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Exploring Spatial Accessibility to Urban Activities Based on the Transit-Oriented Development Concept in Pathum Thani, Thailand

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Abstract: Transit-oriented development (TOD) serves as a model for sustainable urban planning, integrating land use and transport planning. Successful implementation varies across specific geographic locations and has yet to be fully realized in the suburban areas of Thailand. This study empirically examined and searched for understanding of the enhanced accessibility to urban activities through the TOD concept by focusing on bus stops and rail mass transit. The study utilized a network buffer zone approach around transit areas as TOD measurement units, examining distances of 500 m, 1000 m, and 2000 m. Spatial analysis was applied to examine and understand the enhanced accessibility to urban activities through TOD by using network analysis, Getis-Ord Gi* hotspot analysis, and bivariate local Moran's I. The results revealed that this area still has limited access to activities via public transport, particularly in the areas where activities are concentrated, especially in commercial, mixed-use, and residential zones. However, upon examining the relationship between access distance and the intensity of land use activities, it became apparent that within the network buffer zone encircling the transit areas, designated as transit-oriented development (TOD) measurement units, there exists a notable concentration and diversity of land use activities. Specifically, enhanced accessibility to the transportation system corresponded to increased activity density. Nonetheless, this correlation was predominantly observed at stations situated in more central areas, whereas stations located at greater distances exhibited a lower intensity and diversity of activities within the TOD zone.

Keywords: megacities; quality of life; spatial accessibility; sustainable transportation; transit-oriented development

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1. Introduction

Urban development policies, as outlined in the National Economic and Social Development Plan, are designed to foster prosperity, income distribution, and diminish economic disparities between regions, along with mitigating spatial differences between urban and rural areas. Embracing the concept of sustainable urban development, this approach aims to advance economic, social, and environmental facets concurrently with enhancing the overall quality of life. Consequently, these policies lead to the expansion of cities and induce transformations in physical, economic, and social dimensions. Nevertheless, a significant portion of the population remains financially incapable of managing the expenses associated with residing in urban areas. Consequently, urban sprawl emerges, leading to the utilization of inadequately maintained urban infrastructure. This, in turn, gives rise to various repercussions, such as traffic congestion and increased incidents of accidents. These issues stem from the swiftly evolving patterns of urban usage, inevitably exerting a detrimental influence on the quality of life for individuals. The urban scenario is characterized by unregulated expansion in areas beyond the capital or those fostering expansion from the capital region. It gives rise to an imbalance in settlements and connectivity within the transportation system, thereby influencing travel patterns heavily reliant on vehicles [1]. Such situations impart adverse effects on numerous urban areas, posing challenges in terms

of urban management, solutions, and development, particularly in suburban areas. Various development concepts serve as the foundation for urban development and solutions.

Transit-oriented development (TOD) is a concept that contributes to the effective management of settlements and the development of transportation systems. It facilitates the creation of compact urban spaces, ensuring that people can access activities and amenities within convenient proximity. This approach underlines the interconnected development of cities and urban communities with transportation infrastructures. Notably, it emphasizes the development of areas surrounding public transport stations, serving as travel connection centers to encourage public transport activities. Simultaneously, TOD promotes non-motorized travel within the same area. Finally, TOD is considered as an alternative to cope with the situation of urban sprawl, dependency on cars, cost-effective transportation, environmental friendliness, and the fostering of a sense of community [2,3]. Its benefits are interconnected, signifying a comprehensive and holistic approach to development. In addition, this concept is intended to offer a better quality of life to its residents by providing opportunities to access various activities, facilitated by the diversity of land use within the service range of public transportation systems [4,5]. TOD is considered as an appropriate model for implementing urban development solutions to address the challenges posed by urban sprawl in Thailand [3], particularly in metropolitan areas that facilitate expansion from the country's capital. Currently, Thailand is actively advancing plans for the development and expansion of the public transportation network from Bangkok, the capital, extending to the surrounding areas. This initiative encompasses both rail mass transit and public bus systems, concurrently promoting the adoption of the TOD concept to address urban issues. However, the development of the rail mass transit network involves significant investment. While basic public transport systems, such as public buses, provide broader coverage than the rail mass transit system, challenges persist in delivering public transport services to suburban areas grappling with urban sprawl issues.

Therefore, fundamental modes of public transport, such as public buses, constitute the cornerstone of a robust mobility system. This system creates opportunities for accessing various activities within the city through sustainable transportation, aiming to reduce dependence on private cars. Despite the rich historical background and numerous benefits associated with TOD, its effectiveness can vary based on the specific geographic location and urban transportation characteristics [6]. Moreover, TOD presents significant challenges and has not been fully realized in suburban areas in Thailand, including at various transit points such as bus stops and train stations. It is crucial to comprehend the potential opportunities for accessing urban activities through TOD to harness its full potential and ensure equitable outcomes, thereby contributing to the enhancement of people's quality of life.

2. Literature Review

2.1. Transit-Oriented Development (TOD) and Its Implication

While rapid urban growth may pose challenges for cities, urbanization also presents an opportunity to redefine city planning and promote sustainability. The concept of TOD is not novel; it is among the urban development strategies that focus on transforming the expansion of cities into compact urban centers. This approach involves shaping land use patterns to maximize benefits, aligning with the concurrent development of transportation infrastructure [7,8]. By extensively developing an area for mixed use, encompassing both residential and commercial zones, along with various recreational spaces accessible to all citizens, a linkage system to multi-modal travel modes is established [9–11]. This approach aids in mitigating erratic urban sprawl, prompting a shift in travel behavior from private cars towards public transport and non-motorized modes, all within reasonable proximity to public transport stations. Additionally, it contributes to fostering a sense of community [12,13]. Public transport stations, when considered within the framework of TOD, generally refer to propositional higher density near mass transit stations [11,14]. However, the framework of TOD is not restricted solely to rail mass transit stations [15]. It

encompasses various types of public transport facilities, including bus stations, bus rapid transit, train stations, and others. This idea is based on transit points such as stations, bus stops, piers, terminals, etc. There are examples of past literature that have examined the TOD concept. For instance, Currie's study on bus-based TOD strengths and challenges revealed that implementing bus-based TOD faces greater difficulties compared to its rail-based counterpart [16]. Shen et al. investigated the impact of bus-based TOD on housing price premiums [17]. Sun et al. explored TOD theory based on bus stops defined within a 400 m radius [18]. Nadeem et al. attempted to address a research gap by investigating the type of urban fabric created by bus rapid transit (BRT) and its influence on transit-oriented development (TOD) [19]. Rodriguez et al. [20] examined the impact of BRT on land development around stations. Additionally, Cervero et al. explored the opportunities and challenges associated with integrating bus rapid transit into a TOD context [21].

Each public transport station, categorized as a TOD station type, assumes distinct roles, and exhibits characteristic activities within its defined area, typically ranging from 300 to 1000 m or more. For instance, Sarker and Mailer [22] demonstrated variations in catchment areas among different station categories, with walking distances ranging from 300 to 600 m, and in some instances extending to 1500–2000 m. Nadeem et al. defined the buffer transit area of BRT–TOD as 800 m [19]. Rodriguez et al. delineated the buffer zone of BRT into three levels: within 1 km of each terminal, 500 m of each stop, and 200 m of feeder routes [20]. Pan et al. examined the implications for TOD planning regarding rail transit by establishing buffers around each rail station with radii of 500, 1000, and 2000 m [6]. Yen et al. identified an average catchment area of around 500 m [23,24].

2.2. Urban Activity and Opportunity to Quality of Life

Theoretically, TOD is expected to enhance accessibility and mobility within a specified buffer zone around transit areas, serving as TOD measurement units. This improvement is achieved by providing a relatively high level of transport connections and urban activity density [21,25]. Increasing accessibility to desired city activities is a priority for transit users, constituting a crucial aspect of enhancing the capacity of the public transit system [26]. Developments in the area surrounding transit points are anticipated to contribute to increased accessibility and mobility. The TOD concept presently represents a widely adopted approach to accessibility planning, yielding several benefits [27,28]. A key advantage is the enhanced access to activities within a reasonable range for pedestrians and users of public transport. The implementation of TOD concepts facilitates improved access to crucial activities, such as employment and housing. Numerous studies have assessed the potential of TOD in enhancing the accessibility of activities.

For instance, Rahman et al. investigated the outcomes of TOD around central mass transit nodes, emphasizing spatial accessibility to urban facilities [25]. The study revealed a stimulating finding that accessibility to urban facilities in TOD areas has significantly increased over time. Altschuler et al. pointed out that TOD provides greater access to urban facilities, thereby contributing to the overall satisfaction of urban residents [29]. Belzer and Autler highlighted the role of TOD in ensuring better accessibility to urban facilities [30]. The literature review highlights challenges in implementing the TOD concept, stemming from variations in local contexts across different areas, which significantly influence the success of TOD implementation [31]. Particularly noteworthy is the application of the TOD concept to transportation modes beyond rail mass transit systems, an aspect often overlooked in previous studies. Bus TOD emerges as an interesting transportation system, deemed essential for urban areas, with service routes that are often more extensive than those of rail mass transit systems. Therefore, creating opportunities for urban development through current potential is an economical and efficient option to integrate transport planning with land use planning. This integration can elevate urban development standards, foster intensification, and enhance accessibility, ultimately improving the quality of life for residents.

3. Methodology

3.1. Study Area

When examining the urban expansion in Pathum Thani province, it became evident that settlements are widely distributed away from the city center. Pathum Thani province, our study area, plays a crucial role in supporting the expansion from the center of Bangkok, aligning with the objectives outlined in the 4th National Economic and Social Development Plan. The province features land use designed to facilitate both residential living and employment opportunities, complemented by a well-developed transportation and travel network.

Notably, Pathum Thani province (see Figure 1) is location along with National Highway No. 1, Phahon Yothin Road, a significant thoroughfare connecting cities. Additionally, it boasts a dedicated expressway, the Kanchanaphisek Ring Road, which enhances connectivity among cities in the region. The transportation infrastructure in Pathum Thani province provides convenient-for-car access, influencing industrial development and contributing to its status as host to numerous large industrial estates, thereby generating significant employment opportunities. This positive impact extends to achieving a balance between work and housing in the region. Furthermore, Pathum Thani province serves as a hub for research and development, hosting several significant higher education institutions, and functioning as a suburban commercial center. Despite these advantageous aspects within the central city, the consequences of urban development have led to the proliferation of settlements, thereby giving rise to inherent challenges within the city [32].

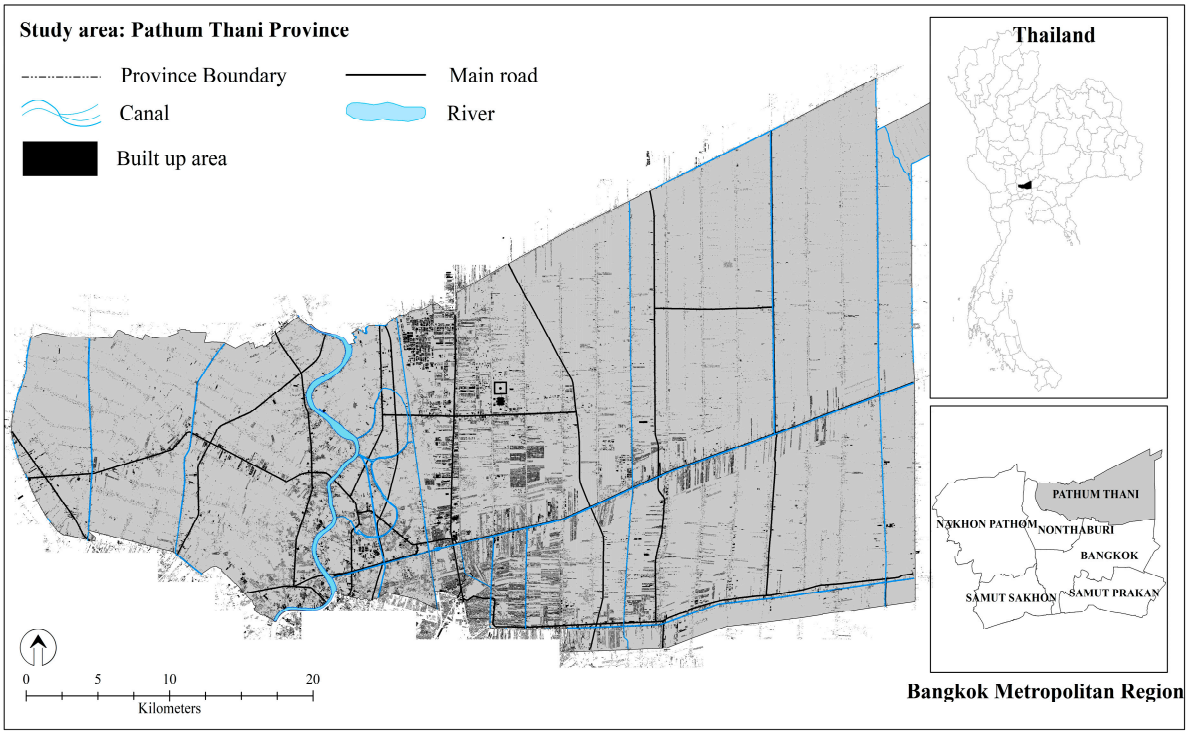


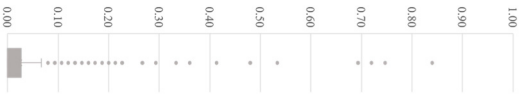
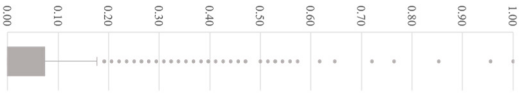
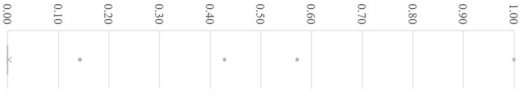
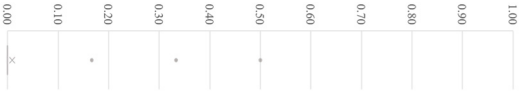
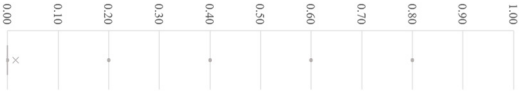
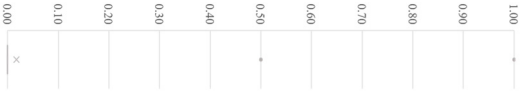
Figure 1. Study area: Pathum Thani province.

3.2. Data Collection

This study empirically examined and sought to understand the enhanced accessibility to urban activities through the TOD concept. The investigation was based on both bus stops and rail mass transit within a specified network buffer zone around transit areas, serving as the TOD measurement. Table 1 provides definitions and descriptive statistics for the variables under consideration. The data used in the analysis comprised two main components: (1) Information pertaining to two types of public transport systems operating within the region of Pathum Thani province, namely rail mass transit systems and public

buses. This involved assessing the service area scope of the network buffer within distances of 500 m, 1000 m, and 2000 m. (2) Data on land use activities categorized into seven distinct types which included commercial, residential, mixed use, recreation, institute, education, and religion. This dataset encompassed the location and quantity of activities within each category. The location data for each type of land use was converted into a grid area of 250 × 250 square meters (totaling 24,808 cells). The data within each grid indicated the frequency of land uses of each type. However, due to the wide range of values for the number of activities per grid across different categories, normalization of these values between 0 and 1 was necessary. The normalized values for the number of activities per grid are presented in Table 1. Subsequently, both sets of data were integrated for a comprehensive analysis of access distances in relation to land use activities.

Table 1. Urban activity data and key variables.

Urban Activities	Descriptive Statistics		
	Average	SD.	Distribution
Commercial	0.011	0.026	
Residential	0.045	0.080	
Mixed use	0.022	0.050	
Recreation	0.001	0.010	
Institute	0.005	0.024	
Education	0.010	0.047	
Religion	0.014	0.060	

Note: Normalized values of the number of activities per grid (250 × 250 sq.m.); grid total 24,808 cells.

3.3. Data Analysis

This study centered on the spatial analysis of physical data related to public transport and land use activities. The analysis employed Geographic Information System (GIS) tools and defined the unit of analysis using a grid of 250 × 250 square meters, resulting in a total of 24,808 cells. The data analysis was structured into three distinct parts, detailed as follows (refer to Figure 2).

(1) The first step involved considering and defining the network buffer of the study according to the concept of TOD that was expected to enhance accessibility and mobility within a specified buffer zone around transit areas such as public transport stations that were not restricted solely to rail mass transit stations, but also included bus stations, bus rapid transit, train stations, and others. In this research, the network buffer area was delineated from the locations of transit points, encompassing both rail mass transit and bus stops. The network buffer zone could be segmented into three distinct distances of 500 m, 1000 m, and 2000 m. These buffer sizes aligned with acceptable

walking distances, as referenced in Zhang et al., where a 1 km buffer represents a 15 min walking distance [33]. While various studies have determined different buffer distances, they typically fall within the range of 300–1000 m or more [6,22,23]. In this phase, GIS-based network analysis techniques were employed to determine the reach distance to transit points based on the network buffer.

(2) The second step involved considering the concentration of land use activities using the Getis-Ord Gi* Hotspot Analysis technique applied to urban land use within the specified network buffer zones around transit areas, serving as the TOD measurement. The Getis-Ord Gi* Hotspot Analysis method is utilized to detect spatial clustering effects and assess the distribution and association of urban land use within a given urban area based on geographical space. This analytical tool not only visualizes data distribution, but also facilitates the identification of areas with concentrated urban land use by evaluating both high and low values, with the Getis-Ord G* statistic representing a modification of the Gi statistic. When Gi > 0, it indicates that a region is surrounded by areas with high values, known as hotspots, signifying denser clusters. Conversely, when Gi < 0, it suggests that a region is surrounded by areas with low values, referred to as cold spots, indicating less dense clusters.

(3) The third step involved considering the spatial relationship of internal accessibility within the network buffer zone around transit areas, serving as TOD measurement units, in conjunction with urban land use. This step aimed to evaluate the potential for enhancing access to utilization activities within the service area of the transportation system. The findings from this analysis will contribute to recommendations for applying the TOD concept to aid in the development of the mass transit system within the suburban area.

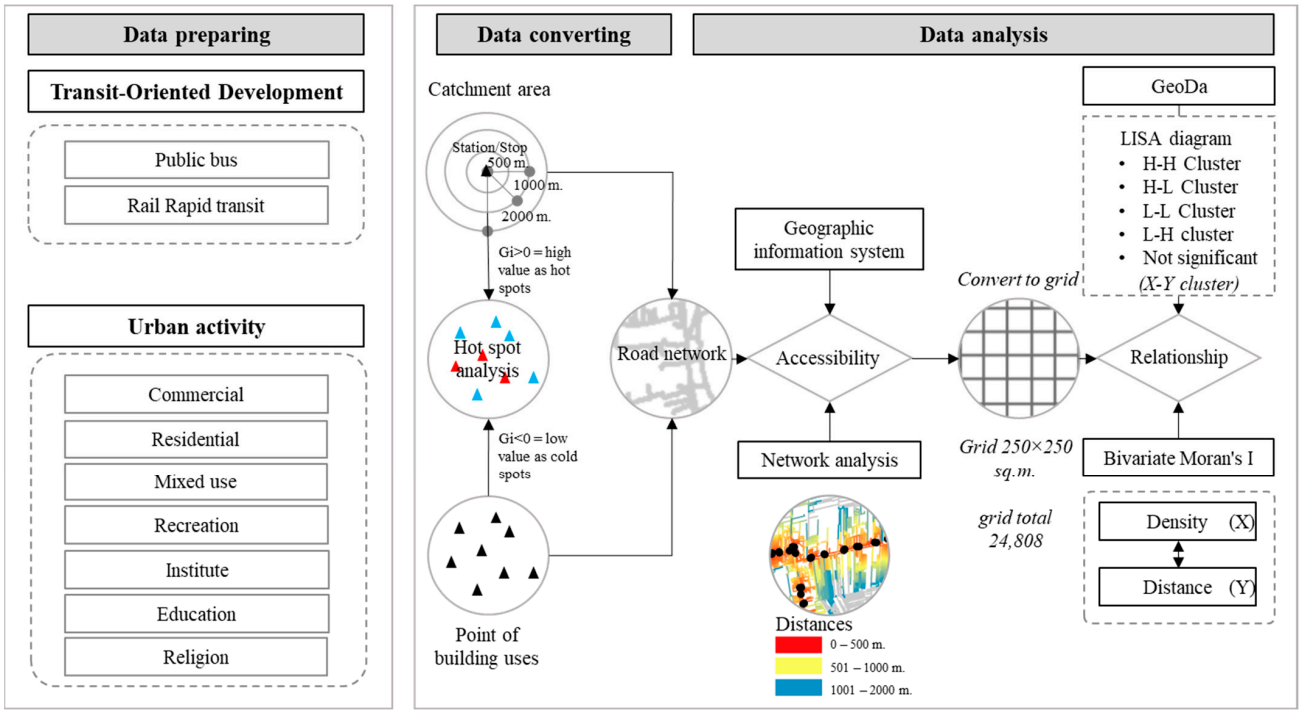


Figure 2. Framework.

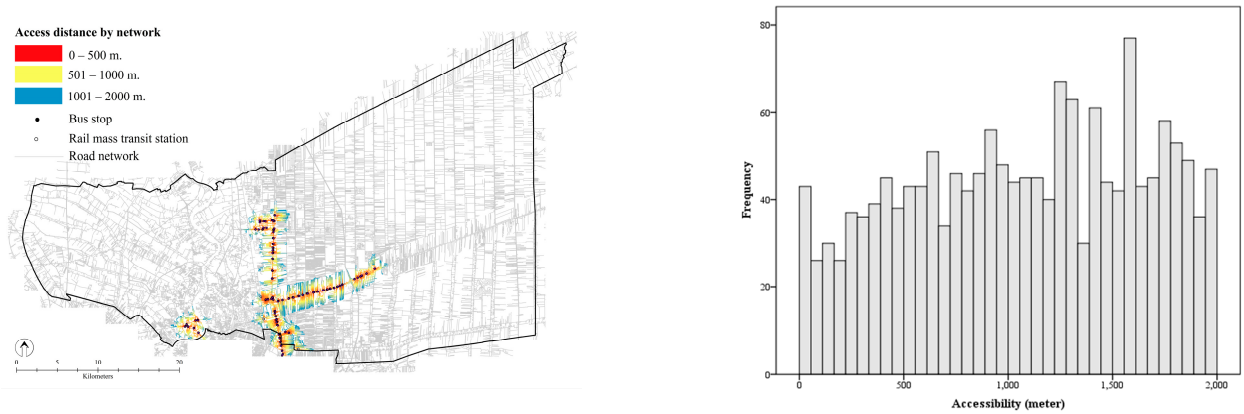
This step was evaluated using bivariate local Moran's I analysis conducted with GeoDa software. The analysis required measuring the travel distance to reach the station and land use concentration using the local bivariate Moran's index and associated *p*-values. The results could be interpreted by identifying high–high and low–low clusters, which could be categorized into five clustering types: (1) Not significant ($p > 0.05$), indicating no significant spatial correlation. (2) High–high clusters, indicating positive spatial matches (high travel

distance and high urban land use density). (3) Low–low clusters, indicating negative spatial matches (low travel distance and low urban land use density). (4) High–low clusters, referring to underserved areas, and (5) Low–high clusters, referring to oversupplied areas.

4. Results

4.1. Accessibility within Transit-Oriented Development (TOD)

In this section, we considered and defined the network buffer of the study area from the locations of the transit points, encompassing both rail mass transit and bus stops, at distances of 500 m, 1000 m, and 2000 m. In this step, network analysis techniques based on GIS were utilized to determine the reach distance to the transit points based on the network buffer zone, as depicted in Figure 3a, which examined the ability to reach the station based on access distances from the network (Figure 3b). From Figure 4, it was observed that within a distance of 500 m, the average access distance through the road network was 263.74 m. For distances ranging from 501 to 1000 m, the average access distance through the road network equaled 758.31 m, while for distances spanning from 1001 to 2000 m, the average access distance through the road network was 1501.20 m. Analysis of the distribution of reach distance values revealed that the majority fell within the range of 1000–1500 m.



(**a**) (**b**)

Figure 3. Accessibility by network. (**a**) Access distance by network. (**b**) Distribution of access distance by network.

Service radius		500 m.	1000 m.	2000 m.
Min	1.55		501.62	1001.43
Max	498.47		996.85	1998.23
Average	263.74		758.31	1501.20
SD.	150.10		146.90	280.70

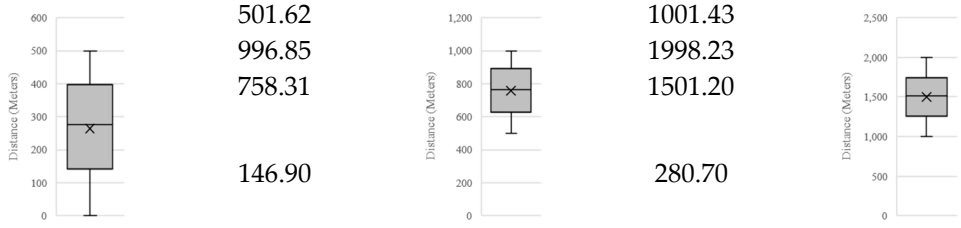


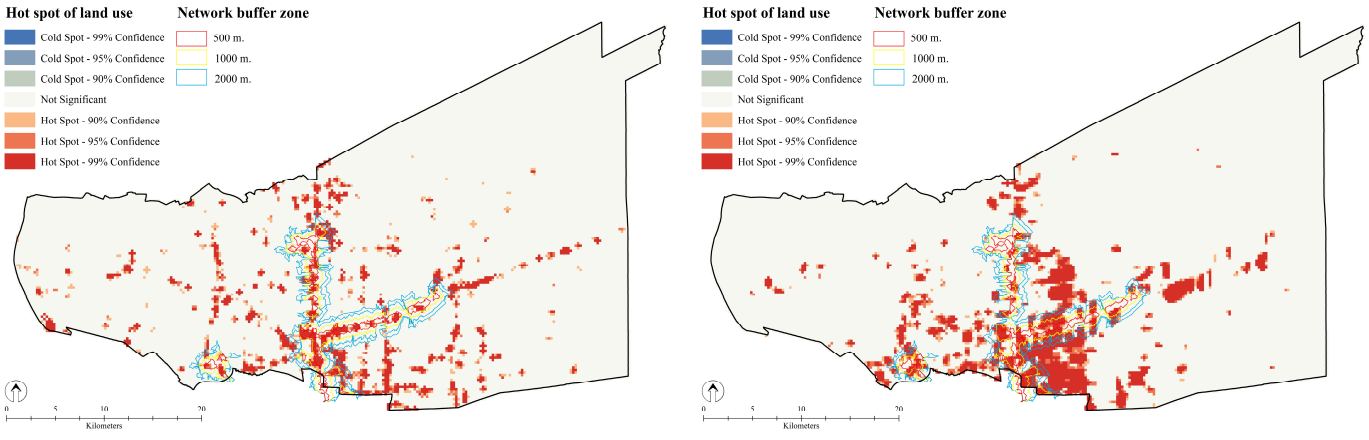
Figure 4. Distribution of access distance by network.

Upon analysis, it was observed that the primary public transportation system within the area is the public bus network, which operates routes and bus stops serving the region. This area supports expansion from the Bangkok area, with the southern part of the province featuring densely located utilization activities along the main road route that originates in Bangkok and extends to the northern and northeastern regions of Thailand. Additionally, a significant arterial road connects Pathum Thani province to neighboring provinces, serving as a conduit for the public transportation system in the form of buses to provide

services along this route. Regarding the rail mass transit system, Pathum Thani currently accommodates two railway lines. The first is the Red Line, destined for Thammasat University Station, though it is presently under construction, with only two stations, Lak Hok Station and Rangsit Station, currently open for service within the province's boundaries. The second line, the Light Green Line, has only one station, Khu Khot Station, operational within the boundaries of Pathum Thani province; other stations are currently in the developmental phase. Nevertheless, when examining the access distance to public transportation within Pathum Thani province, it became evident that the service area remained confined to the city center, connected to the capital area. Furthermore, areas situated at a distance from the city center experience limitations in terms of travel via the public transportation system, leading residents to rely on personal vehicles for commuting. These challenges necessitate thorough consideration in conjunction with land use activities in the subsequent phase, highlighting the interconnectedness of transportation system development and urban planning.

4.2. Hotspot of Urban Activity within Transit-Oriented Development (TOD)

The process of analyzing urban activity hotspots serves as a tool to effectively depict the distribution of land use activities. This analysis reveals statistically significant differences through z-scores and *p*-values. Figure 5 illustrates the results of the hotspot analysis based on Getis-Ord Gi* statistics. The analysis generates a spatial map representing different intensity levels, characterized by distinct color tones. The red color tone indicates high spatial concentration, while the blue color tone indicates low spatial concentration. Figure 6 depicts the results of the analysis, indicating that the average GiZ-score across 90% of commercial, residential, and mixed-use areas was consistent at 1.80, with education slightly lower at 1.66. No statistically significant values were observed for recreation, institutes, and religious sites at this confidence level. In the case of the 95% confidence level, the average GiZ-score for commercial, residential, mixed-use, and education areas closely aligned, ranging between 2.25 and 2.26, with again no significant values for recreation, institutes, and religion. However, when considering the 99% confidence level, it was evident that mixed-use and residential areas exhibited higher values compared to other land uses, with Z-scores exceeding 5.00. These findings suggest a pronounced concentration of hotspot activities in urban areas, with no observed cold spots.



(**a**) (**b**)

Figure 5. *Cont.*

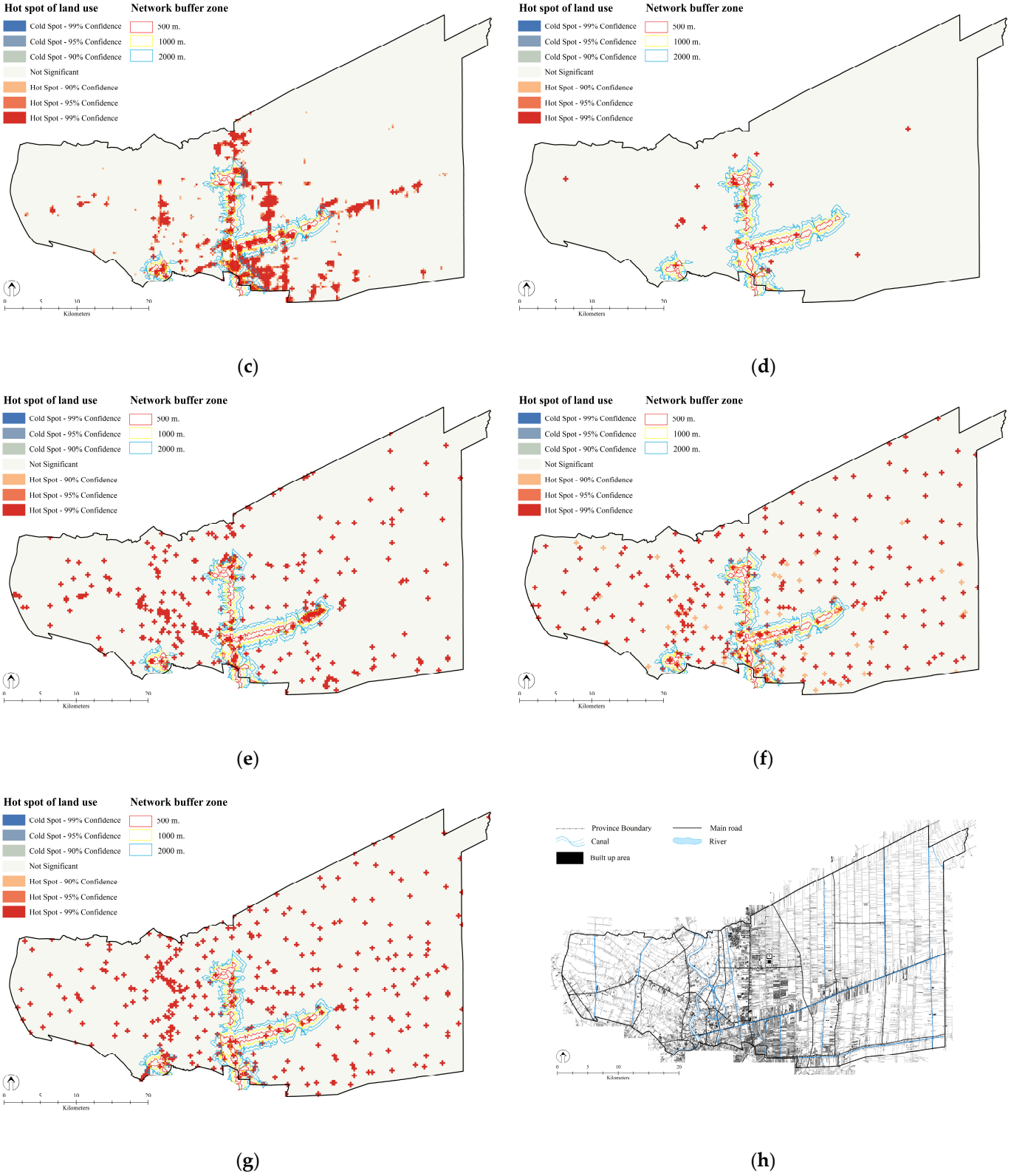


Figure 5. Hotspots of urban activity within TOD. (**a**) Commercial, (**b**) residential, (**c**) mixed use, (**d**) recreation, (**e**) institute, (**f**) education, (**g**) religion, and (**h**) Phathum Thani province.

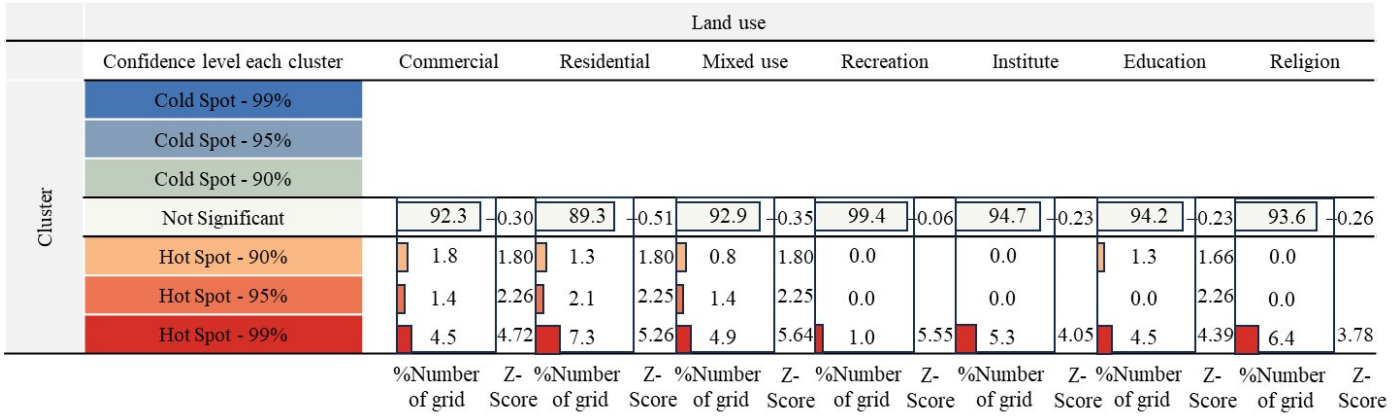


Figure 6. Z-score and percentage of number of grids of hotspot and urban activity.

However, considering each land use activity in the distribution of the grid area, the pattern of activity concentration could be categorized into two distinct types. (1) There was a hotspot concentration observed with varying confidence levels in the urban core zone. Land use activities exhibiting this pattern included commercial, mixed-use, and residential categories. These activities were concentrated within the city center area and along the main roads in the province, particularly in the southern region, which serves as a connecting area to Bangkok, the capital of the country. (2) The concentration of hotspots was observed with varying confidence levels, dispersed across the region. Land use activities demonstrating this pattern included recreation, education, religion, and institutional categories. These activities were marked by a clustering of services dispersed among diverse communities within each district. This phenomenon arises from their role as essential services catering to both urban and rural areas.

However, when considering the map of hotspot concentration together with the network buffer zone of transit around transit areas as TOD measurement units, as shown in Figure 5, it was evident that the network buffer zone (500–2000 m) did not cover areas where activities were concentrated, especially for commercial, mixed-use, and residential activities. These activities are considered as the primary attractions for travel into the area, yet the region still experiences limited access via public transport.

4.3. The Relationship between Distance within Network Buffer Zone and Urban Land Use Concentration

Previous considerations have indicated limited access to activities via public transport in areas with concentrated activity. This section examines the relationship between reach distance and the intensity of activities within the network buffer zone around transit areas, serving as TOD measurement units, to assess the potential application of the TOD concept in the future development of the area. Figure 7 shows the relationship between the distance within the network buffer zone and urban land use concentration by using the local bivariate Moran's I. It measured the travel distance to reach the station and urban land use concentration with spatial statistical significance, indicated by *p*-values at 0.05.

The clusters could be calculated to form five clustering types using GeoDa software, which were: (1) not significant; (2) high–high; (3) low–low; (4) high–low; and (5) low–high clustering. The first and second variable clustering represented urban land use concentration (as the first variable) and travel distance to the transit point within the network buffer zone (as the second variable). This meant that high–high clustering signified high travel distance and high urban land use density; low–low clustering indicated low travel distance and low urban land use density.

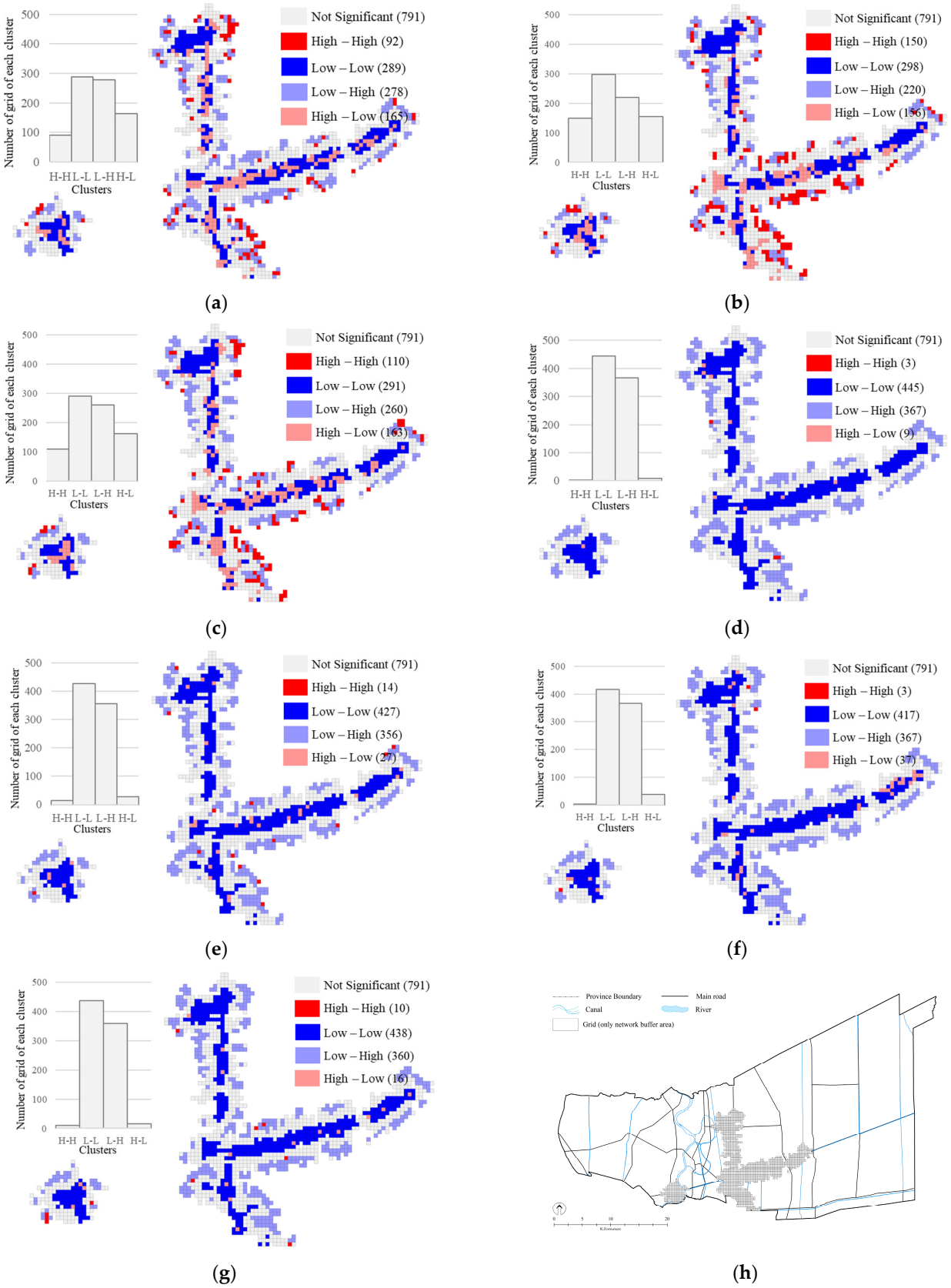
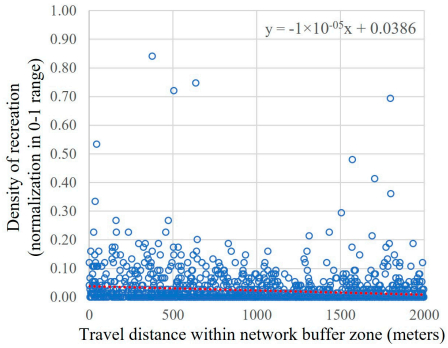
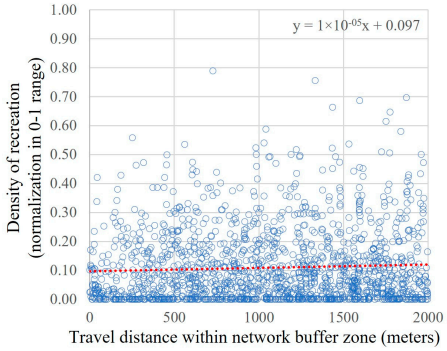
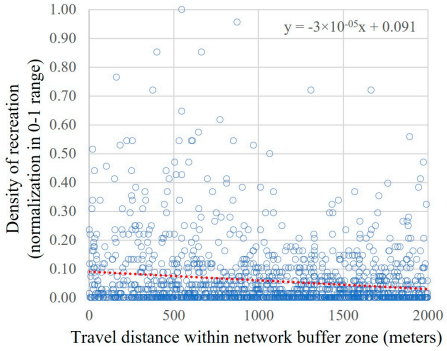
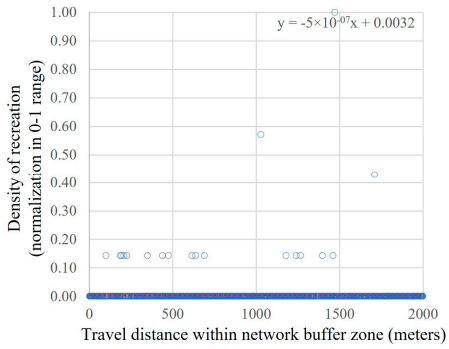
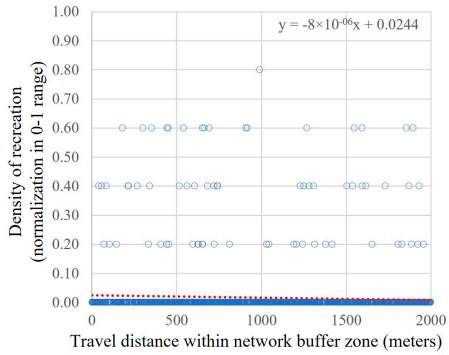
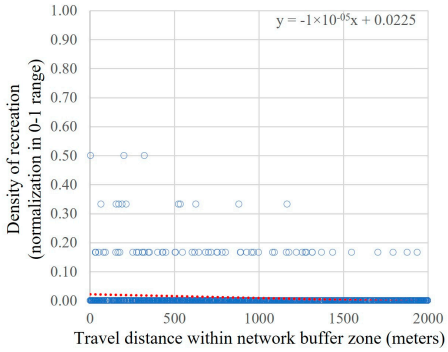
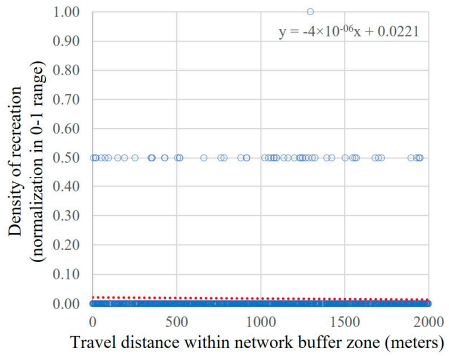


Figure 7. Distance within network buffer zone and urban land use concentration. (**a**) Commercial, (**b**) residential, (**c**) mixed use, (**d**) recreation, (**e**) education, (**f**) institute, (**g**) religion, and (**h**) key map. Note: First variable is land use concentration while second variable is traveling distance to reach the station.

When applying the TOD concept, areas within the transportation system's service boundary that were short (low) distances or close to the station were expected to exhibit density and diversity of land use activities. In other words, the high–low clustering group was considered a category representing an area with the potential for access to utilization activities within the service area. This was because it was a group with a high concentration of activities within the area that had a short distance to reach the station or was close to the station (low). However, upon considering the relationship map, it was observed that more than 35 percent of commercial, mixed-use, and residential land use activities fell into the high–low category. This category represented an area with low activity intensity (low) within a region with a short distance to or close to a station (low). Within the service area according to the TOD's designated range, the majority exhibited low activity intensity, with potential areas (high–low clustering) comprising 20 percent. However, for land use activities such as recreation, education, religion, and institute, over 50 percent fell into the high–low group. Specifically, within the service area according to the TOD's designated range, the majority experienced low activity intensity, with potential areas exhibiting high–low clustering comprising only 3 percent. Considering both the social and economic characteristics, alongside area groups distinguished by population density, it was observed that regions within the network buffer zone were situated within three main districts of Mueang Pathum Thani, Khlong Luang, and Thanyaburi. These districts represent key nodes in the transportation network with particular significance attributed to Khlong Luang intersected by Phahon Yothin Road facilitating connectivity between Bangkok and various northern provinces. Similarly, Thanyaburi district is traversed by the Rangsit-Nakhon Nayok road, enhancing connections with eastern provinces. Consequently, the development of public transportation infrastructure has not kept pace with that of highways. This discrepancy highlights a significant gap in transportation planning and investment priorities, with highways often receiving more attention and resources than public transit systems. As a result, urban areas may experience challenges related to congestion, pollution, and limited mobility options, particularly for those reliant on public transit.

When considering population density, it was observed that the top three districts with the highest population density per area were Thanyaburi district (1938.52 people per square kilometer), followed by Mueang Pathum Thani district (1837.61 people per square kilometer), and Khlong Luang district (1006.01 people per square kilometer). In the remaining four districts, the population density per area did not exceed 1000 people per square kilometer. This data suggests that the area within the network buffer zone has a higher population density compared to areas outside the zone. Consequently, activities within the area, including the public transportation system, exhibited greater density and variety, facilitating increased utilization by residents. When examining the relationship through a trend line graph, as illustrated in Table 2, it was evident that the distance of access to stations or bus stops was significantly linked to the density of land use activities. However, this result exhibited a very low level of correlation across all the land use activities. Upon analyzing the trend lines, it became apparent that commercial, mixed land use, institute, and education activities exhibited a decrease in density as the distance increased. In contrast, residential activities tended to show an increase in residential density with greater distance. Regarding religious and recreation activities, the trend lines remained relatively stable, whether near or far.

Table 2. The relationship between distance within the network buffer zone and urban land use concentration.

a. commercial			b. residential			c. mixed use		
								
R^2	*p*-value	*t*-stat	R^2	*p*-value	*t*-stat	R^2	*p*-value	*t*-stat
0.021	0.000	12.49	0.003	0.034	14.56	0.024	0.000	15.63
d. recreation			f. education			e. institute		
								
R^2	*p*-value	*t*-stat	R^2	*p*-value	*t*-stat	R^2	*p*-value	*t*-stat
0.001	0.746	1.739	0.001	0.037	5.46	0.025	0.000	9.34
			g. religion					
								
			R^2	*p*-value	*t*-stat			
			0.001	0.321	4.36			

5. Discussion

Transit-oriented development (TOD) presents as a strategy that prioritizes the integration between land use and transportation [34]. Coordinating urban planning and transportation infrastructure has become more complex with rapid urban growth. TOD presents itself as a solution to a variety of urban problems. This study incorporated two

forms of public transport which were rail mass transit and bus stops, with a predominant focus on bus stops. The results illuminated the strengths and challenges associated with bus-based TOD. It is noteworthy that while numerous studies have extensively examined rail TOD, research on bus TOD remains relatively scarce and underrepresented in the literature [35]. Nonetheless, bus-based TOD constitutes a distinct subset within the broader framework of TOD implementation and has been acknowledged in typologies delineating TOD characteristics [16]. The development potential between rail TOD and bus TOD exhibited notable disparities, with bus TOD often associated with low-density and small-scale developments, despite offering more comprehensive services. However, success in realizing development opportunities within bus TOD contexts is more likely among certain development groups operating within bus transit systems. Spatial correlation analysis was employed in this study to understand the relationship between the spatial distribution of data and to classify the correlation between accessibility and activity density [36,37]. The Getis-Ord Gi* hotspot analysis tool was utilized to conduct an in-depth examination of activity heterogeneity [36]. It was presented as an aiding tool in the identification of spatial distribution patterns represented by hot and cold spots. Confidence levels of 90%, 95%, and 99% were selected with points having z-values close to 0 indicating nonsignificant spatial clustering. Additionally, bivariate local Moran's I was used to provide a detailed interpretation of regional spatial patterns [38–40].

The findings of this study highlight key challenges in physical development, viewed through the lens of access to activities within the TOD's service area. Only 20 percent of the area within the range of service can promote access to activities, as reflected in the intensive development and diversity of activity use within the transit area. Density and diversity of activity use positively influence accessibility because increased density and intensity reflect the number of opportunities (e.g., hospitals, colleges) to access an activity within a reasonable travel distance, either by public transport or walking. For instance, Kamruzzaman et al. [41] highlight how diverse land use patterns can enhance access. Furthermore, proximity is recognized as one of the contributing factors to improved access, however, it is important to note that various factors often work synergistically to enhance accessibility, particularly in areas characterized by high activity density or diversity. Conversely, accessibility may be constrained if essential activities or amenities are unavailable within close proximity [42]. Additionally, proximity to transportation hubs does not guarantee improved accessibility if the infrastructure is inadequate or if travel options are limited [43]. Significantly, enhancing access to various activities plays a key role in increasing life satisfaction, thereby improving the quality of life for urban residents [29]. The findings emphasize the challenges and opportunities associated with TOD in low-density contexts. While TOD traditionally involves high-density activity clusters and promotes pedestrian mobility, some studies have identified opportunities for development that could enhance its potential. For instance, Nigro et al. conducted a study in the Campania Region of southern Italy, selecting stations situated in municipalities categorized into two types of towns and suburbs contexts [44]. The findings of this study highlighted the potential of TOD in low-density environments by emphasizing the integration of multiple feeder transportation modes. Thus, this research proposed to expand the conceptualization and implementation of land use and public transport integration to encompass areas characterized by low-density, such as suburban regions.

The area context of the aforementioned study aligns with the area context of this study, both focusing on peri-urban areas. Therefore, the results of this study contribute to filling the analytical and application gap in a distinct area context. Additionally, Hrelja and Robert examined TOD in low-density contexts across three Swedish city-regions of Öxnered, Kävlinge, and Västerhaninge. Öxnered, specifically identified as a peri-urban TOD site, along with all the other sites, represented a low-density context [45]. This study sought to deepen our understanding of the prerequisites necessary for planning processes to facilitate TOD in lower density contexts through analyses of actor relationships and market conditions. Their overarching conclusion suggested that planning processes in small cities

with low to medium populations and activity densities do not markedly differ from those in more traditional, highly urban TOD locations. In line with Currie's [16] examination of bus-based TOD strengths and challenges, the findings suggest that implementing bus-based TOD encounters more difficulties compared to its rail-based counterpart. Past studies also provided examples of opportunities and challenges in applying TOD principles to the public bus segment, particularly in low-density contexts such as peri-urban areas. However, bus public transport can play a crucial complementary role in supporting and connecting other travel modes within an area, especially rail mass transit-based TOD. Several studies highlight the option of incorporating buses into TOD development, positively influencing its efficiency [16,46].

On the other hand, considerations focused on rail transit TOD, such as Rahman et al.'s findings, pinpoint that TOD areas have a higher level of accessibility to urban facilities [25]. Nevertheless, this study is subject to certain limitations that merit further investigation in future research. The advancement of TOD involves a multitude of factors that extend beyond traditional accessibility considerations. Future research efforts should prioritize the integration of diverse spatial and institutional contexts, navigating complex governance structures, and addressing attitudinal factors. This involves considering the potential impacts of various measures and regulations to align comprehensively with TOD development principles [44,47]. Specifically, there is a pressing need to prioritize understanding the degrees of the local context, as the transferability of study results to similar contexts does not guarantee success and demands more comprehension. Moreover, promoting development according to TOD principles is poised to increase the density and diversity of urban activities and transportation systems. This necessitates the distribution of developments across various spatial contexts, highlighting the imperative for future studies to address gaps in the application of TOD principles in diverse settings. Of paramount importance is the consideration of equity in urban and transportation development, as an imbalance in urban management planning may lead to unintended consequences.

6. Conclusions

Cities are continually evolving, and a well-planned urban transport infrastructure is essential for optimal and sustainable city functioning. This study empirically examines and enhances the understanding of accessibility to urban activities through the TOD concept, focusing on bus stops and rail mass transit. Spatial analysis was employed to examine and understand enhanced accessibility through TOD, utilizing network analysis, Getis-Ord Gi* hotspot analysis, and bivariate local Moran's I. These tools, especially the bivariate local Moran's I, enable the examination of relationships between two variables. Numerous studies analyzing spatial relationships concerning transportation accessibility have adapted their analytical tools to account for spatial autocorrelation, often visualizing the results through cluster maps. This study's findings suggest that promoting area development through the application of the TOD concept faces challenges, particularly regarding the coverage of public transport systems and the promotion of development within the service area of transport system. Notably, areas with a concentration of mixed land use and commercial activities still encounter limitations in accessing activities via public transportation [1]. Hence, prioritizing and implementing measures to encourage intensified development within the area is essential to mitigate activity fragmentation and reduce reliance on personal vehicles for transportation [44–47]. Urban planners should emphasize the creation of development opportunities centered around alternative transportation modes. Various policies aimed at enhancing the potential and connectivity of public transport systems are noteworthy, such as promoting the development of additional feeder systems to enhance flexibility in accessing primary public transport systems within the area. Furthermore, service management is another crucial factor to consider, encompassing both waiting and travel times to the destination via public transportation. Effective planning in this regard is essential to incentivize greater public transportation usage. As more individuals utilize public transportation and enter the area, a variety of activities and developments will

naturally follow to accommodate their needs and preferences. This includes promoting mixed-use development within the network buffer zone through the implementation of development incentives.

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