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The effect of motorcycle park-and-ride on the performance of Transit-Oriented Development and transit ridership: a case study of Greater Jakarta

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ABSTRACT

Integrating land use and transportation systems, notably through the Transit-Oriented Development (TOD) paradigm, is increasingly vital in urban metropolitan regions. Park-and-Ride (P&R) facilities are integral parts of TOD, facilitating seamless transition from private vehicles to public transit, which through to mitigate traffic congestion in urban areas. Employing a quantitative data analysis that combines primary surveys and secondary data collection, this study assesses the performance of TOD stations in Greater Jakarta (GJ), with a specific focus on the impact of formal and informal P&R provisions. A node-place model is developed, that encompasses both formal and informal P&R spaces, to analyse the relationships between land use activities and transportation accessibility at TOD stations. The findings reveal that P&R facilities, particularly informal motorcycle parking, positively influence transit ridership. Integrating P&R improves transit accessibility, particularly for motorcycle users facing limited public transport coverage. The study highlights the role of P&R facilities in supporting sustainable urban mobility and identifies key factors influencing TOD performance. Based on modelling and data analysis, the study proposes policy interventions, including optimizing land use, enhancing pedestrian networks, and integrating transportation accessibility, with a particular focus on effectively managing both formal and informal P&R facilities for cars and motorcycles.

1. Introduction

The rapid urbanization of Greater Jakarta (GJ) has exacerbated transportation challenges, including severe congestion, inadequate public transit coverage, and increasing reliance on private vehicles (Widita et al., 2023). One potential solution is integrating land use and transportation systems through Transit-Oriented Development (TOD) (Curtis, 2009), which promotes mixed-use neighbourhoods with residential, office, and commercial spaces within walkable distances of transit stations to support sustainable transportation (Calthorpe, 1993). TOD provides benefits across multiple domains globally. Socially, TOD residents have 28 % higher level of trust in their neighbourhood compared to those in non-TOD areas (Kamruzzaman et al., 2014b). Economically, housing values at TOD locations depreciate by only 22.6 %, whereas properties in other areas decline by 63.04 % (Zhang et al., 2021). In terms of transportation, TODs contribute to a regional reduction of 10–20 million daily vehicle miles travelled (Zhang, 2010). Also, individuals within TOD areas are 2.7 times more likely to use metro transit than those outside TOD zones (Supaprasert et al., 2021).

Despite its intended focus on non-motorized and public transport access, TOD implementation in certain regions, including Commuter Line (CL) at GJ, must account for the prevailing role of private vehicles as feeder transport (Singh et al., 2017). Many commuters, particularly those residing beyond TOD catchment areas, rely on Park-and-Ride (P&R) facilities to bridge the first-mile gap between their homes and transit stations. These facilities serve a critical function by enabling mode transfer from private vehicles to public transit, thereby mitigating congestion and reducing greenhouse gas emissions (Cervero et al., 2004; Parkhurst & Meek, 2014). P&R supports TOD objectives in several ways: (1) shortening private vehicle travel distances (Klementschiz & Grass, 2019), (2) Expanding transit accessibility beyond TOD peripheries (Li et al., 2021), and (3) Increasing transit ridership by attracting commuters who lack direct public transport access (Pogodzinski & Niles, 2021). In the context of GJ, the significance of P&R is magnified by

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inadequate public transport coverage (ITDP, 2019), where only 44 % of the population lives near a transit station, dropping to 16 % in suburban areas (WRI, 2018).

TOD implementation in CL-GJ faces unique challenges, due to the prevalence of formal and informal P&R facilities. Formal P&R facilities, those officially designated by transit authorities, are often insufficient to meet demand. As a result, informal P&R spaces have proliferated in surrounding residential areas that offer cheaper alternatives, attract more users, and exhibit higher occupancy rates than formal facilities (M Nazalaputra & Handayeni, 2017), as depicted in Fig. 1. Both formal and informal P&R facilities experience high occupancy rates during office hours and predominantly used by motorcycle (Pramesinta and Hamdala, 2024; Syaiful and Syaifudin, 2018). Data on transportation modal share from GJ (2019 and 2023) indicates an increase in public transport usage from 10 % to 20 % of total trips. However, private vehicles remain the dominant mode, with motorcycles remains unchanged at 80 % of private vehicle trips (CMEAI, 2019; CMMIAI & UNOPA, 2024). Motorcycles offer advantages such as lower costs (Wirakusuma, 2022), shorter travel times, greater schedule reliability, and lower commuting stress (Mukhlis et al., 2019), making them highly adaptable to traffic congestion. The substantial demand for motorcycle-based P&R at CL stations in GJ highlights the crucial role in first- and last-mile connectivity. The popularity of motorcycle-based P&R in CL stations is further driven by cost effectiveness, as a 40–60 km trip costs less than $1, significantly cheaper than commuting via car for the whole journey (Damanik, 2006).

Generally, TOD is designed within an 800-meter radius of a transit station, integrating mixed land use, pedestrian infrastructure, and transit connectivity (Huang et al., 2018; Zhou et al., 2019), as illustrated in Fig. 2. While TOD prioritizes walkability, private vehicles, particularly motorcycles, remain essential feeders from residential areas within and beyond the TOD boundary to transit stations. Many commuters park within 300 m, aligning with their preferred walking distance to and from the station (Tjahjono et al., 2020). Thus, P&R facilities have become integral to TOD, enhancing transit accessibility and multimodal connectivity.

Within the node-place model for evaluating TOD station performance in transportation accessibility (node) and land use activities (place), existing TOD literature predominantly focuses on car parking that examining availability (Vale et al., 2018a; Zhang & Lee, 2023), locations (Dou et al., 2021; Vale, 2015), and lot size (Bertolini, 1999; Lyu et al., 2016), often without distinguishing whether these facilities serve transit riders or general vehicle users (Cao et al., 2020). This misalignment weakens TOD's fundamental goal of reducing private vehicle dependency. To address this gap, this study exclusively analyses P&R spaces, within the node-place model, ensuring the facility primarily supports private vehicle transfer to public transport. Also, to accurately capture transportation dynamics in developing countries like Indonesia, this research considers P&R facilities for cars (Nyunt & Wongchavalidkul, 2020) and motorcycles.

Although TOD principles generally discourage car use, motorcycles are often integrated into planning as their space efficiency and more environmentally friendly than cars (Sunggiardi & Putranto, 2009). In GJ, motorcycle P&R at TODs supports with broader goals of reducing traffic congestion while aligning with commuter behaviour. To the best of the authors' knowledge, no studies have a comprehensive assessment of TOD performance, integrating both formal and informal P&R facilities, with a particular focus on car and motorcycle parking. The contribution of this study are as follows: 1) Analysing TOD performance, incorporating transportation accessibility, land use activities, and both formal and informal P&R, 2) Identifying the role of informal P&R and motorcycle in TOD performance, and 3) Proposing optimization strategies and policy mechanisms to enhance P&R integration within TOD frameworks.

2. Literature review

2.1. The indicators and variables to measure the TOD performance

Various approaches have been employed to assess TOD across diverse global contexts and scales (Kamruzzaman, Baker, et al., 2014; Lyu et al., 2016; Reusser et al., 2008; Singh et al., 2014; Vale et al., 2018b). One widely recognized method is the node-place model, which considers both the "node" and the "place" aspects of TOD station areas (Bertolini, 1999). The 'node' refers to the transport activity and connectivity of a TOD station, including the accessibility of multimodal urban public transportation and private vehicles.

The "place" aspect focuses on the surrounding land use in creating sustainable and vibrant communities. Key components include land use density, mixed-use development, and urban design (Cervero & Kockelman, 1997), all of which contribute to a sense of place and community.

The node (y-axis) and place (x-axis) indices for different TOD stations are then plotted onto a node-place diagram, as shown in Fig. 3a. Such node-place representation categorizes TOD into five distinct categories: accessibility, stress, dependency, unsustained node, and unsustained place. The accessibility category represents optimal performance, where effective integration of transit supply and land use enables diverse individuals to access and engage in various activities. The stress occurs when both activities and transportation services are saturated, creating potential conflict. The dependency category indicates low demand for activities with limited transportation access, positioned at the lower portion of the middle line in the diagram. The unsustained node (top left), indicates that transportation infrastructure exceeds activities, often found in TOD stations around suburban areas without sufficient development. Lastly, the bottom right reflects unsustained place, where the demand for city access exceeds transportation supply, exemplified by inadequate rail connections or poorly designed facilities.

Fig. 1. Informal Motorcycle P&R Areas at Cawang (CWG) and Bekasi (BKS) Station
Source: Primary Data (Taken: May 2024)

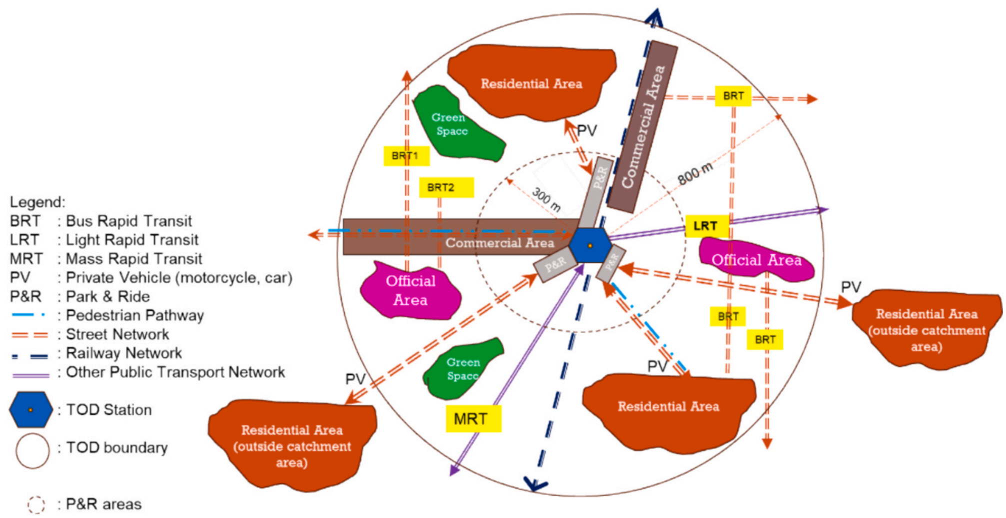
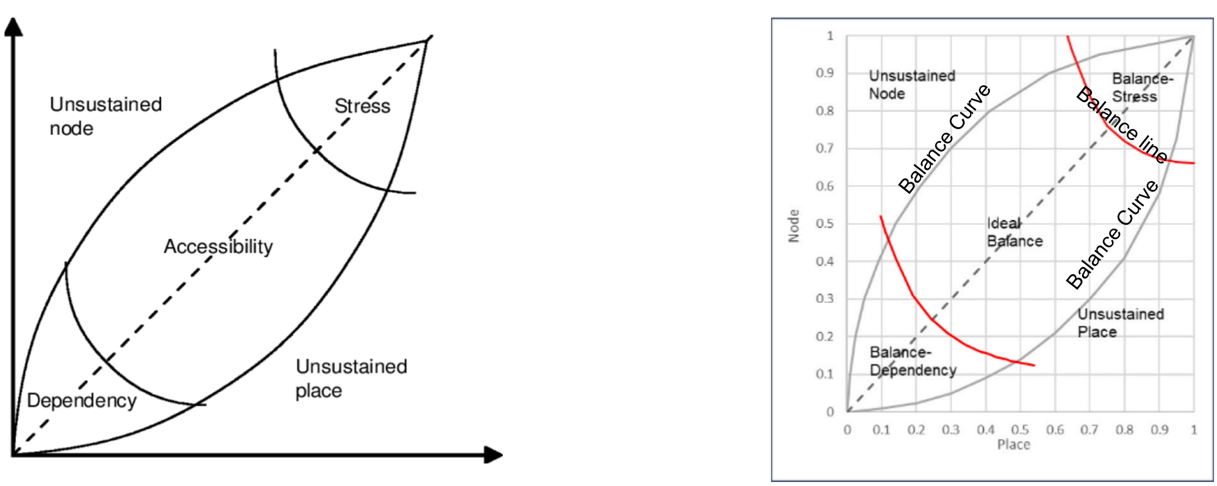


Fig. 2. Conceptual Framework of TOD: Integration of Transportation, Land Use, P&R, and Pedestrian Infrastructure.



a) b)

Fig. 3. a) Original Node-Place Model; b) Node-Place Model based on Cartesian Coordinate.

However, the classification within the Node-Place Model's original diagram is challenging to implement as it remains a conceptual framework that interprets station positions without explicitly defining the expression of each curve (Yang & Song, 2021). There is no formally correct or predetermined method for drawing these curves, as they are conceptually intended to represent idealized scenarios rather than precise boundaries (Bertolini, 2007).

In response, this research adopts a classification system based on Cartesian coordinates (Ma et al., 2022), offering a more structured and precise method for identifying balanced TOD stations (Fig. 3b). It comprises three balance types, defined by the equilibrium between node and place that is separated by the red curve as the balance line: Balance-stress, Ideal-Balance, and Balance-dependency. Balance area within the balance curve represents equal value, allowing up to a maximum 30 % difference between the node and place indices. The "Ideal-balance", positioned between the upper and lower balance lines, occurs when node and place values are equal, providing sufficient space for facility development and comfortable movement for activity. In the top-right is the "Balance-stress" where both the transportation accessibility (node) and land use activities (place) have equally high value. This area, marked by a curve slightly above the upper balance line, represents an index value from 0.7 to 1. Despite the apparent equilibrium, this condition is suboptimal due to the likelihood of conflicts arising from concurrent peaks in activity levels and transportation flow. Moreover, spatial constraints in these area have impeded the expansion of both property development and transportation infrastructure. Conversely, the lowest balance index, known as "Balance-dependency", lies slightly below the down balance line, with values ranging from 0 to 0.45. This area is not struggling with the space for the development, but the demand from the surrounding land use and the supply of transportation are minimal, so the subsidies of government are needed to improve this condition. Additionally, this research will validate clustering results against transit ridership data to ensure accuracy. Clustering was performed based on TOD performance (Ma et al., 2022), considering transportation accessibility, land use activities, and P&R characteristics.

2.2. P&R for TOD

Numerous studies have examined the replacement of parking areas surrounding rail stations with residential spaces to create TODs (Burgess, 2009; Duncan, 2019; Willson & Menotti, 2007), aiming to better integrate transit and land use systems. However, this replacement may not fully address the transportation needs, particularly in areas with irregular or unreliable transit connectivity, infrequent schedules, and weak connectivity.

Research shows that P&R improves TOD performance, particularly in sparsely populated areas, by increasing ridership (Anon, 2004) and reducing travel times (Duncan, 2019). In most suburban TODs, P&R is considered the most effective mode of station access outside Central Business Districts (CBDs) (Martin & Hurrell, 2012). Consequently, P&R-based TODs are often categorized alongside suburban areas (Robillard et al., 2024) to reduce urban congestion by limiting private vehicle entry into city centres (Cavadas & Antunes, 2019; Liu et al., 2022). Though less critical than in suburban areas, P&R in city centres still facilitates the transition to public transit for those living or working nearby (Klementschiz & Grass, 2019).

P&R research of urban areas in the Global North prioritizes car-centric system as automobility reduction strategies (De Gruyter et al., 2020; Piccioni et al., 2019). In America and Europe, P&R facilities are often integrated with sustainable transport solutions, such as regulated parking zones and multimodal transit hubs (Fabusuyi & Hampshire, 2018; Gragera et al., 2021). Cultural commuting patterns further influence P&R effectiveness, with American transit users favouring large-capacity P&R and car-sharing systems (Mounce & Nelson, 2019).

In contrast, studies in the Global South highlight motorcycle-dominated P&R ecosystems (Hoang et al., 2019; Yaldi et al., 2020). In Bandung and Bangkok, motorcycle P&R plays a crucial role in first-mile connectivity, particularly where public transit infrastructure remains underdeveloped (Annisa and Wiradinata, 2019; Long et al., 2023; Saenprasan; et al., 2021). Asian cities tend to develop mixed-use P&R facilities embedded within transit facility improvement (Thanh Truong & Ngoc, 2020). This variation in P&R implementation suggests that TOD-P&R dynamics must be analysed in relation to urban structures and commuting behaviours. Assessing TOD performance requires analysing land use, transit accessibility, and multimodal integration, but the role of P&R requires further investigation. Some researchers argue that P&R are integral to the transportation index (Robillard et al., 2024; Zhang & Lee, 2023), while others contend that P&R should be distinguished (Li et al., 2021). Therefore, this research will assess both perspectives by calculating P&R variables as a separate index and as components of the node index.

3. Study area

TOD stations in GJ serve as key hubs within the public transit system, integrating long-distance transit options like CL, and short-distance systems like Mass Rapid Transit (MRT), Light Rapid Transit (LRT), and Bus Rapid Transit (BRT) (MAASPI, 2017). To support TOD planning, Indonesian government has introduced several regulations within GJ's transportation masterplan that pertaining to the design and location of TOD sites, including the requirement for stations to provide P&R facilities for intermodal transfers (PoI, 2018). Despite there being a total of 64 CL stations in GJ, only 18 have been designated as TOD locations by the Indonesian government (PoI, 2020) and 13 stations will be used as case studies in this research, as in Fig. 4, excluding five due to their low transit demand and inadequate infrastructure.

GJ metropolitan area, frequently referred as Jabodetabek, is an expansive urban territory covering 6,802.1 km^2, including Jakarta and five satellite cities (Bogor, Depok, Tangerang, South Tangerang, and Bekasi), along with three regencies (Bogor, Tangerang, and Bekasi). With a population of 31.24 million people (ICA, 2020), marking it as one of the most crowded urban agglomerations globally. The 13 stations in this study are divided into two groups: seven urban stations in Jakarta (TP, KPB, JAKK, THB, MRI, SUD, CWG) and six suburban stations in surrounding provinces (CKR, BKS, BKST, BOO, DBU, RBU). Fig. 4, highlighting MRI in Jakarta's city centre as the main destination for suburban commuters (indicated by its highest ridership), illustrates the distance between the city centre and suburban stations around 20–40 km. The study focuses on an 800-meter catchment area around each TOD station (MAASPI, 2017) since this range is ideal for integrating mixed land use and public transportation.

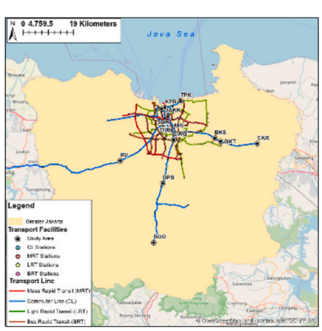
4. Data Source and Method

In this section, we introduce the data sources obtained and the variables used in measuring the node and place indices for the case study. Table 1 provides a summary of the variables and the data sources. N_i, P_i, and PR_i represent individual node, place, and P&R variables ($i = 1, 2, \cdots, n$). The variables are chosen based on: i) the theoretical logic of their contribution to the success of TOD (Khare et al., 2021; Papa & Bertolini, 2015; Reusser et al., 2008; Zhou et al., 2019); ii) the presence of data redundancy within each index; iii) data availability (Chorus & Bertolini, 2011). The data employed in the study comprise both secondary sources, freely accessible from online and government websites, and primary data from direct surveys specifically designed for this study.

4.1. Secondary data sources

The secondary data come from three main sources:

1) Statistics data from Indonesian government on the general population and population-in-work for each sub-district in Jakarta. A sub-district is defined as an administrative subdivision within a district, functioning as the local agency of a regency or city. Population data served as variables for measuring P_2 and P_3.



Notes: BOO=Bogor, MRI=Manggarai, CKR=Cikarang, BKS=Bekasi, CWG=Cawang, DBU=Depok Baru, THB=Tanah Abang, SUD=Sudirman, RBU=Rawa Buntu, KPB=Kampung Bandan, TP=Tanjung Priok, BKST=Bekasi Timur, JAKK=Jakarta Kota

Fig. 4. Research Locations: 13 TOD Stations in GJ.

Table 1
Data Collection.

Code	Indicator	Variables	Description	Data and Source
N_1	Transportation Accessibility (Node)	Number of CL lines	Number of CL services offer by a TOD station	CL website (2023) (https://commuterline.id/)
N_2		Daily frequency of CL services (train departure/ day)	Number of train departures per line per direction	
N_3		Number of other public transport lines	Number of MRT, LRT, BRT and feeder buses operating within TOD catchment area	Integration map of public transport and route service website (2023) (https://transjakarta.co.id/ and Dashboard Jaklingko (jakarta.go.id)
N_4		Daily frequency of services by other public transport (vehicles departure/ day)	Number of MRT, BRT, and feeder buses service frequency per direction operating through the TOD catchment area	Secondary data (formal letter requests to PT. Trans Jakarta as the operator of BRT and feeder buses, and the official website of MRT and LRT) (2023)
N_5		Distance from the closest motorway access to station (meter)	The distance of the exit/entrance access of TOD station to the closest street	Street view and primary data (2023)
P_1	Land Use activities (Place)	Land use diversity	The proportion of land use/building facilities' categories area: residential, commercial, official, green space, transportation, and public service, to the total area	Government's spatial data, OSM, primary data, and Street view map 2024
P_2		Number of residents (people/km^2)	Population density within TOD catchment area	The government's statistical data on the population per sub-district (https://data.jakarta.go.id/, https://opendata.jabarprov.go.id/) (2023)
P_3		Number of workers (people/ km^2)	Employment density within TOD catchment area	The government's statistical data on the number of workers per subdistrict (https://data.jakarta.go.id/, https://opendata.jabarprov.go.id/) (2023)
P_4		Intersection Density (number of intersections/ km^2)	Number of intersections in TOD catchment area	Government's spatial data, GIS analysis, and primary data (2024)
P_5		Accessible pedestrian network length (meters)	Length of the accessible pedestrian pathway within catchment area	
PR_1	The Characteristics of P&R	The area of formal car P&R spaces	The area of formal and informal off-street P&R for car and motorcycle within 300 m from TOD station (m^2). There is no informal car P&R within TOD station in study locations	Street view and primary data (2024)
PR_2		The area of formal motorcycle P&R spaces		
PR_3		The area of informal motorcycle P&R spaces		
PR_4		Proximity of P&R area to TOD station (m)	The distance from the closest P&R to the station (m)	
Daily Ridership	Transit Ridership	Ridership/ days	The total number of passengers per 24-hour period in January 2023	Secondary data (formal letter requests to PT. KAI as the operator of CL) (2023)
Peak-time Ridership		Ridership/ peak-hour	The average number of passengers/hours between 06.00–08.00 AM and 05.00–07.00 PM in January 2023	

2) Data from the stake holders (such as CL website) for the route map and daily schedule of public transport. These data are used to measure N_1-N_4;
3) Spatial geographical data collected from government websites (https://jakartasatu.jakarta.go.id/,https://satupeta.jabarprov.go.id/, https://tanahair.indonesia.go.id/portal-web/) and from Open Street Map through http://download.geofabrik.de/asia/indonesia/java.html. These data are collected for analysing N_5, P_1, P_4 to P_5, and for PR_1 to PR_4.

4.2. Primary data collection

Spatial data from secondary sources only covers basic data with limited aspects required and lacking key details like floor levels for land use diversity, pedestrian pathway positions, and P&R space. Obtaining the data via street view is possible but time-consuming, taking around two–three weeks for each station. Hence, the primary survey is necessary for speedily gathering data, as described below.

Three qualified surveyors–graduates from a top-10 Indonesian public university with relevant degrees, field experience, and ArcGIS proficiency–conducted fieldwork using survey form as in Appendix A, with base map from Jakarta Government website and OSM. All surveyors participated in a zoom briefing by the Lead Researcher covered study objectives, data collection protocols, and ArcGIS data input methods. Through four months (April-July 2024), continuous communication via email and WhatsApp facilitated the resolution of challenges, such as land use classification. Data validation was performed by the Lead Researcher through cross-referencing with OSM. To simplify the survey process, an initial land use classification has been conducted, based on raw classification in the street-view-app. Consequently, the base map is colour-coded according to the initial classification. The survey will collect three types of data, which are elaborated upon below.

1) Land Use Criteria, Number of Floor Level, and P&R spaces.

The surveyors must classify every land use by the land use criteria code such as R for Residential, C for Commercial, etc, to label each building unit with the number of floor levels, as outlined in the base map at the survey form. It consists of colourful spatial representations based on OSM, which categorise each building unit. For instance, if the area contains a four-level mall, the surveyor will designate the space on the map as C4, following the initial classification scheme. Those data will support the variable P_1 (land use diversity) and P&R spaces for PR_1 to PR_4. A key limitation of this study is the potential bias in identifying P&R users as transit riders versus other users. However, primary observations and informal discussions with owners of informal P&R facilities near TODs, particularly in suburban areas, indicate that these facilities primarily serve transit users. Our assumption that facilities within a 300-meter radius primarily serve transit users is supported by the high demand among CL users (Ellisa & Ramadityo, 2019; Syaiful et al., 2018). Most informal motorcycle P&R facilities are located adjacent to CL stations and accessible via pedestrian pathways used by daily commuters. These locations are largely unknown for occasional visitors, such as shopping mall customers, reinforcing their role in transit-supporting function.

Although data on other significant land use criteria within a 300-meter radius, such as malls and offices, are available, the absence of trip-purpose data limits the ability to determine how much the P&R usage is for transit versus other activities. The proximity of these land use criteria introduces the possibility that some users may utilize P&R facilities for non-transit purposes. Future studies should incorporate on collecting detailed trip-purpose data to validate these findings and provide a more comprehensive analysis of P&R usage patterns in TOD context.

2) Pedestrian Pathway.

To identify streets with pedestrian pathways, the surveyor should examine the main streets highlighted in orange colour on survey form which represent transportation facilities such as streets and roadways. The surveyor should sketch a line connecting the beginning and ending points of the pedestrian pathway along the streets. Similar to the procedure outlined in survey method number 1, this task will involve two surveyors; however, it is expected to be completed within a single day. The data collected will serve as evidence for the variable P_5, which measures the accessible pedestrian network length.

3) Exit/Entrance Access of the Station to the Street.

The surveyor is required to verify the location of the station's exit/entrance access concerning the nearest two-way street capable of accommodating two cars. Once identified, the surveyor should draw a double line indicating the nearest access point for private vehicles from the station's exit/entrance to the street. This data will be used to confirm the variable N_5, which measures the distance from the TOD station's exit/entrance to the closest street.

4.3. Variables used to measure node- and place-index

N_1 computes the total number of CL lines of TOD stations (Bertolini, 1999; Dou et al., 2021; Lyu et al., 2016; Reusser et al., 2008; Vale, 2015), while N_2 quantifies the total daily frequency of CL services by line and direction (Bertolini, 1999; Dou et al., 2021; Lyu et al., 2016; Monajem & Ekram Nosratian, 2015; Vale, 2015; Zemp et al., 2011). Both were sourced from the official CL website. N_3, refers to the total number of public transport lines passing through or stopping within the catchment area that is obtained from transit operator websites for MRT and LRT, BRT, and feeder buses in Jakarta Province, that was calculated using Eqn. (1). For feeder buses at stations outside Jakarta Province (BOO, CKR, RBU, DBU, BKST, and BKS), manual calculations using Google Maps are conducted.

$$N_3 = \sum_{j=1}^{M} l_j \quad (1)$$

With l_j = number of lines for public transport mode. M = total number of public transport modes considered. In this study, M = 4, comprising LRT, MRT, BRT, and feeder buses. However, when applying this model in other locations, should reflect the total number of public transport modes present within the study area.

N_4 represents the transit daily number per direction from various public transportation modes (Bertolini, 1999; Lyu et al., 2016; Monajem & Ekram Nosratian, 2015; Vale et al., 2018b; Vale, 2015), including MRT, LRT, BRT, and feeder buses, that either stop at stations or pass through the catchment area (as some feeder buses may stop at multiple locations). The calculation was performed using Eqn. (2) and the data used was obtained in the same manner as that for N_3.

$$N_4 = \sum_{j=1}^{M} f_j \quad (2)$$

With

f_j = daily frequency of public transport mode. M = total number of public transport modes present in this research. As in N_3, M = 4 (LRT, MRT, BRT, and feeder bus).

N_5 measures the shortest distance from the TOD station to the nearest two-way street accessible by two cars (Bertolini, 1999; Dou et al., 2021; Reusser et al., 2008; Vale et al., 2018b; Vale, 2015). Land use diversity (P_1) is quantified using Simpson's index of diversity (Simpson, 1949) derived from Eqn. (3). To improve accuracy, the total area for each land use category is derived from the total floor area, which significantly influences land use performance assessments (Ji et al., 2016). It calculates by multiplying the footprint area by the number of floor levels, reflecting full space utilization. Building footprint data is obtained from government spatial datasets for Jakarta Province, supplemented by OSM and street view imagery for the other locations. The number of floors and land use characteristics are refined using primary data sources.

$$P_1 = 1 - \sum_{n=1}^{N}\left(\frac{a_n^2}{A}\right) \tag{3}$$

With

a_n = total area of 'n[th]' land use category at the TOD catchment area = *number of floor level* × *foot print area*; Six land use characteristic are: a_1 = residential (houses, hotel, and apartment); a_2 = commercial (shops, traditional market, mall, and restaurant); a_3 = official (public and private office); a_4 = green space (park, river, and pier); a_5 = transportation facilities (roadway, railway, bus stop, and train station); a_6 = public service (school and worship facilities); A = total land use area in the TOD catchment area.

P_2 is determined by estimating the number of residents within TOD catchment area, utilizing ArcGIS calculation, using Eqn. (4). The original data for P_2 and P_3 are coming from Indonesian government as mentioned in Table 1. Population, along with workers density, are crucial factors in TOD (Calthorpe, 1993; Renne et al., 2005) due to their potential to generate the demand.

$$P_2 = \frac{1}{A_{Catchment}} \sum_{n=1}^{N}\left(r_n \frac{A_{cn}}{A_n}\right) \tag{4}$$

With

r_n= Populations in subdistrict n; A_{cn} = Area of subdistrict n within catchment area; A_n = Total area of subdistrict n. $A_{Catchment}$ = TOD catchment area. Since TOD catchment area in this research is an 800-m radius, $A_{Catchment} = \Pi \text{ x } (800\text{m})^2 = 2{,}010{,}619.3 \text{ m}^2 = 2.0106 \text{ km}^2$

P_3, representing the employment density within the TOD station catchment area. The estimation is performed using Eqn. (5)

$$P_3 = \frac{1}{A_{Catchment}} \sum_{n=1}^{N}\left(w_n \frac{A_{cn}}{A_n}\right) \tag{5}$$

With

w_n= Number of workers in subdistrict n; A_{cn} = Area of subdistrict n within catchment area; A_n = Total area of subdistrict n. $A_{Catchment}$ = TOD catchment area. Since TOD catchment area in this research is 800-m radius, $A_{Catchment} = \Pi \text{ x } (800\text{m})^2 = 2{,}010{,}619.3 \text{ m}^2 = 2.0106 \text{ km}^2$

P_4 employs ArcGIS analysis, leveraging government spatial data, to determine the number of intersections in the roadway network (Dou et al., 2021; Kamruzzaman et al., 2014a; Lyu et al., 2016; Vale et al., 2018b), including primary, secondary, tertiary, living, and residential streets, which are all considered accessible for cyclists and pedestrians. P_5 is derived from direct observation of roads with pedestrian pathways (Dou et al., 2021; Vale et al., 2018b). For undivided roads, sidewalks on both are counted once since they serve pedestrians in both directions. while divided roads with medians or barriers are counted for each side, as they function independently and restrict crossing between directions. PR_1 to PR_4 are identified using OSM data and validated through direct observation to accurately identify the locations of off-street P&R spaces, which are not captured by OSM. Since most P&R locations exhibit a high parking capacity index of ≥1 (Pramesinta & Hamdala, 2024; Yusfida and Syabr, 2015), data for the parking area is collected through actual measurements.

Data from Table 1 undergoes several processes to transform each variable into an index and plot the results on a graph. Each variable is normalized to a range 0–1 per station (Suarez-Alvarez et al., 2012) using Eqn. (6) (Dou et al., 2021; Lyu et al., 2016; Papa & Bertolini, 2015; Reusser et al., 2008; Singh et al., 2014):

$$x' = \frac{x - \text{Min}(x)}{(\text{Max}(x) - \text{Min}(x))} \tag{6}$$

x' represents the normalized value of variable x, Min(x) represents the minimum value of variable x, and Max (x) represents the maximum value of variable x.

This step is crucial to ensure all variables have equivalent rank (Vale et al., 2018a; Vale, 2015), thus simplifying index calculations. Once normalized, the index is defined as the average of the normalized values (Vale et al., 2018a; Zhang et al., 2019). To determine the relationship between variables, Pearson-correlation method is derived from Eqn. (7), with *xi* and *yi* represent variable values. A correlation coefficient of ±0.3 indicates a significant and strong relationship (Monajem & Ekram Nosratian, 2015).

$$\rho(X,Y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{7}$$

where: $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$; $\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n}$

This study constructs multiple regression models to investigate the causal relationships between P&R facilities, node and place indexes, and peak-time ridership. The base model is formulated as in Eqn. (8).

$$Peak - timeridership = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \cdots + \beta_n x_n + \varepsilon \tag{8}$$

With α represents the intercept, $\boldsymbol{\beta}_1, \cdots, \boldsymbol{\beta}_n$ denotes the coefficient of each independent variable $\boldsymbol{x}_1, \cdots, \boldsymbol{x}_n$ is the possible independent variables between P&R facilities, node, and/ or place indexes, and ε is the error term. TOD station typology is developed based on the performance results and transit ridership. A higher ridership level is expected to correlate with improved TOD performance (Huang et al., 2018), reflecting human mobility within TOD areas.

5. Result

5.1. Descriptive analysis

Based on data from 13 stations across all variables (Appendix B), in terms of transportation accessibility (N_1-N_5), hub stations exhibit the greatest frequency and variety of CL directions, underscoring their central role in the transit network. A substantial gap exists between stations, with differences in public transport frequency and lines averaging between 85 % and 97 %, respectively. However, the distance to the nearest station remains relatively consistent at approximately 116 m, suggesting uniform spatial accessibility.

Land use diversity (P_1) ranges from 0.6 to 0.8, indicating a balanced mix of uses. Both population and number of workers ($P_{2\text{-}3}$) show high standard deviation, indicating significant variability across the dataset. Notably, there are some stations that have similar counts of around 20,000 people/km^2, including KPB, SUD, BOO, and BKST. Pedestrian accessibility (P_4) is significantly greater in business districts due to concentrated activities, fostering a conducive environment for pedestrian movement. While intersection density (P_5) ranges from 3,639 to 16,379 per square meters, reflecting choice movement for the pedestrian. TOD station has P&R capacities of around 0 to 14,644 square meters, dominantly with informal and motorcycle parking.

As illustrated in Appendix C, our analysis reveals a positive and strong relationship among most variables, suggesting that as one factor improves, the others tend to enhance as well. Six variables have a crucial influence on transit ridership: number of CL lines (ρ = 0.645), daily frequency of CL services (ρ = 0.838), proximity of TOD stations to the street (ρ = 0.577), number of residents (ρ = 0.737), and number of workers (ρ = 0.739). These correlations highlight the importance of these factors in increasing transit ridership and optimizing the transit

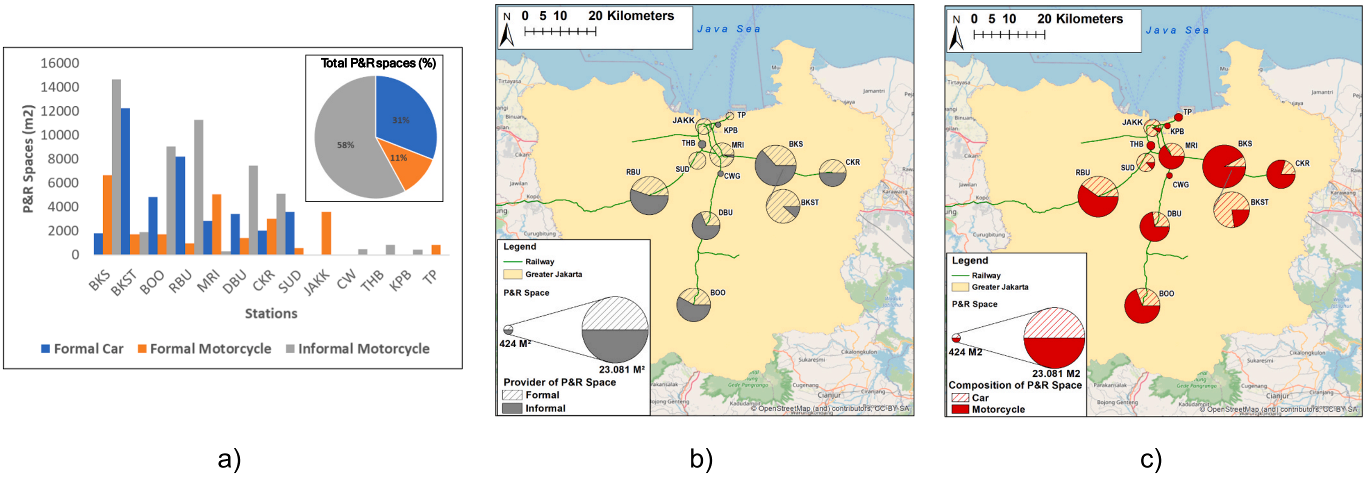


Fig. 5. P&R proportion: a) The Spaces; b) The Providers: Formal-Informal; c) The Modes: Car-Motorcycle.

system's effectiveness.

5.2. P&R characteristics

Compared to other studies that evaluate TOD performance by focusing only on formal car parking spaces (Vale et al., 2018a; Zhang & Lee, 2023), emphasizes the inclusion of informal and motorcycle parking, revealing significant differences in validity. Empirical data indicates that only 31 % of P&R spaces are designated for formal car parking, with no informal car spaces due to low demand (Mukhlis et al., 2019; Yusfida and Syabr, 2015). Incorporating data on motorcycle parking, including formal and informal, enhances the accuracy of P&R characteristics by nearly 70 %, as demonstrated in Fig. 5a). Informal motorcycle parking dominates the chart, indicating its significant role in the overall P&R system and highlighting gaps in formal infrastructure. Recognizing and quantifying this space is crucial for improving safety, organization, and service quality.

Fig. 5b) illustrates that informal P&R spaces are either larger or comparable to formal areas in suburban regions. For instance, BOO has a balanced mix of both while BKS and RBU exhibit substantial P&R capacities, with a larger informal share. Conversely, P&R spaces in city centres such as JAKK and MRI have more formal P&R spaces, indicating limited informal parking in residential areas and low users' demand. CW station, however, lacks formal P&R, relying entirely on residential area parking.

As illustrated in Fig. 5c), the majority of P&R spaces are dedicated to motorcycles, with high occupancy during office hours (Suryandari et al., 2015), reflecting the heavy reliance on motorcycles to reach TOD stations (Chandika et al., 2019). This highlights the critical role of motorcycles in the P&R system in GJ and the need to improve infrastructure to manage increasing demand.

5.3. P&R characteristics that influence the TOD performance and transit ridership

In order to delineate the characteristics of P&R and validate findings, a correlation analysis was conducted between P&R variables ($PR_{1\text{-}5}$) with transportation accessibility, land use activities, and peak-hour transit ridership. This study analyses the relationship between peak-hour commuter flows and P&R facility utilization at TOD stations by examining passenger volumes entering stations in the morning (6:00–8:00 AM) and exiting in the evening (5:00–7:00 PM).

Table 2
Regression Model Result.

Variable	VIF	Model 1		Model 2		Model 3		Model 4	
		Coefficient	p-value	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
Intercept		−0.110	0.698	−0.232	0.092	−0.412	0.117	−0.145	0.641
X_1	1.631	−0.313	0.257	–	–	0.098	0.688		–
X_2	1.447	0.263	0.306	–	–	–	–	0.235	0.396
X_3	2.605	0.671	0.049*	–	–	–	–	0.723	0.049*
X_4	1.223	0.164	0.478	–	–	−0.127	0.539		–
X_5	4.183	−0.984	0.132	0.002	0.996	0.966	0.067**	−0.552	0.351
X_6	2.405	1.288	0.043*	0.505	0.225	0.562	−0.525	0.978	0.099**
X_7	1.631	–	–	0.678	0.039*	–	–	–	–
X_8	1.447	–	–	–	–	0.476	0.070**	–	–
X_9	2.605	–	–	–	–		–	−0.044	0.918
R^2		0.820		0.753		0.767		0.741	
Adjusted R^2		0.639		0.671		0.600		0.555	
Significance F		0.044*		0.004*		0.035*		0.049*	
F Statistics		4.541		9.149		4.604		3.996	

Notes: Y= Peak-time ridership, X_1 = Capacity of formal car P&R, X_2 = Capacity of formal motorcycle P&R, X_3 = Capacity of informal motorcycle P&R, X_4 = The distance between P&R with a TOD station, X_5= Node index, X_6 = Place index, X_7 = P&R index, X_8 = The capacity of motorcycle P&R (the accumulation of X_2 & X_3), X_9 = Other P&R variables except the capacity of motorcycle P&R (the accumulation of X_1 & X_4).
*Significance at 95% confidence level, **Significance at 90% confidence level.

As presented in Appendix D, most P&R variables exhibit negative correlations with other variables, indicating that increases in these variables are associated with a decline in other TOD performance. A notable finding is the strong negative correlation between the number and capacity of P&R facilities with the accessibility of other transit modes except CL. This relationship is logical, as this increased demand for P&R options highlights their importance in facilitating access to transit systems where direct public transport alternatives are insufficient. The lack of correlation between population or worker density and the formal P&R availability suggests that P&R infrastructure provision at stations is not dependent on population density within 800 m from the station but beyond that area (Ginn, 2009). Importantly, there is a strong positive correlation between motorcycle P&R capacity and peak-hour ridership, indicating that motorcycle P&R facilities significantly boost ridership. Conversely, car parking capacity shows no correlation with peak-hour ridership, due to the lower popularity compared to motorcycles.

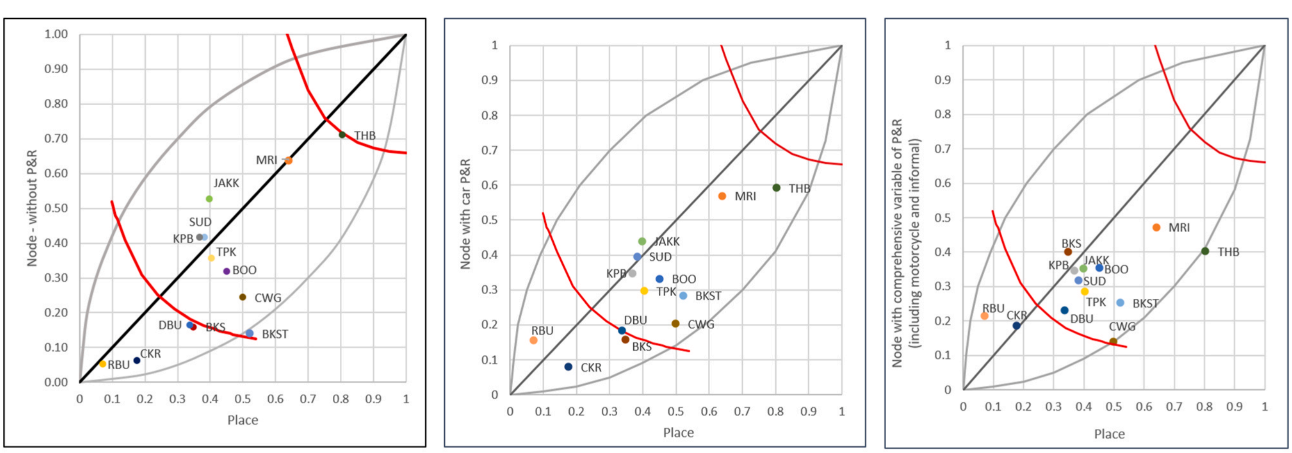
To investigate the causal relationships between P&R facilities and transit ridership, four regression models were developed (Table 2), using peak-time ridership as the dependent variable. Independent variables related to P&R facilities, node index, and place index were incorporated, with all input normalized. The decision to develop four separate regression models stems from the need to disentangle the individual and combined effects of P&R facilities, node, and place index on peak-time ridership (Olaru et al., 2019). This approach allows for a nuanced analysis of each factor's contribution and its potential interactions. Model 1 focuses on the direct impact of the disaggregate P&R characteristics alongside node and place indexes on ridership. This model enables a granular assessment of how each variable contributes independently within the broader urban transport. Model 2 adopts a composite index approach, in which P&R, node, and place are each presented by a single averaged index. This abstraction enables us to test an integrated Node–Place–P&R hypothesis, examining how these consolidated dimensions collectively explain ridership patterns. Model 3 introduces a composite index for motorcycle P&R (X_8) but still considers car P&R, reflecting regional travel behaviours while retaining node and place indexes in disaggregated form to explore potential synergistic effects. Model 4 reverses this focus by preserving the node and place indexes while disaggregating motorcycle P&R variables and aggregating other P&R features (e.g., car park capacity) into a composite index, thus isolating the influence of motorcycle access in particular. By employing multiple models, we are able to validate the robustness of our findings, avoid overfitting, and generate theoretically informed insights about the nuanced relationships among variables.

Each model is generally significant at the 95 % confidence level, with Significance-F below 0.05. Variance Inflation Factors (VIF) below 5 indicating no severe multicollinearity. Among the models, Model 1 explains the strongest explanatory power with the highest R^2 (0.82), indicating that 82 % of the variance in ridership is explained by the predictors. X_3 and X_6 have a statistically significant positive impact on ridership (low p-values), while other variables, though not individually significant, may contribute to the combination with other factors. Despite fewer predictors, Model 2 shows robustness with the highest adjusted R^2 and the strongest F-statistic. X_7 is the only significant predictor, playing a critical role in explaining ridership. Model 3 balances complexity and explanatory power ($R^2 = 0.767$ and adjusted $R^2 = 0.600$), with X_5 and X_8 emerging as significant predictors. Model 4 is the weakest, with the lowest R^2 and adjusted R^2 (0.741 and 0.555, respectively), showing reduced predictive capacity. Across all models, motorcycle P&R consistently shows a positive coefficient, suggesting that expanding these facilities increases transit ridership. Notably, informal motorcycle P&R (X_3) is the strongest predictor of ridership, while place index maintains a positive association, highlighting the importance of land use conditions in fostering transit ridership.

5.4. Node-Place Model

Fig. 6a), with the detail value at Appendix E, illustrates the node index without considering P&R facilities, showing a significant gap between city and suburban stations. All "Balance-dependency" stations are located in suburban areas, such as RBU, CKR, DBU, BOO, since the position of those stations is under the below-balance line, indicating low of activity demand and limited transportation facilities. However, BOO's classification is inaccurate, as it is one of the busiest stations in its province, with high ridership. While the "Ideal-balanced" category is mostly found in urban areas, including MRI, SUD, etc, with equal node and place index. These stations maintain smooth activity flow and offer sufficient space for facility improvements. In contrast, THB in the city is classified as "Balance-stress" and BKST in the suburbs as "Unsustained-place".

Incorporating P&R as a third index in a 3D node-place model reveals a surprising pattern: stations with high transportation accessibility and land-use performance, such as MRI and THB, are classified as unsustained category (Appendix F). This is counterintuitive given that these



a) b) c)

Fig. 6. Node-Place diagram: a) Node-without P&R; b) Node-with comprehensive variable of P&R; c) Node with car P&R-without motorcycle.

Table 3
The average value of the TOD performance Based on Four Typologies.

Typologies	Location	Transportation Accessibilities	Land-use activities	P&R	Daily ridership (passenger/day)	Peak-time Ridership (passenger/hr)
Urban 1	Urban	0.674	0.728	0.142	172,427	588
Urban 2		0.359	0.413	0.164	32,948	350
Suburban 1	Suburban	0.196	0.414	0.453	47,079	2,528
Suburban 2		0.058	0.123	0.377	20,390	951

a) b) c)

Fig. 7. TOD Performance based on the typology: a) Transportation Accessibility; b) Land use activities; c) P&R characteristics.

stations have high commuter activity and public transport usage. Therefore, P&R should not be treated as a standalone index since P&R performs well in peripheral areas but is less effective in urban centres, contradicting the assumption that the index should have a consistent impact across all TOD stations with similar typology. Moreover, the P&R variable is expected as a temporary measure, as improved feeder networks are expected to reduce private vehicle use. Based on these findings, incorporating P&R, through the comprehensive variables, into the node index calculation (Robillard et al., 2024; Zhang & Lee, 2023) indicates more accurate calculation, as presented in Fig. 6b).

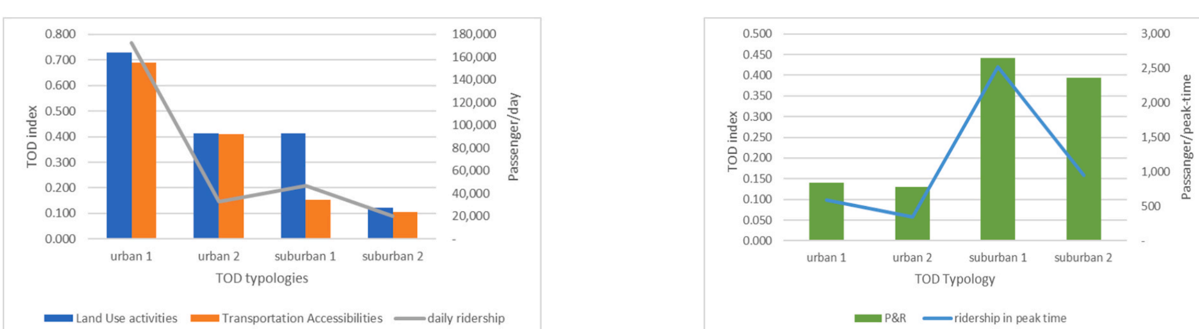
On average, incorporating comprehensive P&R variables including the capacity of formal car, formal, and informal motorcycle has more accurate node index by 35 %, compared to 18 % accuracy when only formal car P&R is included, as illustrated in Fig. 6c). It is indicated that including motorcycle and informal P&R significantly improves the performance calculation. P&R facilities enhance TOD performance in suburban more than in city areas, particularly for motorcycles and informal. This suggests a need for tailored P&R strategies in suburban areas while adjusting approaches in urban centres. However, RBU and CKR still dominate the “dependency” category in both models, as these peripheral stations have limited public transportation options.

6. Discussion

6.1. *TOD typology*

We classify TOD typologies based on TOD performance (Ma et al., 2022), considering transportation accessibility, land use activities, and P&R characteristics. This approach is validated by analysing station locations, daily ridership, and peak-time demand. The average characteristics of four typologies, Urban 1 (MRI and THB), Urban 2 (KPB, TP, THB, JAKK, SUD, and CWG), Sub-urban 1 (BKS, BKST, DBU, BOO) and Sub-Urban 2 (CKR and RBU), are outlined in Table 3.

The stations’ typologies reveal a clear gradation from highly integrated, heavily utilized urban stations to less connected and less utilized suburban ones (Fig. 7a). On average, Urban 1 demonstrates the highest level of transportation accessibility, with Urban 2 following behind. Suburban 1 and Suburban 2 exhibit lower scores of 0.196 and 0.058, respectively, reflecting fewer transit options and greater dependence on personal vehicles.



a) b)

Fig. 8. TOD Performance and the transit ridership based on typology.

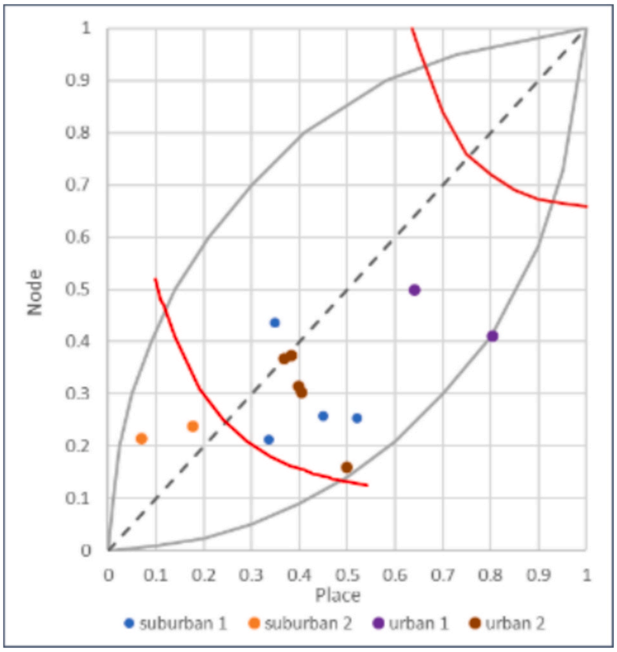


Fig. 9. Node-Place model according to stations typology.

Fig. 7b) shows a similar pattern for land use activity. Urban 1 leads with the highest score, supporting diverse activities and balanced transit demand. With lower score than Urban 1, Urban 2 and Suburban 1 have similar land use scores. In contrast, Suburban 2 has the lowest score, suggesting minimal land-use activity and reduced public transit demand.

Fig. 7c) reveals a differing pattern, with low P&R rates in Urban 1 and 2, and significantly higher rates in Suburban 1 and 2. This reliance on P&R in suburban, especially in Suburban 1, arises from residents driving motorcycles to transit stations for commutes 20–40 km (Chandika et al., 2019). Suburban TODs, aiming to capture a broader area, require larger P&R facilities to meet demand, whereas urban residents typically walk or use public transit due to better accessibility.

The typologies classification shows a clear relationship, where higher indices in both transportation accessibilities and land-use activities are associated with increased daily ridership, as in Fig. 8a). Urban 1, which has the highest indices for both, records the greatest daily ridership, followed by Urban 2 and Suburban 1, which have similar indices and daily ridership levels. Conversely, Fig. 8b) shows a relationship between P&R rates and peak-time ridership across various TOD typologies. Suburban 1 shows the highest P&R rates and peak-time ridership, indicating a reliance on P&R to manage commuter demand.

The combination of both indices is illustrated in the node-place diagrams as in Fig. 9, revealing that Urban 1 stations are in areas with the highest accessibility and land-use activity. Urban 2 and Suburban 1 have similar indices but differ in locations: Urban 2 in peripheral urban areas and Suburban 1 in developed suburban areas. Meanwhile, Suburban 2 stations are positioned in a 'dependent' zone with low indices, indicating a need for government intervention.

Typology's characteristics are summarized in Fig. 10 and illustrated in detail at Fig. 11. Urban 1 exhibits very high transportation accessibility, particularly within CL (the highest N_1 and N_2), alongside the highest population and workers. Moderate land-use diversity representing strong station demand. An extensive pedestrian network enhances sustainable transport, while limited P&R facilities show less reliability to private vehicles.

Urban 2, though located in CBD, serve fewer transit facilities than Urban 1. For instance, TP station has the lowest CL frequency and connectivity due to its port adjacency and terminus position. However, these stations provide the highest accessibility to BRT, MRT, LRT, and feeder buses. Pedestrian accessibility remains strong, reinforcing their role in sustainable urban transport.

Suburban 1 reflects dispersed land use activities like Urban 2, but faces greater public transit challenges, increasing reliance on private vehicles. This typology depends heavily on P&R facilities, particularly informal motorcycle parking, extending into surrounding areas.

Suburban 2 is the least integrated, serving peripheral suburban areas with the lowest accessibility scores. Sparse land-use activity, dominated by residential developments, limits station demand. Despite this, they maintain high P&R capacity, with substantial formal car and informal motorcycle parking, reflecting reliance on personal vehicles, albeit slightly less than Suburban 1.

6.2. *Challenges, strategies, and policy mechanisms across TOD typologies*

In addressing the unique challenges of various TOD typologies, an integrated approach combining land use, transportation, and P&R facilities is proposed (Appendix G).

Urban 1, located in Jakarta's CBD, experiences peak accessibility constraints within CL. Solutions include dynamic train scheduling, adjusting frequency and length during peak hours, and integrating transit modes through consolidated schedules. High-density land use should be reinforced with zoning policies that promote mixed-use, multi-level developments. While formal P&R facilities are limited, maintaining and prioritizing motorcycle parking is essential (Adi et al.,

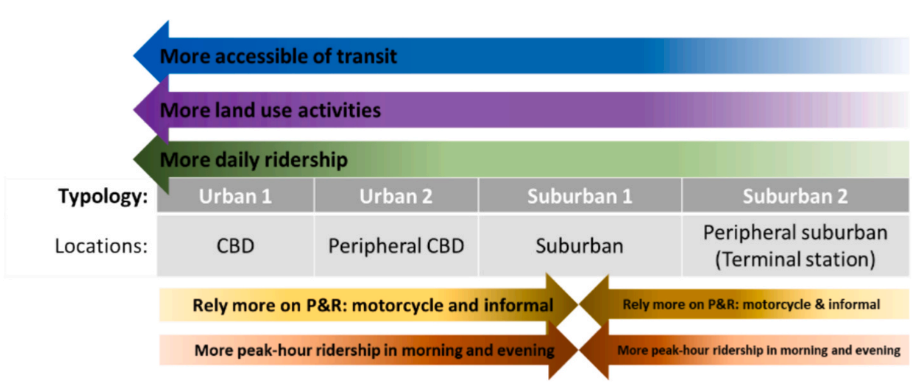


Fig. 10. Characteristics of TOD Typology.

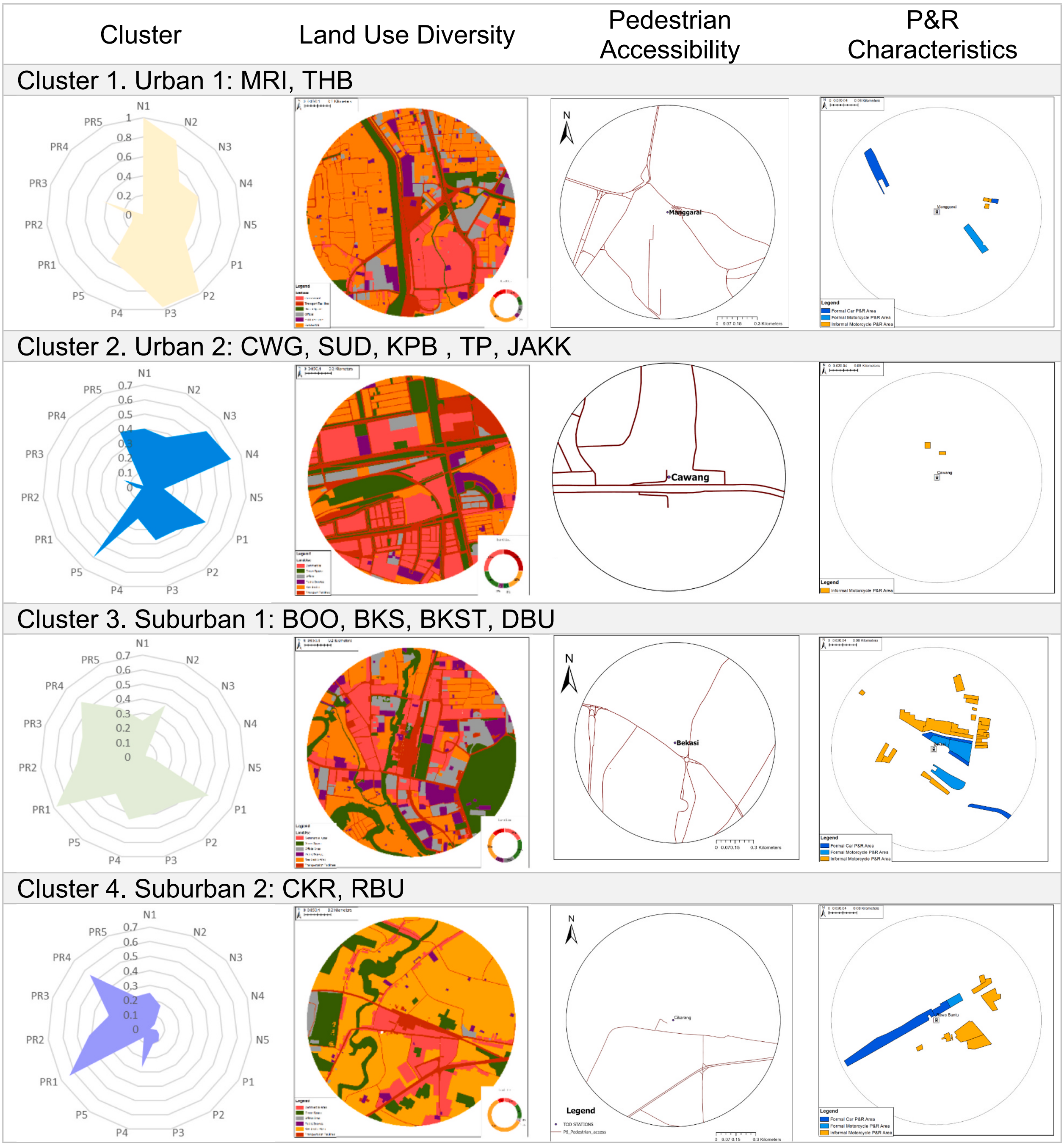


Fig. 11. The Features of The Typology.

2023).

Urban 2 faces accessibility challenges related to non-CL transit modes, necessitating CL integration with other transit, route consolidation, and synchronized schedules to enhance connectivity (Chen, 2019). With similar characteristics as urban 1 for the high pedestrian network, enhancing pedestrian pathways with tree shading can improve user convenience (Zhao et al., 2017). Enforcing regulations against street vendors and implementing traffic signage for 'No Parking' and 'No Stopping' zones can prevent misuse of these facilities and enhance walkability (Khairunnisa et al., 2022). Despite space constraints, formal P&R facilities should be introduced, with motorcycle prioritization to reduce space usage.

Suburban 1 suffers from moderate CL frequency and low transit accessibility, requires expanded CL routes and enhanced feeder services, guided by regulations mandating minimum service levels. For moderate-density land-use, a density gradation strategy can lead to TOD integration with surrounding neighbourhoods (Tong et al., 2018), alongside zoning policies for diverse land use (Dittmar & Ohland, 2004). The high prevalence of informal motorcycle P&R needs strict regulations management (Banister, 2008). For instance, standardized tariffs, one-gateway system, smart parking technologies, and incorporating sustainability features like electric vehicle charging (Handayeni et al., 2018).

Suburban 2 with low transportation accessibility and limited land-use activity requires feeder transport improvement and strategic land-use planning (Pengjun & Shengxiao, 2018) to integrate commercial and residential functions near TOD stations, thereby enhancing ridership. Given the high dependence on motorcycle P&R, optimizing its capacity, accessibility, and safety through strict regulations is crucial, especially for informal facilities.

7. Conclusion and future research

This study provides a comprehensive analysis of TOD performance in GJ, integrating transportation accessibility, land-use activities, and formal/informal P&R facilities. The application of Node-Place model reinforces the transport-land use feedback cycle (Wegener & Fuerst, 2004), providing a robust framework for assessing the balance and imbalance between urban transport and urban land-use. Incorporating comprehensive P&R variables into the node index calculation (Robillard et al., 2024; Zhang & Lee, 2023) yields a more accurate performance measure than treating P&R separately. The accuracy improves by 35 % when informal and motorcycle P&R are included, compared to only 18 % when considering formal car P&R alone. It shows the significance of motorcycle P&R and its crucial role in suburban areas, where P&R supports commuting to urban centres. A positive correlation and strong dependency exist between P&R, especially motorcycle parking, and peak-time ridership, while the correlation of formal car P&R and transit ridership is minimal, indicating limited influence of TOD performance.

Based on the node-place index result that is in line with the location and transit ridership, this research categorises TOD stations into four typologies: Urban 1, Urban 2, Suburban 1, and Suburban 2. Urban TODs exhibit higher transportation accessibility and land-use diversity, fostering sustainable commuting patterns, while suburban TODs rely heavily on P&R, particularly motorcycle parking, due to limited transit coverage for other than CL, such as feeder buses or BRT. The similar land-use characteristic of Urban 2 (peripheral urban zones) and Suburban 1 (developing suburban zones) suggests that similar land-use planning and management strategies can be effectively applied in both contexts.

These findings challenge TOD models, specifically in the Global South, urging policymakers to 1) Regulate and formalize informal P&R through ownership restructuring and management improvements; 2) Prioritize motorcycle parking in TOD design; 3) Establish minimum transit service frequency standards, particularly for feeder buses and BRT, and 4) Align land-use policies to station typologies, promoting denser mixed-use development in urban peripheries.

This study is limited to data collected within a single year from 13 stations. Although station selection followed government regulations and was constrained by data acquisition time, efforts were made to mitigate these limitations by ensuring data accuracy and consistency through rigorous validation with OSM and cross-referencing with official datasets. Future research could broaden the scope by including more stations to enhance data richness for regression analysis and TOD classification. Also, small sample size poses limitations for regression analysis, particularly when incorporating multiple explanatory variables. A low observation-to-variable ratio can increase the risk of overfitting, reduce statistical power, and limit the generalizability of findings. To address these concerns, a stepwise modelling strategy and composite indexes are employed to reduce dimensionality, as well as monitored multicollinearity through VIF diagnostics. Future research should aim to expand the sample size, either by including more stations across the region or by incorporating longitudinal data, to enhance the statistical endurance of regression modelling.

While this study provides insights into TOD performance in GJ, its applicability extends to other developing cities with similar reliance on motorcycles and informal solution to address transportation challenges. In GJ, where motorcycles account for 80 % of total mode share (CMMIAI & UNOPA, 2024), local residents near TOD stations create informal motorcycle P&R facilities that, while unregulated, provide essential service in the absence of sufficient formal infrastructure. Similar practices occur in Padang, where motorcycles represent 70 % of total mode share, and parking facilities are often poorly managed and often operated illegally (Yaldi et al., 2020). In Hanoi, motorcycle ownership grows 10–15 % annually, yet the city provides less than 15 % of the required parking space, triggering informal parking (Vu, 2017). In Delhi, with 7 % annual growth rate in motorcycle ownership, parking saturation for motorcycles are twice that of car (Parmar et al., 2020). The findings from this study could inform policies in other rapidly growing cities by emphasizing the need to formalize and integrate informal P&R systems into TOD strategies to improve connectivity on urban mobility. Furthermore, it is recommended to evaluate the role of regulatory frameworks and multimodal transit solutions in optimizing the synergy between P&R facilities and TOD stations in both urban and suburban contexts.

CRediT authorship contribution statement

Prima J. Romadhona: Writing – review & editing. **Ronghui Liu:** Writing – review & editing, Validation, Supervision, Methodology. **Chandra Balijepalli:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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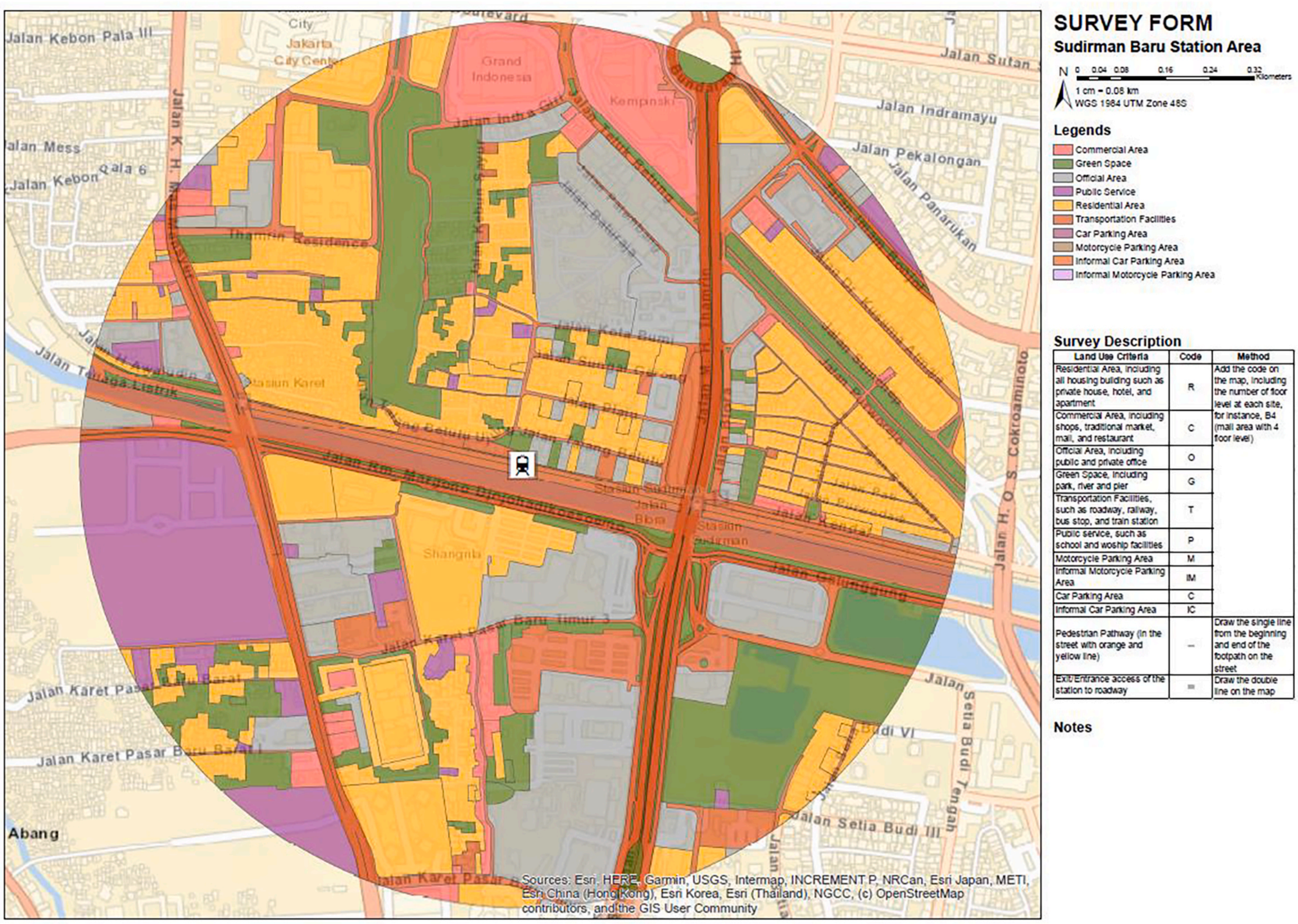
Appendix A. Survey form



Appendix B. . Descriptive Statistics

Variables	Unit	Minimum	Maximum	Mean	Std. Deviation
N_1	–	1.00	2.00	1.31	0.48
N_2	Train departure/day	86.00	646.00	319.92	147.21
N_3	–	1.00	22.00	12	5.38
N_4	vehicles departure/day	21.00	3,831.00	1,313.46	1,437.55
N_5	meter	11.91	280.00	115.96	84.78
P_1	–	0.59	0.82	0.69	0.08
P_2	people/ m^2	13,531.00	50,531.00	29,416.08	11,214.03
P_3	people/ m^2	10,554.00	39,473.00	22,997.85	8,730.87
P_4	number/m^2	555.00	2,081.00	1,097.77	457.42
P_5	meters	3,639.04	16,379.69	9,024.91	3,729.61
PR_1	m^2	0.00	12,223.21	2,984.89	3,689.38
PR_2	m^2	0.00	6,648.52	1,953.67	2,069.61
PR_3	m^2	0.00	14,644.18	3,950.36	5,048.41
PR_4	m	2.00	248	49.96	82.76
Daily ridership	Number of passenger/day	9,580.84	190,597.10	57,430.62	55,135.32
Ridership in peak time	Number of passenger/peak-hour	75.74	3,412.24	1,155.72	1,177.27

Appendix C. . Correlation analysis of transportation Accessibility, land-use activity, and daily ridership

	N_1	N_2	N_3	N_4	N_5	P_1	P_2	P_3	P_4	P_5	Daily Ridership
N_1	1.000										
N_2	0.479	1.000									
N_3	0.295	0.123	1.000								
N_4	0.254	0.006	0.902	1.000							
N_5	0.232	0.481	-0.018	0.060	1.000						
P_1	-0.001	0.067	0.077	0.277	0.181	1.000					
P_2	0.502	0.614	0.261	0.295	0.400	0.025	1.000				
P_3	0.511	0.619	0.268	0.299	0.396	0.022	1.000	1.000			
P_4	0.203	0.206	-0.095	-0.053	-0.077	-0.429	0.629	0.627	1.000		
P_5	0.332	0.323	0.816	0.638	0.075	0.223	0.140	0.150	-0.205	1.000	
Daily Ridership	0.645	0.838	0.210	0.167	0.577	0.184	0.737	0.739	0.199	0.310	1.000

Appendix D. . The correlation of P&R characteristic with TOD performance and transit ridership

	N1	*N2*	*N3*	*N4*	*N5*	*P1*	*P2*	*P3*	*P4*	*P5*	*PR1*	*PR2*	*PR3*	*PR4*
PR1	-0.215	-0.306	-0.497	-0.565	-0.127	-0.456	-0.085	-0.088	0.415	-0.396	1.000			
PR2	0.204	0.283	-0.426	-0.468	0.395	0.222	-0.159	-0.161	-0.157	0.001	-0.002	1.000		
PR3	-0.386	-0.177	-0.681	-0.671	-0.282	0.092	-0.515	-0.521	-0.167	-0.487	0.304	0.429	1.000	
PR4	0.117	-0.421	-0.041	0.066	-0.169	0.395	-0.358	-0.357	-0.577	-0.084	-0.219	0.009	0.127	1.000
Ridership in peak time	-0.300	0.082	-0.527	-0.543	-0.122	0.383	-0.173	-0.179	-0.176	-0.193	0.085	0.484	0.757	0.136

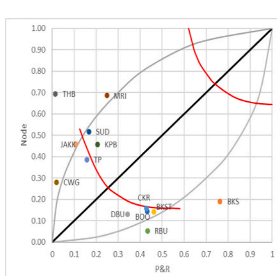
Notes: darker green means more positive correlation and darker red means more negative correlation

Notes: darker green means more positive correlation and darker red means more negative correlation

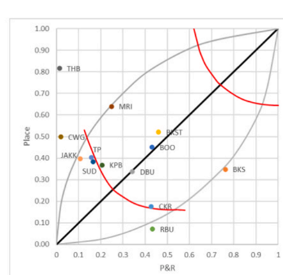
Appendix E. . Node and place index with original Node, node with comprehensive variable P&R, and node with car P&R

	BOO	MRI	CKR	BKS	CWG	DBU	THB	SUD	RBU	KPB	TP	BKST	JAKK
Place	0.450	0.640	0.176	0.348	0.498	0.337	0.803	0.382	0.071	0.368	0.404	0.521	0.398
Node	0,320	0.637	0.063	0.160	0.244	0.165	0.711	0.417	0.053	0.418	0.357	0.141	0.528
Node (including comprehensive P&R variables)	0.355	0.472	0.472	0.401	0.139	0.232	0.403	0.317	0.214	0.347	0.285	0.253	0.353
Node (including only car P&R)	0.33	0.57	0.57	0.16	0.20	0.18	0.59	0.40	0.16	0.35	0.30	0.28	0.44

Appendix F. . The scatter plot of node VS P&R (a) and place VS P&R (b).



a)



b)

Appendix G. . Challenges, strategies, and policy mechanisms across TOD typologies.

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No	TOD Typology	Challenges	Strategies	Policy Mechanism
1	Urban 1	Peak CL accessibility	Dynamic scheduling with integrated routing with other public transport	Formulate a consolidated transit schedule and route
		High land use density	Develop multi-level, mixed-use buildings	Enforce zoning policies
		Limited Formal P&R	Improve P&R signage and regulations	Regulate limited P&R capacity, prioritizing motorcycles
2	Urban 2	Peak accessibility for non-CL modes	Implement integrated scheduling and routes between CL and other transit modes	Formulate a consolidated transit schedule
		Moderate land use density	Create density gradation of land use with dedicated pedestrian network and tree-shade pathway.	Enforce zoning for mixed-use, multi-level development and prohibit street vendors from pedestrian pathways
		Limited Formal P&R	Improve P&R signage and regulations	Regulate limited P&R capacity, prioritizing motorcycles
3	Suburban 1	Moderate CL frequency and low accessibility of other transit modes	Expand CL routes/frequencies and enhance other public transport options.	Establish minimum frequency standards for CL and other modes based on demand
		Moderate land use density	Diversify land use and enhance pedestrian networks	Ensure land-use planning management that prioritize multi land use types near TOD stations
		High informal motorcycle P&R	Apply the strict regulation related to informal P&R and enhance P&R connectivity with station	Enforce strict regulations for informal P&R, including standardized tariffs and safety measures
4	Suburban 2	Low transit accessibility	Increase transit frequency and options	Develop minimum route and frequency standards based on demand and land use
		Low land use activity	Promote mixed-use development aligned with suburban context	Ensure affordable housing near TOD stations to attract diverse populations
		High informal motorcycle P&R	Apply the strict regulation related to informal P&R and enhance P&R connectivity with station	Enforce strict regulations for informal P&R, including standardized tariffs and safety measures

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