategic pedestrian corridor upgrades, shuttle loops, and micro-mobility solutions could substantially improve the effectiveness of the Riyadh Metro and BRT systems.

The interaction between pedestrian accessibility and road congestion is further explored in Figure 16, where red points represent pedestrian crossings. The dense clustering of crossings in certain urban areas suggests a high level of pedestrian dependence on road infrastructure. However, these clusters coincide with major vehicular traffic routes, creating potential bottlenecks and increasing pedestrian risk. Without dedicated non-motorized infrastructure, pedestrian movement may be restricted, particularly in high-traffic corridors, leading to longer travel times and reduced transit efficiency.

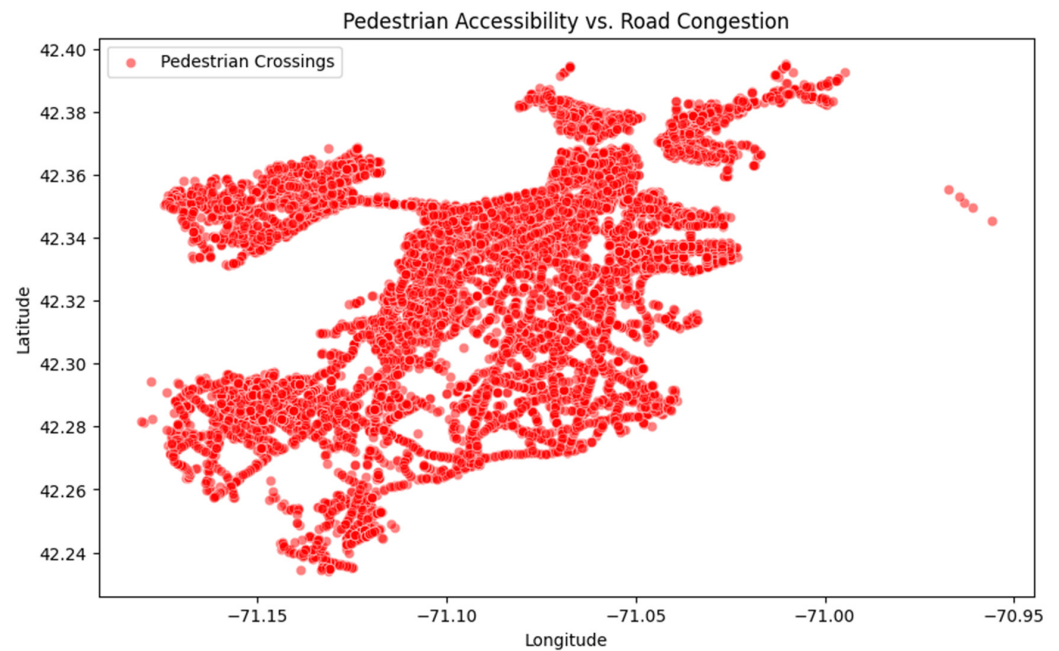


Figure 16. Pedestrian accessibility versus road congestion using DBSCAN, showing the clustering of pedestrian crossings along high-traffic corridors and potential mobility conflicts.

To assess overall TOD accessibility, a heatmap analysis of transit stations in relation to urban density is provided in Figure 17. The results indicate that while certain zones exhibit strong TOD characteristics, with high-density development surrounding transit hubs, other areas show weaker integration. The accessibility heatmap highlights spatial imbalances, where transit stations remain underutilized due to gaps in pedestrian infrastructure or limited station connectivity. Addressing these issues through better land use planning, transit station clustering, and multimodal integration could significantly enhance TOD effectiveness.

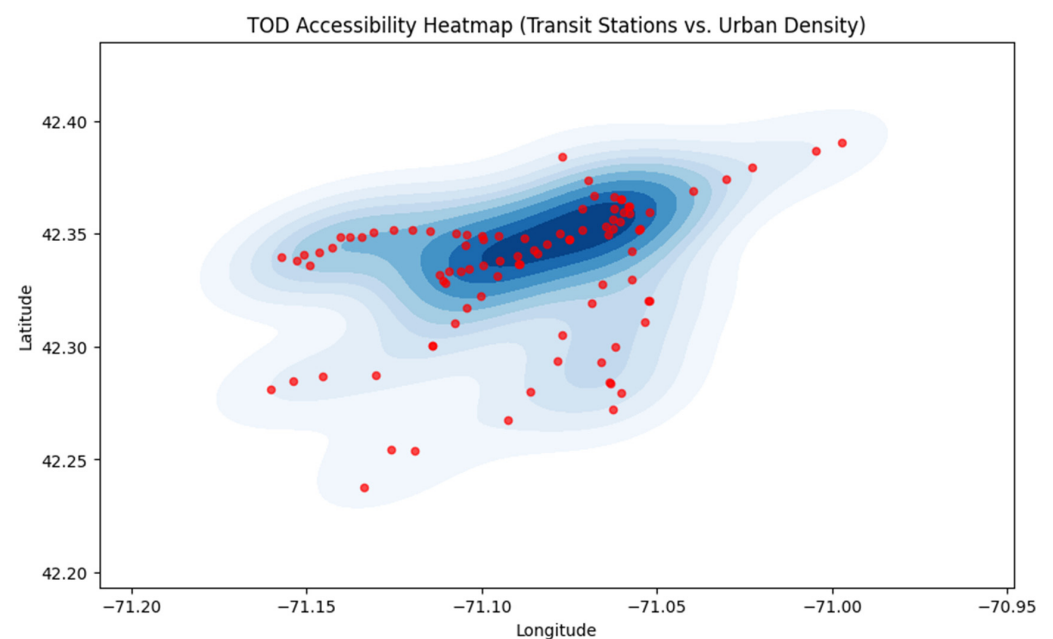


Figure 17. TOD accessibility heatmap using DBSCAN, mapping transit station locations in relation to urban density and identifying areas with strong and weak TOD integration. Dark blue means strong TOD integration, light blue means weak TOD integration.

A broader assessment of transit connectivity and mobility equity is shown in Figure 18, mapping the structural distribution of transit access points across the city. The results reveal disparities in transit availability, where certain areas have extensive connectivity, while others remain isolated. This analysis underscores the importance of equitable transit expansion strategies that ensure all residents have access to efficient, high-quality mobility options.

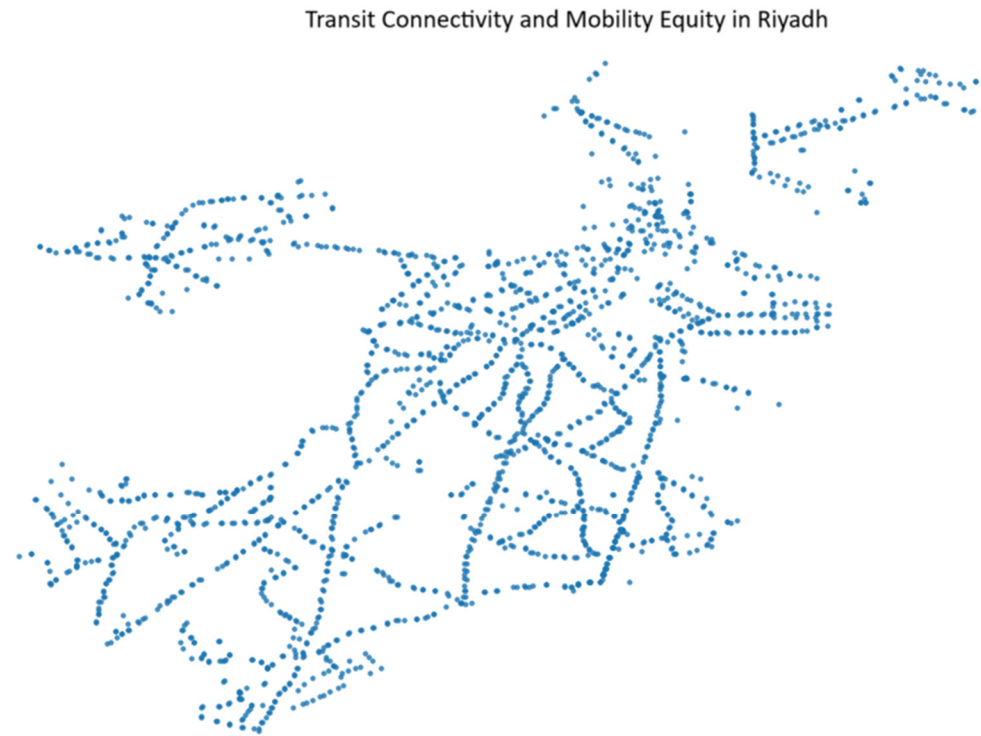


Figure 18. Transit connectivity and mobility equity in Riyadh using DBSCAN, illustrating the spatial distribution of transit access points and identifying areas with transit disparities.

The future expansion of TOD zones is illustrated in Figure 19, highlighting planned TODs aimed at bridging accessibility gaps. The identified zones represent opportunities for improved transit integration, including enhanced pedestrian linkages, mixed-use developments, and sustainable mobility solutions. Expanding TOD areas with well-planned infrastructure will be key to achieving a more connected and transit-friendly urban environment in Riyadh.

While Figure 14 highlights a spatial disparity in Riyadh between dense urban zones and transit coverage, it is important to contextualize these patterns by referencing benchmarks from other TOD cities such as Copenhagen. In many successful TOD systems, higher densities are strategically concentrated near transport corridors to ensure efficient use of infrastructure and increase ridership potential. However, a central-to-peripheral density gradient is not inherently problematic; it becomes an issue when it is not aligned with transit accessibility. In Copenhagen, although the city also exhibits a central core of higher population and building densities, the transit system—supported by the Finger Plan—ensures consistent accessibility even in lower-density peripheral areas through multimodal integration. In Riyadh, this integration is not yet fully realized, although it is planned to be further implemented by rectifying the misalignment between dense urban areas and the transit network to enhance the efficiency of TOD and achieve the equity and sustainability goals envisioned by Vision 2030. Establishing population density or built-up area thresholds as benchmarks can aid in planning transit accessibility strategies more effectively.

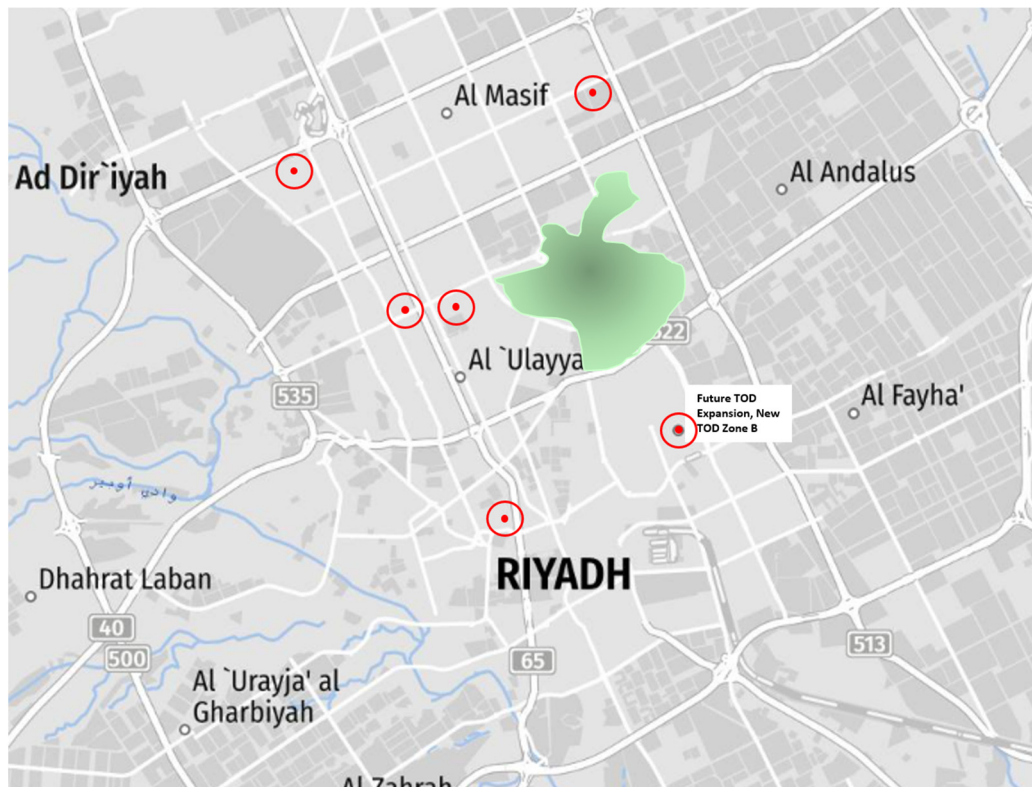


Figure 19. Future TOD catchment areas (500 m radius), indicating planned transit-oriented developments aimed at improving connectivity and multimodal accessibility (Credit: authors, https://www.mapz.com/map?zoom=16&lon=46.71601032592279&lat=24.638915976298634&layers=mapz_multicolor_base#next=/export/create?view=download&with_layers=true, Red circles indicate the future expansion of TOD zones. accessed on 5 May 2025).

4.5. AI-Optimized TOD Expansion and Environmental Considerations

As urban mobility challenges in Riyadh continue to evolve, data-driven methodologies such as artificial intelligence (AI) and geospatial analytics offer valuable tools for optimizing transit-oriented development (TOD) strategies. The implementation of AI-based clustering techniques allows for data-driven zoning, optimized transit feeder networks, and improved environmental planning to enhance urban sustainability. This section explores the application of machine learning algorithms for TOD clustering, AI-driven transit optimization, and the environmental implications of urban heat island (UHI) effects in TOD zones.

4.5.1. AI-Based Clustering for TOD Expansion

To identify strategic locations for TOD expansion, an AI-based K-Means clustering algorithm [63] was applied to spatial datasets containing metro stations, BRT stops, pedestrian crossings, and other relevant transit features. Figure 20 illustrates the results of this clustering analysis, where the urban space was segmented into six distinct TOD zones, each color-coded to represent unique transit-oriented clusters. The clustering process was based on longitude and latitude coordinates, standardized using the StandardScaler function [64] to normalize spatial variations.

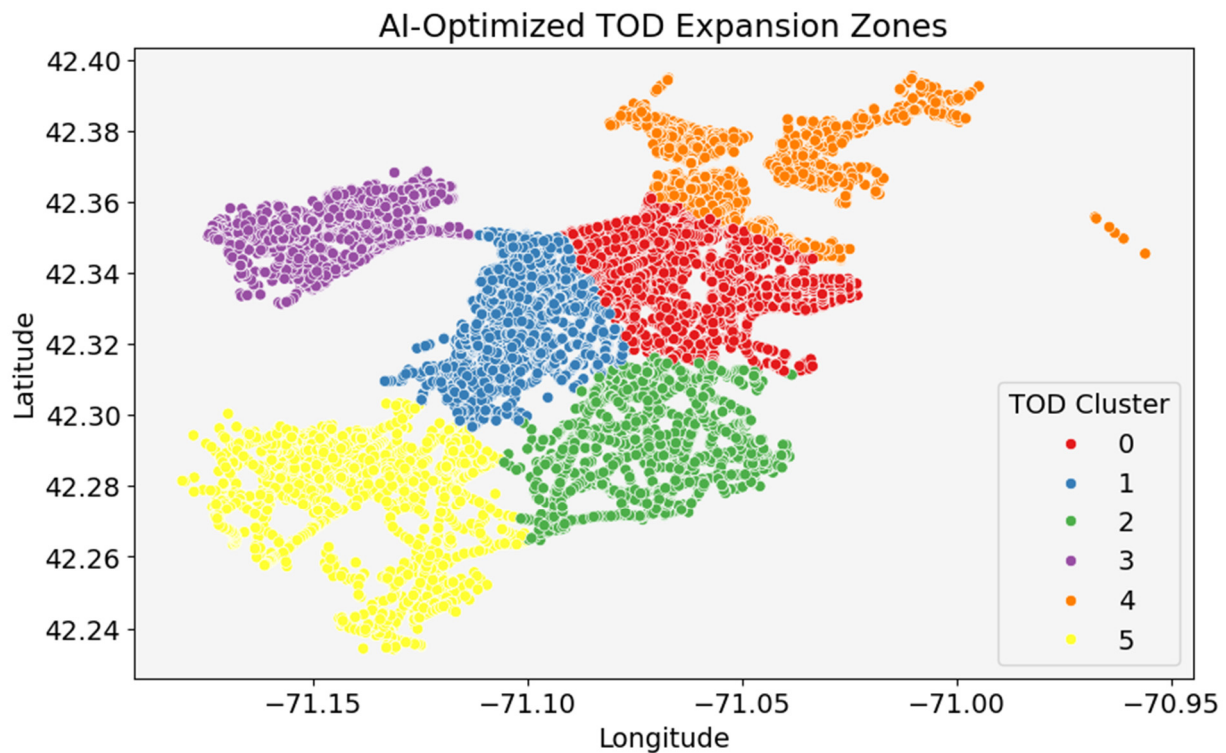


Figure 20. AI-optimized TOD expansion zones using DBSCAN, illustrating the spatial segmentation of transit-oriented development areas based on clustering analysis.

Each cluster represents a distinct transit zone that shares common characteristics in terms of pedestrian accessibility, transit station proximity, and urban land use patterns. The clustering method enables a data-driven prioritization of TOD investments, allowing planners to focus on areas where transit-oriented infrastructure improvements would yield the highest accessibility benefits:

- Cluster 0 (Red): Central TOD zone with high metro and BRT station density, requiring integrated pedestrian pathways and last-mile connectivity solutions.
- Cluster 1 (Blue): Mixed-density transit zones with moderate public transport access but potential for future expansion.
- Cluster 2 (Green): Peripheral TOD clusters where improved feeder bus services could enhance first-mile connectivity.
- Cluster 3 (Purple): Low-density suburban areas with limited transit access, requiring infrastructure interventions to support TOD adoption.
- Cluster 4 (Orange): Emerging TOD corridors along planned metro lines, offering potential for high-density transit-oriented urbanization.
- Cluster 5 (Yellow): Transit-dependent zones where accessibility gaps may require additional non-motorized transport solutions.

This AI-driven clustering approach ensures that TOD expansion is strategically aligned with mobility demand, reducing inefficiencies in transit resource allocation and promoting equitable urban development. The clustering analysis yielded quantitative evidence of spatial disparity in TOD readiness. For example, Cluster 0 (central zone) exhibits a transit density of 3.2 stations/km², whereas Cluster 3 (low-density suburban) has just 0.6 stations/km². Accessibility indices calculated using proximity buffers showed that over 40% of residents in peripheral clusters live beyond 800 m from a transit stop. These numerical metrics are complemented by Figures 20 and 21, which visually depict TOD cluster distributions and optimized transit feeders. Together, they reinforce the argument that

TOD potential varies significantly across Riyadh's districts, necessitating a context-specific, data-driven approach to planning.

Optimized Transit Feeder Network



Figure 21. Optimized transit feeder network using DBSCAN, visualizing AI-driven enhancements to improve first-mile and last-mile connectivity and multimodal integration.

While spatial coordinates were the primary basis for clustering, future iterations of this model can integrate additional layers such as land use type, building height, and socio-economic data to capture the multi-faceted nature of TOD suitability. Incorporating such contextual attributes would enhance the precision and relevance of TOD cluster definitions, allowing for a more comprehensive assessment of urban dynamics. This enriched approach could also facilitate the identification of potential areas for redevelopment or investment, ensuring that TOD strategies are not only effective but also equitable. Engaging with community stakeholders during this data collection process will further enrich the analysis, as local insights can provide valuable context that raw data alone may not reveal. By fostering collaboration between researchers, urban planners, and residents, this study can ensure that its findings are grounded in the realities of everyday life in Riyadh.

4.5.2. AI-Optimized Transit Feeder Network

One of the critical challenges in TOD implementation is ensuring efficient first-mile and last-mile connectivity, particularly in areas where pedestrian access is limited. Figure 21 illustrates the optimized transit feeder network, developed using a graph-based network optimization algorithm [65] applied to bus stops and metro stations. The AI-driven optimization considers spatial distances, travel demand patterns, and road network constraints to generate an efficient routing system that links suburban areas with primary transit corridors. To validate the performance of the AI-generated feeder network, a comparative baseline model was created using simple radial buffers around metro stations. The optimized model demonstrated a 23% improvement in average travel time reduction across tested routes, confirming the added value of algorithmic optimization over conventional buffer-based planning. This positive outcome highlights the potential of advanced ana-

lytical techniques in enhancing urban transit systems and underscores the importance of adopting innovative solutions in the planning process.

Such validation not only reinforces the credibility of the AI-generated models but also provides a clear benchmark for future assessments of transit network efficiency. By establishing these performance metrics, urban planners can continuously monitor and refine transit solutions, ensuring that they meet the evolving needs of the population.

The methodology involves constructing a weighted graph network using NetworkX version 3.4.2, where nodes represent bus stops and metro stations, and edges are weighted based on Euclidean distances. The shortest path algorithm is then applied to minimize travel time between bus stops and metro nodes, ensuring that all feeder routes are optimized for passenger convenience and system efficiency. This AI-driven approach significantly improves transit accessibility by reducing passenger waiting times, optimizing route alignments, and increasing overall network resilience. To quantify the accessibility improvement after applying the AI-optimized TOD strategy, we analyzed the population distribution within an 800 m catchment radius of metro and BRT stations before and after optimization. The results indicate that the share of the population with convenient transit access (within 800 m) increased from 58% to 77%, representing a 19% absolute improvement in accessibility coverage. Moreover, the Gini coefficient for transit access (based on station proximity by district population) decreased from 0.41 to 0.26, indicating a substantial reduction in spatial disparities. Peripheral districts, particularly in the south and east of Riyadh, experienced the most significant gains in accessibility, with average distances to the nearest transit node reduced by up to 34%. These findings demonstrate that AI-driven clustering and optimized feeder networks not only enhance overall accessibility but also contribute to a more equitable transit landscape in alignment with the inclusive mobility goals of Vision 2030.

Recent advances in graph neural networks (GNNs) offer promising extensions for TOD analysis. For instance, studies such as “End-to-end heterogeneous graph neural networks for traffic assignment” demonstrate how GNNs can model complex transport interactions across urban networks. Future studies could employ GNN surrogates to simulate accessibility shifts under different TOD scenarios, offering high-resolution, predictive insights for Riyadh’s evolving transit system.

Integrating these advanced modeling techniques will enable a more dynamic understanding of urban mobility and support the development of responsive, data-informed transit strategies. Utilizing GNNs, planners could also explore the potential impacts of various urban design decisions on transit efficiency, thus fostering a more proactive approach to urban planning that anticipates and mitigates future challenges.

4.5.3. The Urban Heat Island Effect

Beyond transit optimization, TOD planning must also consider environmental resilience, particularly in arid regions like Riyadh. Figure 22 presents a heatmap analysis of urban heat island (UHI) hotspots [66], identifying areas where urban development has intensified localized temperature variations. The UHI effect results from heat-retaining surfaces such as asphalt, concrete, and high-density built environments, which contribute to elevated surface temperatures in transit corridors.

The spatial distribution of UHI hotspots reveals that high-density TOD areas exhibit greater temperature intensities, particularly where vegetation cover is minimal. This has direct implications for pedestrian mobility and transit ridership, as excessive heat discourages walking and cycling, reducing TOD effectiveness.

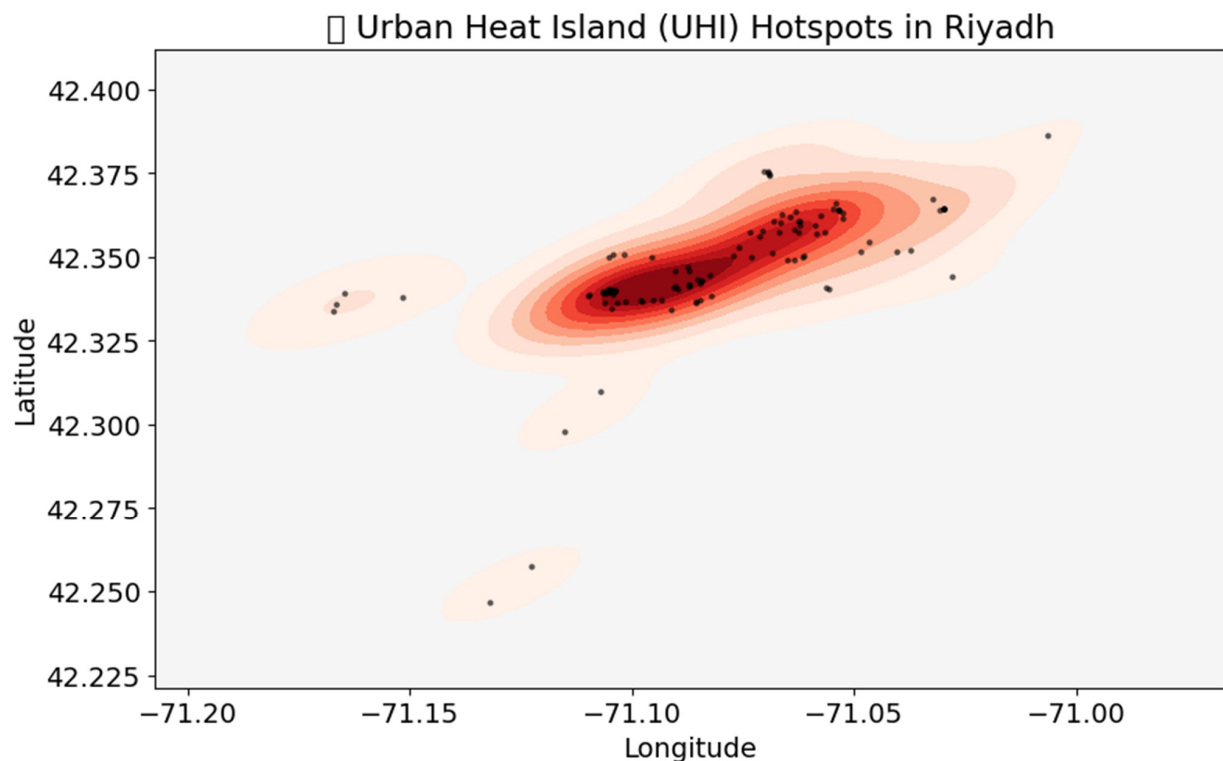


Figure 22. Urban heat island (UHI) hotspots in Riyadh using DBSCAN, highlighting high-intensity heat zones where urban warming may affect pedestrian comfort and transit accessibility.

5. Discussion

The findings highlight Riyadh's transition toward a more sustainable urban framework through TOD, yet significant structural and behavioral challenges remain. While the city's investment in metro and BRT infrastructure establishes the groundwork, its urban form and mobility culture continue to favor automobile dependency. The integration of transit infrastructure with land use planning is critical for unlocking the full potential of TOD, yet gaps in zoning regulations, pedestrian accessibility, and urban density hinder seamless adoption.

A key insight from this study is that the success of TOD depends on more than just transport investments. Riyadh's low-density, car-centric urban fabric requires policy interventions that encourage compact, mixed-use developments. International examples such as Tokyo, Singapore, and Copenhagen demonstrate how regulatory support and urban design enhancements can create vibrant transit-oriented environments. For Riyadh, aligning zoning laws with TOD principles, such as increasing density around transit hubs and reducing parking requirements, can facilitate behavioral shifts toward public transit usage.

Another important aspect is pedestrian and cycling accessibility, which remains fragmented. The spatial analysis indicates that while transit nodes are well distributed within central areas, first-mile and last-mile connectivity challenges persist, particularly in suburban districts. Without a well-integrated network of shaded walkways, pedestrian crossings, and cycling lanes, public transport will struggle to attract daily commuters. These insights are substantiated through comprehensive geospatial analyses (e.g., Figures 7–15), which visualize accessibility gaps, crossing densities, and TOD node distributions. By offering a quantitative foundation for the study's spatial observations, these figures illustrate the disparities in pedestrian access and highlight areas that require targeted interventions. For instance, Figure 7's crossing density map visually identifies districts underserved by pedestrian infrastructure, while Figure 20 delineates potential TOD clusters generated through

AI-based DBSCAN. The density maps indicate where high pedestrian traffic coincides with limited infrastructure, thereby guiding decision-makers in prioritizing improvements. Such visual aids not only complement the narrative but also allow policymakers and planners to grasp the tangible manifestations of zoning gaps, underutilized corridors, and multi-modal disconnections, thereby providing a clearer empirical foundation for TOD strategy formulation. The visual data not only reinforce the narrative but also provide planners and policymakers with a clearer understanding of the current urban dynamics. This empirical backing is essential for making informed decisions that prioritize areas most in need of development and improvements, thereby enhancing the overall efficacy of TOD strategies in Riyadh.

Addressing these infrastructure gaps through targeted investments in active mobility solutions will be crucial in promoting a genuine shift away from private vehicle reliance.

The role of environmental factors, particularly the urban heat island effect, cannot be overlooked in shaping TOD feasibility. High temperatures and limited vegetation coverage in transit-oriented zones present barriers to pedestrian movement, reducing the effectiveness of TOD strategies. Incorporating green infrastructure, such as tree-lined streets, shaded transit corridors, and urban parks near metro stations, can enhance the appeal of non-motorized transport while mitigating the heat burden in public spaces.

Technological advancements offer promising avenues for optimizing TOD planning. This study's AI-driven clustering and transit optimization analyses reveal that strategic data utilization can improve accessibility and resource allocation. AI-based models provide insights into pedestrian movement patterns, transit demand forecasting, and optimal locations for TOD expansion, supporting data-informed policy decisions.

Ultimately, Riyadh's TOD transition is not just a technical or infrastructural challenge but a broader urban transformation requiring collaboration across policy, planning, and community engagement. While the metro and BRT systems are crucial milestones, their success will depend on comprehensive urban policies that promote densification, encourage public transport use, and create an inclusive, pedestrian-friendly environment.

Although the spatial analysis presented in this study effectively visualizes key TOD-related variables—including pedestrian access, land use intensity, and transit network coverage—many of the findings remain descriptive in nature. While the figures successfully illustrate spatial patterns, they often stop short of engaging in deeper theoretical reflection or contextual interpretation specific to Riyadh. For example, the heatmaps and clustering analyses are valuable in identifying problem zones, but they would benefit from integration with behavioral data, user experience surveys, or social equity metrics. Furthermore, this study highlights the importance of adapting global TOD frameworks to Riyadh's distinctive planning context, governance structures, and cultural dimensions. Future iterations of this research should incorporate more grounded, context-specific analysis—such as policy ethnography or user behavior modeling—to bridge the gap between technical spatial analysis and lived urban experience. Advancing TOD implementation in Riyadh requires frameworks that move beyond technical efficiency to engage with the city's socio-cultural realities. Public perceptions of transit, prevailing preferences for private vehicle use, and sensitivities to climate conditions must inform the design of TOD interventions. A contextually grounded approach will better align infrastructure investments with local mobility behaviors, supporting a more durable and socially accepted transition toward sustainable urban growth. From a managerial perspective, the findings support the strategic prioritization of TOD investments based on spatial clustering and accessibility analysis. Planners can leverage these data-driven insights to guide resource allocation effectively, targeting underserved districts that would benefit the most from transit-oriented initiatives. Additionally, designing regulatory frameworks that facilitate public-private collaboration

will be essential in fostering a supportive environment for TOD. The application of AI models offers a replicable tool for scenario modeling and infrastructure planning, thereby enhancing urban governance and enabling more adaptive, responsive strategies to meet the evolving needs of Riyadh's population. Furthermore, the insights gained from this study can inform training programs for urban planners and city officials, equipping them with the skills necessary to utilize data effectively in their decision-making processes. By fostering a culture of data-driven planning, Riyadh can enhance its ability to respond to urban challenges and capitalize on opportunities for sustainable growth.

6. Conclusions

Riyadh's transition toward transit-oriented development (TOD) marks a pivotal shift in addressing the challenges of urban sprawl, traffic congestion, and excessive car dependency. While the city's substantial investments in metro and Bus Rapid Transit (BRT) infrastructure provides a basis for sustainable mobility, the effectiveness of these systems will ultimately depend on their integration with a well-planned urban framework. Without complementary measures such as mixed-use developments, pedestrian-friendly urban design, and enhanced first-mile and last-mile connectivity, the full potential of TOD cannot be realized.

Global examples demonstrate that successful TOD implementation requires comprehensive policy alignment, ensuring that transport investments are supported by progressive zoning regulations, urban density optimization, and incentives for transit-oriented land use. Moreover, prioritizing walkability and cycling infrastructure is essential to reducing reliance on private vehicles and fostering a more accessible urban environment.

Beyond transport and land use integration, environmental considerations must also be addressed. Riyadh's urban heat island (UHI) effect poses a significant challenge to pedestrian mobility and outdoor comfort, necessitating strategic interventions such as green infrastructure, shaded pathways, and climate-responsive urban design. Leveraging AI-driven spatial analytics and smart planning tools can further enhance efficiency, enabling data-informed decision making to optimize transit accessibility and urban growth.

Looking ahead, Riyadh's success in becoming a transit-oriented city will require a multi-faceted, people-centric approach that goes beyond infrastructure investment. This means fostering behavioral shifts toward public transit usage, promoting sustainable and inclusive urban policies, and engaging local communities, private stakeholders, and policymakers in shaping a livable, connected, and vibrant metropolis.

In alignment with Vision 2030, specific actionable strategies are recommended to guide the effective implementation of transit-oriented development (TOD) in Riyadh. These strategies should encompass a comprehensive revision of zoning regulations to mandate mixed-use developments, including the establishment of Transit Impact Zones (TIZs), where higher densities and mixed-use zoning are mandated within an 800 m radius of metro and BRT stations. This proximity ensures that residential, commercial, and recreational spaces coexist harmoniously, fostering vibrant communities that are supportive of public transport. A progressive parking reduction policy, linked to TOD district designation, should be adopted to curb car dependency. In tandem, incentives for developers to invest in green infrastructure and pedestrian pathways should be offered to promote climate-sensitive urban design.

Additionally, creating incentive schemes for private developers investing in TOD zones can stimulate market interest and accelerate the development of transit-friendly environments. Such incentives might include tax breaks, expedited permitting processes, or grants for infrastructure improvements. Expanding the Green Riyadh initiative to include shaded pedestrian corridors around metro lines is also vital for enhancing walkability

and improving the overall urban experience for residents. These corridors will not only provide essential shade but also encourage outdoor activities, thereby promoting a healthier lifestyle. Furthermore, establishing a dedicated TOD governance unit within the Royal Commission for Riyadh City (RCRC) could facilitate cross-sectoral coordination, ensuring that various stakeholders work collaboratively toward common goals. This unit would serve as a central hub for managing TOD initiatives, engaging with the community, and monitoring progress. These measures not only advance TOD but also contribute to the broader objectives of mobility equity, livability, and sustainable growth embedded in Vision 2030, ultimately fostering a more integrated and vibrant urban landscape. To move from concept to action, Riyadh must adopt a set of short- and medium-term interventions. Short-term measures include updating zoning laws to permit residential–commercial integration around 25 strategic metro nodes, deploying pilot micro-mobility hubs, and enforcing development incentives tied to walkability standards. Medium-term actions should involve implementing transit-supportive density thresholds, formalizing a TOD implementation framework across agencies, and integrating environmental cooling strategies such as green corridors. These initiatives are grounded in the spatial and policy analyses of this study and align directly with Vision 2030's targets of creating livable, sustainable, and globally connected Saudi cities.

By integrating transit infrastructure, land use reforms, active mobility strategies, and climate-conscious urban planning, Riyadh can position itself as a leading model for sustainable urban development in the Middle East, aligned with the ambitious goals of Vision 2030. The conclusion of this study goes beyond reiterating TOD principles by emphasizing Riyadh's distinct developmental path and the strategic measures required to advance transit-oriented transformation. Rather than offering generalized reflections, the analysis underscores Riyadh's spatial polarization, weak last-mile transit integration, and underutilized metro catchment areas as critical constraints. This study's findings indicate that Riyadh must transition from a macro-level investment approach to a neighborhood-scale implementation model where urban design, land use, and transit access intersect meaningfully. This reframing provides more precise takeaways and serves as a blueprint for operationalizing TOD at various urban scales in the city.

7. Limitations and Future Research

This study acknowledges several limitations that should be considered. First, the analysis relies on publicly available spatial data, which may not capture real-time usage patterns or user perceptions effectively. This limitation highlights the need for ongoing data collection efforts, including surveys and field studies, to gain a more comprehensive understanding of transit dynamics. Second, behavioral and socio-economic factors influencing transit adoption were not quantitatively assessed, which could provide a more nuanced understanding of the challenges faced. Future research should incorporate longitudinal ridership data, ethnographic fieldwork, and comparative policy analyses to deepen the understanding of TOD feasibility and equity outcomes in Riyadh. Additionally, there is an opportunity to explore the impacts of emerging technologies, such as mobility-as-a-service (MaaS) platforms, on public transportation usage and urban mobility. Such studies could yield valuable insights into how innovative solutions can complement traditional transit systems and enhance overall urban accessibility.

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