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GIS-BASED PEDESTRIAN ACCESSIBILITY ASSESSMENT IN TOD CATCHMENT AREAS: THE CASE OF KIM MA UNDERGROUND STATION, HANOI

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ABSTRACT: Pedestrian accessibility to public transport is not only a primary concern in urban planning but also a core element of the Transit-Oriented Development (TOD) model, which promotes public transit usage and reduces reliance on private vehicles. This study utilizes GIS-based network analysis to assess accessibility within the TOD catchment area of Kim Ma underground station in Ngoc Khanh Ward, Hanoi, Vietnam. The catchment area is defined within a 400–1200 m radius, corresponding to a 5–20 minute walk, in alignment with TOD principles and residential unit theories. The analysis reveals that effective accessibility within a 5-minute walk (400 m radius) accounts for only 55–60% of the theoretical TOD area, while accessibility within a 10-minute walk (800 m radius) reaches approximately 75–80%. This highlights a significant discrepancy between theoretical and actual accessibility. Field surveys indicate that these gaps stem from discontinuous pedestrian networks, widespread sidewalk encroachment, construction barriers, and traffic conflicts at major intersections, all of which increase actual walking time by approximately 1.0–1.3 times compared to ideal conditions. These findings demonstrate that GIS-based network analysis provides a more precise evaluation than traditional buffer-based methods, offering a robust scientific basis for TOD implementation at Kim Ma and other metro stations in Hanoi.

Keywords: Public transport accessibility, Transit-Oriented Development, Walkability analysis, GIS, Kim Ma underground station.

1. INTRODUCTION

Nowadays, most public transportation infrastructure in major cities is facing overload due to rapid urbanization and inefficient land use, leading to increasingly serious traffic congestion, air pollution, and atmospheric emissions [1]. Transit-oriented development (TOD) is considered an effective approach for big cities because its model uses high-volume public transport hubs (metro, BRT, buses) as the nucleus for urban spatial development [2]. The TOD model focuses on urban planning and development by orienting the public transportation systems around transport hubs, using them as centers of population concentration to improve the efficient use of land and public facilities, thereby reducing traffic congestion and environmental pollution [3]. As a result, the TOD model is considered a long-term, sustainable solution to address rampant urbanization, over-reliance on private vehicles, promote public transport, protect the environment, and ensure efficient land use planning [2, 3].

Compared with other urban transport and spatial planning approaches, TOD provides a more integrated framework. Traditional land-use planning, characterized by functional segregation and low-density expansion, as well as urban sprawl and dispersed rural settlement patterns, tends to increase travel demand and dependence on private vehicles. Transit supply-oriented models improve public transport infrastructure but lack strong integration with land use, while Traffic Demand Management (TDM) focuses on regulating travel behavior through policy measures without fundamentally restructuring urban form [4]. Similarly, Compact City, Smart Growth, and polycentric development models promote density and spatial distribution of activities but do not consistently organize development around transit nodes. In contrast, TOD explicitly integrates land use and transport by concentrating development within walkable catchment areas of transit hubs, thereby improving accessibility and land-use efficiency while shaping more sustainable travel behavior [5]. Despite its advantages, a comprehensive understanding of TOD is necessary, particularly given its central role in this study. TOD is characterized by key features such as high-density and mixed-use development, pedestrian-oriented design within walkable distances (typically 400–800 m), strong integration between land use and public transport, and the structuring role of transit nodes in urban form. However, the model also presents several limitations. In practice, TOD often relies on simplified assumptions, including uniform service radii and ideal pedestrian conditions, that may not accurately reflect real-world accessibility. Variations in pedestrian network connectivity, infrastructure quality, and spatial heterogeneity are frequently overlooked, especially in rapidly urbanizing cities such as Hanoi. Therefore, there remains a critical need to evaluate actual accessibility within TOD catchment areas empirically.

In recent decades, Geographic Information Systems (GIS) have become an effective tool for analyzing, managing, storing, and visualizing complex, multi-source geographic data [6]. In urban planning, GIS enables planners to test alternative development scenarios and evaluate their potential environmental impacts, including land-use patterns, public transport systems, and trends in public transport accessibility within TOD zones [7]. Accordingly, GIS utilizes various spatial analysis techniques to link non-spatial policies with spatial planning, enabling the efficient and rapid construction and evaluation of spatial planning models [8]. Faced with increasing population pressure in urban areas and the overload of public transportation networks, many recent studies have applied GIS to assess public transport accessibility in affected areas, particularly within the framework of TOD. For instance, [9] promoted walkable communities, compact urban development, and transit-oriented mixed-use development, including neighborhood schools, retail and business spaces, and various types of housing within walking distance in Faridabad city. Studies [10, 11] proposed a multi-objective optimization model to determine land-use types, floor area ratios, and green network design in TOD station planning at some stations in Beijing, using an improved immunogenetic algorithm. In another study, [12] introduced a new concept, called the Dependent Component Area (DCA) of a metro station, and the Virtual Functional classifications of public transport stations of metro stations (urban connection stations, suburban connection stations, destination stations, and destination connection stations) at the Doha Exhibition and Convention Centre metro station in Qatar. Study [13] developed the Comprehensive Socio-Economic Development Index (CSEDI), based on four TOD site performance indicators, to assess rail transport accessibility performance in Shanghai. In the latest study, [14] used data sources including public transport ticket data, population density at residential and workplace locations, and the number of bus stops and subway lines, to measure and evaluate accessibility distances to subway and bus stations. Meanwhile, some studies in Vietnam primarily use expert opinions to explore and rank barriers to transport-oriented development (TOD) through various criteria [15, 16]. Generally, there is a lack of research evaluating and measuring travel time, as well as the actual accessibility of pedestrians to public transportation locations.

The Kim Ma underground station is located in Ngoc Khanh ward, located in the important administrative and political center area of Hanoi, where many state agencies, educational and medical facilities, and existing residential areas with high population density are concentrated [16]. The accessibility of public transport to the Kim Ma subway station for residents has not been thoroughly considered and evaluated. Addressing this gap, this study applies a GIS-based network analysis combined with field survey data to assess pedestrian accessibility to the Kim Ma underground station in Hanoi. By comparing theoretical TOD service areas with real-world conditions, the study provides a more accurate understanding of accessibility patterns. It contributes to improving the practical implementation of TOD in complex urban environments.

The content of this study includes the following main sections: the first section describes the methodology used to determine the TOD catchment area and develop a public transport database for Kim Ma underground station; the second section focuses on how to find the shortest path, assess the accessibility of Kim Ma underground station by digital simulation in GIS, and propose some solutions for urban restructuring; and the final section focuses on limitations and future directions.

2. RESEARCH SIGNIFICANCE

This study used GIS-based network analysis to assess actual pedestrian accessibility to Kim Ma underground station by incorporating route length and field-measured impedance coefficients. These coefficients reflected real-world barriers such as uneven sidewalks, intersections, and construction obstructions. Calibration against actual walking conditions revealed that the 5-minute zone covers only 55–60% of the theoretical TOD area, and the 10-minute zone 75–80%, indicating a systematic overestimation by conventional buffer methods. These findings provide planners and policymakers with spatially explicit evidence to prioritize pedestrian infrastructure, offering a replicable framework for TOD readiness evaluation at other urban rail stations in Hanoi.

3. A CASE STUDY AREA

The Nhon–Hanoi Station urban railway project includes four underground stations: Kim Ma (S9), Cat Linh (S10), Van Mieu (S11), and S12underground station, which is located in front of Hanoi Railway Station and serves as the terminal of the line (available at https://mrb.hanoi.gov.vn/). Among these, Kim Ma (S9) is the first underground station on the route. It is situated at the base of the Vinhomes Metropolis complex on Kim Ma Street, Ngoc Khanh Ward, Hanoi (Figure 1).

Fig. 1 Kim Ma underground station and its service radius in Hanoi, Vietnam (Source: Google Earth).

4. METHODOLOGY

4.1 Transit-Oriented Development (TOD) theoretical framework

TOD is a model of urban development that focuses on public transport hubs, especially metro stations, BRT (Bus Rapid Transit), and urban rail stations, within a convenient walking radius (usually 400 - 800m) [2]. Generally, TOD is not just about transport development, but a comprehensive urban development strategy, with the station as the central hub for organizing urban space [2] (Figure 2).

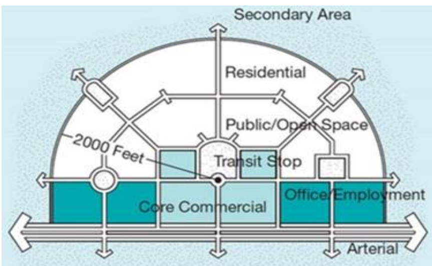

Fig. 2 TOD theoretical framework [9].

4.2 Determination of the TOD catchment area around Kim Ma underground station

The TOD influence zone around Kim Ma underground station was identified based on a combination of a TOD-integrated urban development model and residential unit planning theory. This boundary adheres to the service radius and access distance criteria stipulated in QCVN 01:2021/BXD of Vietnam. Instead of applying a rigid geometric circle with a radius of 1km, the influence zone boundary is established based on the Walking Catchment Area method. With Kim Ma Metro station as the center, the boundary is adjusted to curve along existing surrounding traffic routes such as Kim Ma, Lieu Giai, Nui Truc, and Giang Vo streets (Figure 1).

The actual distance from the station center to the boundary edges is controlled within the range of 400m to 1200m, corresponding to the theory of the effective walking threshold. This distance range is selected to ensure that residents' travel time on foot remains within 15 minutes, in line with contemporary neighborhood unit planning standards and the "15-minute city" model. This approach not only encourages walking and reduces reliance on private vehicles, but also optimizes multimodal connectivity. Specifically, the defined boundary incorporates nearby bus stops, facilitating convenient transfers between feeder bus services and urban rail, thereby contributing to a seamless and user-friendly public transport system.

4.3 GIS-based development of a public transport database for Kim Ma underground station

The input data for this study were derived from various sources and are listed in Table 1, including: 1) A 2017 land use map of Ngoc Khanh ward at a scale of 1:2000, in *.dwg format in AutoCAD software; 2) A 2022 map of the road network planning for subdivision area H1-2 of Ngoc Khanh ward at a scale of 1:2000, in *.dwg format in AutoCAD software; and 3) GPS-derived coordinates of bus stops and underground stations were collected through field surveys. These input data were converted and normalized to coordinate systems to create layers (residential areas, road network, bus stops, and underground stations) in GIS. A public transport database around the Kim Ma underground station in the GIS environment is represented in Figure 3.

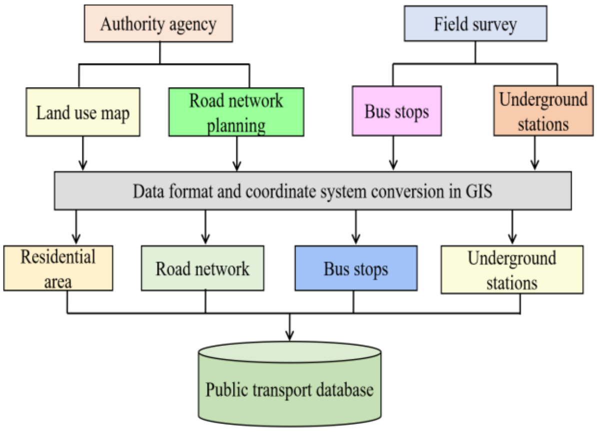

Fig. 3 A public transport database around Kim Ma underground station in GIS (Source: Authors' work).

Table 1. Information on input data used in this study.

Layers	Format	Scale	Year
Residential area	Polygon	1:2000	2017
Road network	Polyline	1:2000	2022
Bus stops	Point	-	2025
Underground station	Point	-	2025
TOD catchment area	Polygon	-	2025

4.3.1 Filtering residential area and road network data

From the 2017 land use map of Ngoc Khanh ward at a scale of 1:2000, in *.dwg format in AutoCAD software, this study filtered the residential area information layer and removed unnecessary objects (i.e., drainage pipes, transformer stations, trees, notes). Then, the residential data layer was converted into a shapefile format in a GIS environment using the *Feature class to Feature class* tool.

Similarly, the road centerline data layer was extracted from a 2022 road network planning map for subdivision H1-2 of Ngoc Khanh ward at a scale of 1:2000, in *.dwg format in AutoCAD software. This road centerline system was then assigned attribute information, like name, class, and length. Intersecting road segments in the road centerline data layer must have connecting nodes to ensure continuity.

4.3.2 Creating bus stop and underground station data

Numerous bus routes operate around the Kim Ma underground station, including routes 09, 14, 18, 25, 32, 34, 45, 50, and 51, located along Kim Ma, Ngoc Khanh, Lieu Giai, Nguyen Chi Thanh, and De La Thanh streets, serving the high transportation needs of residents in the central Ngoc Khanh ward. Thus, the bus stops around the Kim Ma underground station play a crucial role in connecting public transportation.

The coordinates of bus stops and underground stations within Ngoc Khanh ward were determined in the field using GPS devices.

These data were subsequently imported into the GIS environment using the *Add XY data* tool and displayed as point data layers in shapefile format. Attribute information was assigned to each specific object, including name, code, street, and image.

4.3.3 Coordinate system normalization

The *Project* tool in the GIS workspace was employed to normalize all shapefile layers to the VN-2000 National Coordinate System.

This coordinate system uses the map projection of UTM, projection zone 6°, a central meridian (Lo) of 105°00', a distortion coefficient (k_0) of 0.9996, and is positioned on the WGS-84 ellipsoid (Figure 4).

5. RESULTS AND DISCUSSION

5.1 Querying information

One advantage of the GIS tool is that it enables visualization, querying, and spatial searching of data. In this study, data layers, including residential areas, road networks, bus stops, and underground stations, are compiled and standardized synchronously within the GIS environment, making it easier to display, search, and update information (Figure 5).

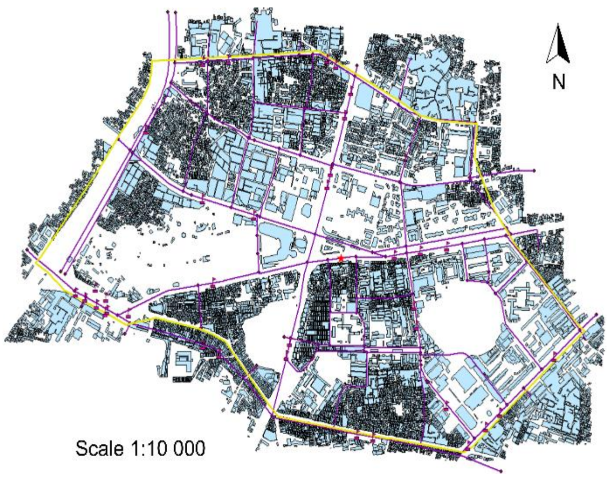

Fig. 4 Data layers were normalized in GIS (Source: Authors' work)

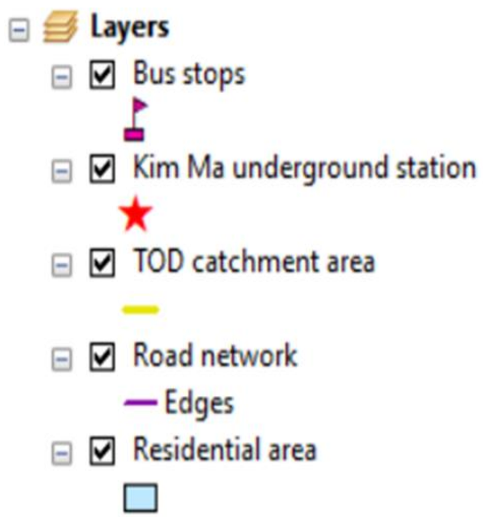

Fig. 5 GIS layers for assessing public transport accessibility within Kim Ma underground station TOD catchment area (Source: Authors' work)

In addition to information retrieval, displaying images of bus stops and underground stations in GIS also provides a visual understanding of the locations and characteristics of the public transportation system in the study area. (Figure 6).

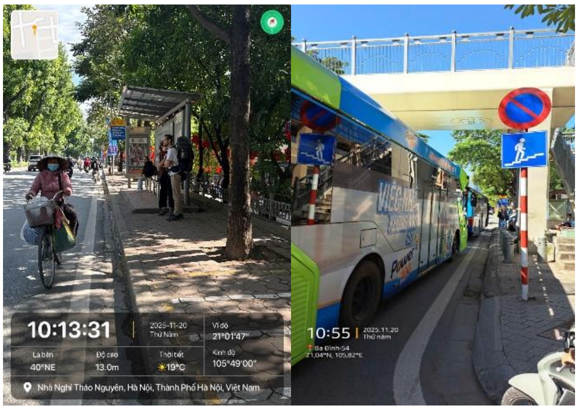

Fig. 6 GPS-derived coordinates of bus stops and underground stations (Source: Authors' work)

5.2 Finding the shortest path

After creating the route data required for network analysis, the Network Analyst tool in GIS was used to efficiently solve network analysis problems. After modifying and assigning values to the Oneway field used by Network Analyst, the data were input into the tool to perform analysis and generate a new Network Dataset. Next, a Network Layer was added to the map. The Create Network Location tool was then used to add stops; at least two stops are required to generate a route. After adding two stops - from bus stop 1 to bus stop 2

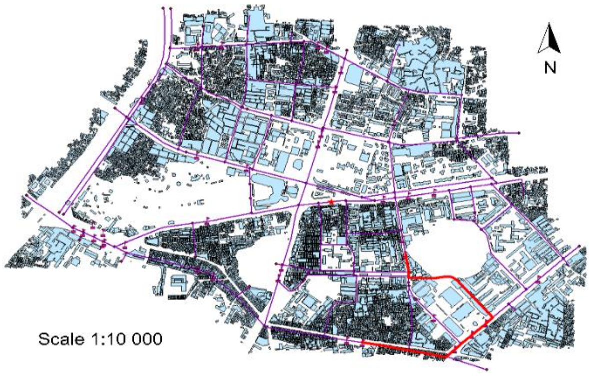

Fig. 7 Illustration of finding the shortest path in GIS (Source: Authors' work).

- The Solve function was executed to determine the route. The results display the shortest path between the two selected stops (Figure 7). The results showed that the shortest route distance between bus stops ranged from approximately 150 m to over 800 m, with travel time increasing significantly depending on the complexity of the route.

5.3 Assessing the accessibility of Kim Ma underground station by digital simulation in GIS

5.3.1 Surveying and determining the impedance coefficient

This study conducted field surveys to assess the quality of transportation infrastructure and the factors influencing pedestrian behavior, including sidewalk conditions, obstacles, slope, and traffic density. This results in the actual travel time (T_{act}) being longer than the theoretical travel time (T_{theo}). As a result, the impedance factor is determined based on the cost-distance method. Accordingly, the impedance factor (f) is the ratio between the actual travel time and the theoretical travel time in GIS [17].

Based on the survey findings, routes were classified and assigned specific impedance factors to represent the actual effort required for travel accurately. In this study, impedance factors were assigned specific values, including 1, 1.1, 1.2, and 1.3.

5.3.2 GIS simulation

The Network Analyst tool in GIS was utilized to simulate the actual walking time from bus stops connecting to the Kim Ma underground station. In this study, the actual walking time is identified based on the combination of the shortest path algorithm and the impedance coefficient, which was directly investigated by the authors at Kim Ma underground station.

The actual walking time was calculated by using the following equation [18]:

$$T_{walk} = \frac{L}{\left(V_{sta}/_{f}\right)\times 60} \quad (1)$$

Where T_{walk} is the actual walking time from bus stops to Kim Ma station, L denotes the length of routes within the study area, V_{sta} describes the standard walking velocity of adults (V_{sta} = 4.5km/h), and f signifies the impedance factor.

The obtained results were visualized using a color scale ranging from green (good accessibility) to red (poor accessibility), corresponding to sequential walking-time thresholds of 5, 10, 15, and 20 minutes (Figure 8).

Based on these parameters, the Service Area algorithm in the Network Analyst toolkit was used to generate irregular polygonal regions representing the actual accessibility of the Kim Ma underground station. These polygons incorporate the results of direct field investigations conducted by the authors. Routes with higher impedance coefficients result in increased travel times and, consequently, lower accessibility. As a result, the simulated accessibility zones exhibit non-uniform and distorted shapes, reflecting the real-world constraints of the urban pedestrian environment (Figure 9).

Figure 9 reflects that accessibility zones around Kim Ma station are affected by two main factors: route length (*L*) and impedance coefficient (*f*). Zones within 5–10 minutes (green) are concentrated near direct routes with low impedance, while zones within 15–20 minutes (red) reflect longer or more obstructed routes. The irregular, heterogeneous polygonal shape comes from the authors' field survey results, including uneven sidewalks, intersections, constructions, and varying quality of pedestrian infrastructure. These factors were recorded through direct field investigations and integrated into the Network Analyst simulation via the impedance coefficient (*f*).

5.3.3 Comparing practical and theoretical accessibility

The theoretical catchment area is defined by concentric buffer zones with standard TOD radius of 400 m (green circle), 800 m (yellow circle), and 1,200 m (red circle). This represents an ideal scenario, assuming straight-line ("as-the-crow-flies") movement without obstacles (Figure 8).

The actual service area is delineated using GIS-based network analysis algorithms and displayed as red, yellow, and orange polygonal areas. This represents the real service area based on the existing pedestrian and road network (Figure 9).

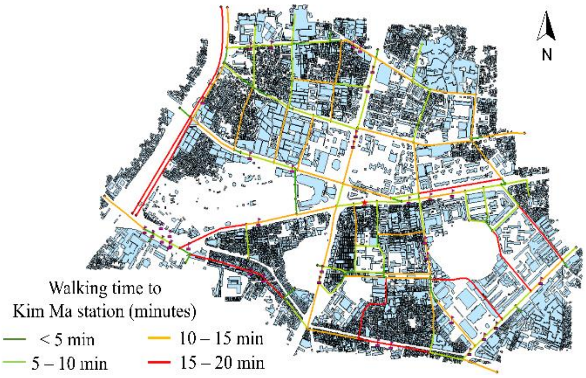

Fig. 8 GIS-based network analysis for determining walking time thresholds (Source: Authors' work).

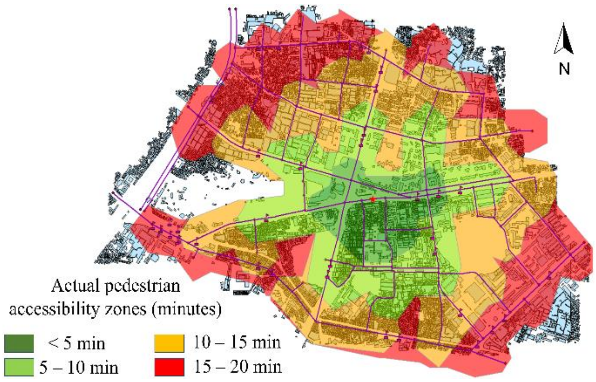

Fig. 9 Actual pedestrian accessibility zones at Kim Ma underground station (Source: Authors' work).

To evaluate the practical effectiveness of the pedestrian transport network around Kim Ma underground station, the study overlaid two spatial data layers onto the same base map (Figure 10).

The obtained results reveal a clear mismatch between the theoretical and actual accessibility models around Kim Ma underground station. While regular circular buffers represent the theoretical catchment areas, the actual service areas are irregular and unevenly distributed. Several locations within the theoretical 400-800 m buffers are not covered by the actual service area, indicating that, despite short straight-line distances, pedestrians cannot reach the station within the expected 10 - 20 minutes. Accessibility is greatest along the East-West axis (Kim Ma - Nguyen Chi Thanh corridor), where sidewalks are wide and continuous, whereas north–south accessibility is significantly constrained, particularly in the southern (Ngoc Khanh and Giang Vo lakes) and northern residential areas. Overall, the actual accessible area reaches only about 55-60% of the theoretical TOD area at the 400 m threshold and declines to approximately 75-80% at the 800 m threshold.

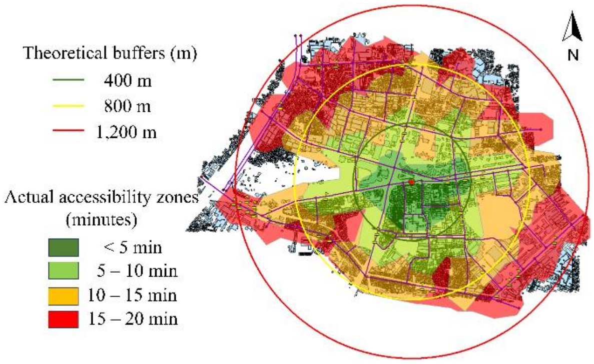

Fig. 10 Comparison between theoretical buffers and actual pedestrian accessibility zones at Kim Ma station (Source: Authors' work)

5.4. Proposal for urban restructuring around Kim Ma underground station

Based on the results of GIS-based accessibility zoning, this study proposes defining the scope of urban restructuring within a 10-minute walking radius (approximately 400 - 800 m) around Kim Ma underground station. Urban restructuring should follow the core principles of TOD model, including maximizing land-use density in the core area, promoting functional diversity, and gradually reducing density toward the periphery, thereby encouraging a modal shift from private to public transportation. Based on TOD principles, this study proposes a three-zone urban restructuring strategy around Kim Ma underground station: *the core zone* (within 200 m) prioritizes maximum density and connectivity through mixed-use development (commercial, services, offices, and hotels), the creation of public plazas, underground parking, and direct underground connections between buildings and the metro station to enhance passenger flow and reduce traffic conflicts along Kim Ma Street; *the transition zone* (200 - 400 m) focuses on increasing residential density by promoting high-rise mixed housing with commercial podiums that provide on-site services and reduce travel demand; and *the peripheral zone* (400 - 800 m) maintains the existing low-rise residential structure while emphasizing infrastructure upgrading and the provision of essential small-scale public facilities, such as kindergartens, healthcare stations, and pocket parks, to improve overall living quality.

6. CONCLUSION

This study applied GIS to assess the accessibility of public transportation in the affected area according to the TOD model of the Kim Ma underground station in Ngoc Khanh ward, Hanoi. The study area was defined within a radius of 400 – 1,200 m around this underground station, corresponding to a 5 - 20 minute walk, consistent with TOD theories and residential units. The GIS analysis results showed that, when assessed according to the theoretical service radius of 800 m, the affected area of the Kim Ma underground station covers most of the Kim Ma, Ngoc Khanh, and Lieu Giai wards, with an estimated population density of over 18,000 - 22,000 people/km². The main contribution of this study lies in calibrating the theoretical TOD service radius against actual pedestrian network conditions derived from field investigation. While the standard TOD model assumes a uniform 800 m service radius, GIS-based network analysis indicated that actual coverage within a 5-minute walk (~400 m) reaches only 55-60% of the theoretical TOD area, and 75-80% within a 10-minute walk (~800 m) - demonstrating a systematic overestimation by conventional buffer methods. The TOD model in this study focuses on the accessibility to the Kim Ma underground station for pedestrians and buses. While the TOD framework broadly accommodates multiple vehicle types, like motorcycles and private cars, their integration was beyond the scope of this study due to limitations in implementation time and data collection capabilities. Future studies will incorporate multi-modal vehicle analysis to provide a more comprehensive traffic safety assessment within the TOD catchment area.

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8. REFERENCES

1 Shahidehpour M., Li Z., and Ganji M., Smart Cities for a Sustainable Urbanization: Illuminating the Need for Establishing Smart Urban Infrastructures, IEEE Electrification Magazine, Vol. 6, No. 2, 2018, pp. 16-33. https://doi.org/10.1109/MELE.2018.2816840

2 Iamtrakul P. and Chayphong S., Exploring Spatial Accessibility to Urban Activities Based on the Transit-Oriented Development Concept in Pathum Thani, Thailand, Sustainability, Vol. 16, No. 5, 2024, p. 2195. https://doi.org/10.3390/su16052195

3 Stojanovski T., Urban Design and Public Transportation-Public Spaces, Visual Proximity

and Transit-Oriented Development, Journal of Urban Design, Vol. 25, No. 1, 2020, pp. 134-154. https://doi.org/10.1080/13574809.2019.1592665

4 Johnstone L. and Ratanavaraha V., Public Transport Initiatives in West Africa, a Case Study of Abidjan, International Journal of GEOMATE, Vol. 19, No. 72, 2020, pp. 197-204. https://doi.org/10.21660/2020.72.5529

5 Papa E. and Bertolini L., Accessibility and Transit-Oriented Development in European Metropolitan Areas, Journal of Transport Geography, Vol. 47, 2015, pp. 70-83. https://doi.org/10.1016/j.jtrangeo.2015.07.003

6 Tong N.T., Nguyen V.P., and Ha H., GIS-Based Construction Ground Level Management in Urban Planning: A Case Study in Hanoi, Vietnam, International Journal of GEOMATE, Vol. 29, No. 134, 2025, pp. 93-100. https://doi.org/10.21660/2025.134.5034

7 Hasibuan, H., Moersidik, S., Koestoer, R., and Soemardi, T. P., Using GIS to integrate the analysis of land-use, transportation, and the environment for managing urban growth based on transit-oriented development in the metropolitan of Jabodetabek, Indonesia. IOP Conference Series: Earth and Environmental Science, Vol. 18, No. 1, 2014, p. 012177. https://doi.org/10.1088/1755-1315/18/1/012177

8 Giaoutzi, M. and Papadopoulou, C.-A., The role of visualisation in spatial planning: A GIS-based approach. In: A Broad View of Regional Science: Essays in Honor of Peter Nijkamp. Springer, Singapore, 2021, pp.275–300. https://doi.org/10.1007/978-981-33-4098-5_15

9 Pal, S., Measuring transit-oriented development of existing urban areas around metro stations in Faridabad city. International Journal of Built Environment and Sustainability, Vol. 5, No. 1, 2018. https://doi.org/10.11113/ijbes.v5.n1.251

10 Ding, C., Song, Y., Qiao, X., Zhang, Y., Yu, B., and Zhang, X., Integrating land use and greenway network for metro station area transit-oriented development. Transportation Research Part D: Transport and Environment, Vol. 113, 2022, p. 103539. https://doi.org/10.1016/j.trd.2022.103539

11 Ma, X., Chen, X., Li, X., Ding, C., and Wang, Y., Sustainable station-level planning: An integrated transport and land use design model for transit-oriented development. Journal of Cleaner Production, Vol. 170, 2018, pp. 1052-1063. https://doi.org/10.1016/j.jclepro.2017.09.182

12 Jamaleddin, M., Ibrahim, H., Ferwati, M. S., Khamidi, M. F., and Indraganti, M., Pre-transit oriented development assessment guidelines for assessing metro station dependent component area. Designs, Vol. 6, No. 3, 2022, p. 56. https://doi.org/10.3390/designs6030056

13 Chen, H., Zhao, K., Zhang, Z., Zhang, H., and Lu, L., Methods for the performance evaluation and design optimization of metro transit-oriented development sites based on urban big data. Land, Vol. 13, No. 8, 2024, p. 1233. https://doi.org/10.3390/land13081233

14 Kim, H., Park, S. H., and So, J., Identifying walkability factors for urban metro station areas toward transit-oriented development. International Journal of Urban Sciences, Vol. 29, No. 4, 2025, pp. 804-824. https://doi.org/10.1080/12265934.2024.2429814

15 Son P.V.H. and Duong L.T., A Multi-Criteria Approach for Prioritizing Transit-Oriented Development Barriers in Vietnam, Innovative Infrastructure Solutions, Vol. 10, No. 5, 2025, p. 208. https://doi.org/10.1007/s41062-025-02023-9

16 Van P.M., Nhu L.Q., and Trung V.T., Public Transport Development Orientation with Transit and Land-Use Integration toward a Livable Environment, AIP Conference Proceedings, Vol. 2560, No. 1, 2023, p. 020016. https://doi.org/10.1063/5.0125564

17 Gutiérrez J. and García-Palomares J.C., Distance-Measure Impacts on the Calculation of Transport Service Areas Using GIS, Environment and Planning B: Planning and Design, Vol. 35, No. 3, 2008, pp. 480-503. https://doi.org/10.1068/b33043

18 Toma-Danila D., Transport Network Vulnerability Assessment Methodology, Based on the Cost-Distance Method and GIS Integration, in Intelligent Systems for Crisis Management: Geo-information for Disaster Management (Gi4DM) 2012, Zlatanova S., Peters R., Dilo A., and Scholten H., Eds., Springer Berlin Heidelberg, Berlin, 2013, pp. 199-213. https://doi.org/10.1007/978-3-642-33218-0_15