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REVIEW ARTICLE

An Overview of TOD Level Assessment Around Rail Transit Stations

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Abstract By integrating land use and transportation systems, transit-oriented development (TOD) focuses on transit and land development, development potential, and the balance between transportation and land use. The TOD level assessment not only helps optimize existing TODs but also guides TOD planning. Based on previous literature, methods for assessing TOD around rail transit stations can be roughly divided into three categories: TOD index, the node-place model, and the data envelopment analysis (DEA) model. The TOD index aggregates indicators from different dimensions into a single value for evaluation. The node-place model emphasizes transportation, land use, and the balance between them, as well as expansion factors. And the DEA model is suitable for situations without input indicator weights or consideration of different units of measurement. TOD indicators are the basis of the evaluation, and in both the TOD index and node-place models, indicator weights are mostly determined by using subjective methods. Furthermore, a limited number of studies to date have pre-evaluated the implementation of TOD at rail stations under construction or in planning. This paper aims to assess the level of TOD areas at the rail transit station level, which can help in constructing the evaluation index system, selecting TOD stations, and optimizing them.

1 Introduction

First proposed by the American scholar Peter Calthorpe in the 1990s, transit-oriented development (TOD) has attracted a great number of researchers and practitioners in related fields, such as urban planning and urban rail transit development. They are dedicated to optimizing city structures and alleviating urban congestion and other problems through this mode. Although the TOD mode originated in the United States, it has been highly regarded and adopted in various countries around the world, including Japan, Singapore, China, and other countries. Moreover, cities in many countries are planning new TODs and hoping to achieve new urban development by making full use of land around rail stations. The TOD model has gained prominence in recent years and has become an important direction for urban development and transportation development [1].

TOD creates lively, sustainable, pedestrian-friendly and cycling-friendly communities by integrating land use and transportation systems [2]. TOD encourages public transportation usage and eco-friendly travel. The implementation of TOD programs can bring numerous economic, social, and environmental benefits, such as promoting economic growth, increasing the proportion of public transport trips, reducing traffic congestion, increasing employment, and reducing energy consumption and pollution emissions. [3, 4].

Despite its enormous benefits, TOD has not always yielded the expected outcomes in cities that have tried to implement it in Asia, Western Europe, and North America [3]. Furthermore, not all sites are suitable for TOD implementation. Therefore, the TOD level needs to be evaluated

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to determine the degree of its development and optimization, or to identify sites with potential for development.

The evaluation of TOD focuses on three distinct analytical layers: the city, the transit line, and the station. At the city level, TOD focuses on the integrated development of both the city and the line network. On the transit line level, it stresses the interaction among different stations along the line. At the station level, it considers the coordinated development of the station and its surrounding area, as well as the interaction of the various functions within the station. This paper mainly concentrates on evaluating TOD at the rail transit station level.

This paper provides a summary of the literature on the evaluation of TOD levels at rail transit stations. The remainder of the paper is organized as follows: First, the definition of TOD and the selected catchment areas for TOD studies are presented. Next, three widely used methods for TOD assessment are introduced. We summarize the weighting, aggregation, and clustering methods used in different studies. We also propose an adaptation analysis of the three methods. Finally, the conclusion section includes recommendations and methods for assessing TOD.

2 TOD Assessment Basis

2.1 TOD Concept

The concept of TOD was introduced by Calthorpe in his book *The Next American Metropolis*. He defines TOD as a community with a walking radius of approximately 2000 feet, centered around a transit stop and main business center. Residences, shops, office buildings, open spaces, and other public facilities are integrated into a walkable environment [5]. The idea of TOD is influenced by the garden city and linear city movements. Both the garden city and TOD are designed around a center. The garden city's core encompasses health, administrative, and cultural sites, with radial roads. In contrast, TOD is constructed around a transit station, emphasizing the significance of transportation infrastructure [6]. In the linear city, communities are arranged along public transportation corridors to form a linear structure. TOD is a continuation of community planning centered around transit stations [6]. TOD programs generally represent high-intensity integrated development around the transit node, but not all such development constitutes TOD. Transit adjacent development (TAD) involves property development near transit stations, but lacks the integration of transportation functions in land use and site design [6]. TOD emphasizes the promotion of public transportation as the leading idea and effectively combines public transportation infrastructure with urban functions to guide the orderly growth of urban space.

2.2 Station Catchment

In evaluating the TOD level at a rail transit station, delineation of the station catchment area is crucial. The station catchment is typically limited to walking distance. In fact, there are no fixed criteria to determine a specific value for walking distance, and various site-specific distances have been used [7], as shown in Table 1. The catchment area threshold typically falls within the range of 400–800 m [8–13]. Some researchers have investigated both the 400- and 800-m ranges [14, 15], while others have more often used areas of 500- and 700-m for study [16–25]. Vale et al.

Table 1 An overview of the station catchment for TOD

Station catchment	Area	References
800 m	Depok; Addis Ababa, Ethiopia; Perth; Jakarta; Arnhem and Nijmegen; Shenzhen	[8–13]
400 m and 800 m	Montréal; Azambuja	[14, 15]
500 m	Dhaka in Bangladesh; Lisbon; Chengdu; Singapore; Beijing; Seoul	[16–21]
700 m	Tokyo; Lisbon; Switzerland; Tehran	[22–25]
600 m	Shanghai	[26]
1000 m	Tokyo; Tehran and Qazvin	[27, 28]
1000 m and 1500 m	Beijing	[29]
1500 m	Tokyo Metropolis and Kanagawa; Beijing	[30–32]
300 m	Seoul	[33, 34]
15-min walk	Shanghai	[4]
960 m (12-min walk)	London	[35]
800 m and 10-min walk	Toronto	[36]
5-min and 10-min walk	Portland	[37]

[17] conducted a face-to-face passenger survey at stations using the average passenger walking distance as the station catchment. Ma et al. [18] employed the shortest straight-line distance from each station entrance. Other studies have adopted study areas of 600, 1000, and 1500 m [26–32]. Guo et al. [30] identified a 1500-m station catchment area using the boundary method through a national passenger trip survey. In the case of Seoul transit stations, two studies set the research area at 300 m [33, 34]. Another group of researchers divided TOD areas based on walking time: Li et al. considered 15 min [4], Zhang et al. focused on 12 min (960 m) [35], Higgins and Kanaroglou used 800 m and 10 min [36], and Schlossberg and Brown used 5 and 10 min [37]. TOD catchment areas are determined by various factors, including the compactness of different cities, the average walking time of commuters, and the time and distance commuters are willing to walk, among other factors.

2.3 TOD Assessment Method

According to Galelo et al., we need to calculate what can be calculated, measure what can be measured, and transform the unmeasurable into the measurable [38]. Effective evaluation is essential for TOD planning and optimization. The primary methods for assessing TOD can be categorized into three groups: the TOD index, node-place model, and data envelopment analysis (DEA). Although genetic algorithms [39] and cellular automata [40] have also been used, they are rarely studied and will not be discussed in detail here. The flowchart of the development process for the assessment of TOD levels at rail stations is shown in Fig. 1.

3 TOD Index

TOD-ness is a principle to gauge the extent to which a site aligns with TOD concepts. The use of the "TOD index" is essential to quantify the degree of TOD-ness in a region [29]. Singh et al. emphasized the importance of measuring

Fig. 1 Flowchart of the development process for assessing TOD levels at rail stations
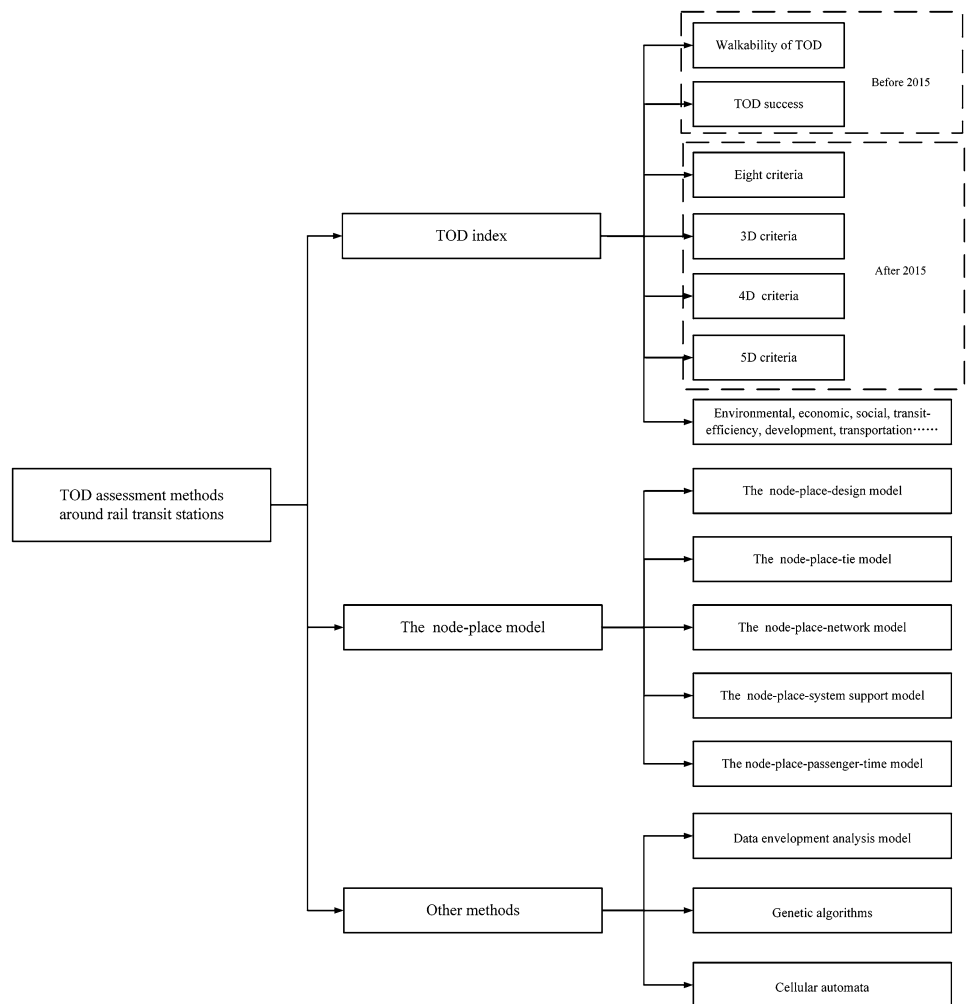
various indicators associated with TOD and combined them into a single index. This index assists in making effective planning decisions [41]. An indicator usually represents a variable or a group of variables that capture a specific aspect or characteristic [42]. Currently, representative variables related to TOD are mainly selected from transportation, population, and land aspects. These variables are employed to evaluate TOD projects and determine their development status and trends.

3.1 TOD Indicators

Schlossberg and Brown [37] evaluated walkability indicators at 11 rail stations in Portland, Oregon, USA. This study, relatively early in measuring TOD-ness, focused solely on walkability. They used the number of accessible paths and impedance paths, pedestrian catchment area (PCA) and impedance pedestrian catchment area (IPCA) ranking, intersection, and dead-end density.

Scholars have also explored methods for determining the success of TOD. Renne [10] suggested measuring density, ridership, and property appreciation indicators to evaluate the success of TOD projects. The Institute for Transportation and Development Policy (ITDP) [43] quantified TOD by proposing eight principles based on urban mobility principles. Other researchers [44] have selected 20 indicators from the eight principles of ITDP (walking, cycling, connectivity, transit, mixing, density, compactness, and shift) to assess the level of TOD around tram stations.

The 3D criteria for TOD, including density, diversity, and design, were proposed by Cervero and Kockelman [45]. On this basis, the 5D criteria were proposed, including density, diversity, design, destination accessibility, and distance to transit [46]. The criteria and indicators for evaluating TOD basically evolve around the 3Ds and 5Ds, and then indicators such as economic development, traffic flow, and parking space are added. Zhou et al. [47] applied the 3Ds to measure station TOD-ness. Density indicators are measured using population and employment density, and density gradient. Diversity indicators include retail density at ground level, land use mix, and bus lines. The design indicators are road network density and the number of parking facilities. Taki et al. [11] selected density, diversity, and economy as evaluation criteria and indicators. Density criteria encompass various infrastructure densities, including school and hospital densities, as well as housing mix, parking area mix, and open space mix. Diversity indicators are calculated based on entropy. Economic indicators include population density, floor area ratio (FAR), and building coverage ratio (BCR). Uddin et al. [16, 48] chose density, diversity, destination accessibility, and design as criteria for establishing the indicator system on two occasions. The distinction between the two studies lies in the allocation of walkable and cyclable lengths and intersection density, incorporated within the destination accessibility criteria initially and subsequently within the design criteria. The remaining indicators are population, business, and job density to convey the density criteria. Land use diversity is quantified using the entropy index. Destination accessibility indicators encompass land use mixedness. Design indicators are parking utilization and open spaces.

The 5D index of the built environment variable has been measured by various researchers [9, 14, 19, 28]. The selected indicators for each facet of the 5Ds display significant variations, as illustrated in Table 2. When examining density, population density is generally used,

Table 2 Selected statistics of indicators based on the 5D principles

Density	Diversity	Design	Distance to transit	Destination accessibility	References
Population density Commercial density	Land use mix	Parking utilization Open space	Pedestrian path Intersection density	Land use mixedness	[9]
Transit captive user density Labor density Population density Building density	Land use mix	Green space Pedestrian network connection Compactness	Station service area	Easy access to transit networks and station areas	[14]
Development intensity	Land use mix	Street connectivity Walkability Cyclability Open space	Bus stop accessibility	Regional destination accessibility	[19]
Total population and net population density Gross residential density Net housing density Compactness	Land use mix Mixedness Car parking area Local destinations	Street pattern Percentage of built-up area land Average residential land area Number of blocks Average block area Street network density Connected node ratio Permeable network ratio		Ped-Shed, Transit accessibility IPCA	[28]

along with other indicators, such as commercial density or building density [9, 14, 28]. However, Niu et al. [19] only used development intensity as a density indicator. The diversity criteria are all based on entropy measures [9, 14, 19]. Notably, Abdi and Soltani [28] added three indicators—mix, parking, and local destinations—and merged the design and destination accessibility indicators. Regarding design indicators, open/green space indicators are used more frequently, and indicators such as walkability, cyclability, connectivity, and built-up area land percentage are also considered [9, 14, 19, 28]. Distance-to-transit criteria include pedestrian path and intersection density [9], station service area [14], and bus stop accessibility [19]. Destination accessibility criteria comprise land use mixedness [9], easy access to transit networks and station areas [14], regional destination accessibility [19], Ped-Shed, transit accessibility, and IPCA [28].

Singh et al.'s [41] extensively cited research constructs a synthetic index of TOD indicators using eight rules, through which cities and transportation jointly influence the TOD-ness of an area. The eight criteria focus on the following considerations: an important factor for the TOD development is urban density; the diversity of land use is determinative for the vitality of the nodes; designing spaces in areas that are walkable and bikeable is a necessity in TOD; economic development is directly related to TOD development; more passengers means higher TOD-ness; transit systems need to be user-friendly; a node that provides high accessibility and high-frequency transit service will increase the opportunity to create TOD; and convenient parking for bicycles and cars will increase the proportion of public transport trips.

Based on the eight rules, Singh et al. [41] determined eight measurement criteria: urban density, diversity of land use, walkability and cyclability, economic factors, transit capacity utilization, transit system user-friendliness, accessibility, and parking. The urban density criteria encompass population and commercial density. Land use diversity is calculated using the entropy method. Walkability and cyclability criteria include land use type mix, the length of walkable/cyclable paths, crossing density, and IPCA. Economic development criteria include business establishment density, municipal tax revenue, and employment levels. Transit capacity utilization criteria are peak and off-peak ridership. The user-friendliness of the transit system encompasses passenger safety, basic facilities, and the presence of an information display system. Accessibility criteria include transit service frequency, transfers between different lines of the same transit mode, transfers to other transit systems, and opportunities within a walkable distance. Parking criteria are parking utilization for cars and for cycles. Based on these eight rules, a set of 17 indicators was established [8]. The indicators largely resemble those proposed by Singh et al., but the pedestrian-friendliness criteria, cyclability and walkability criteria, and economic development criteria are different. The pedestrian-friendliness criteria include the number of accessible paths, intersection density, and IPCA. The economic development indicator is the number of business establishments. Lukman [12] identified 25 indicators, and only eight criteria and 18 indicators were ultimately selected.

The above outlines the more frequently used indicator categories. The following is a classification of indicators used by other researchers. Ke et al. [27] grouped the indicators into environmental, economic, social, and transit-efficiency categories. Environmental indicators encompass factors such as energy consumption, pollutant emissions, green infrastructure, and accessibility of the park. Economic indicators include BCR, FAR, land use diversity, concourse, and commercial facilities density. Social indicators include density of disabled facilities, density of police boxes, and passenger safety. Transit efficiency indicators include parking areas for cars and bicycles, railway lines, IPCA, station connectivity, and integration with other transit modes. Zhang et al. [29] classified the TOD indicators based on the network-activity-human framework. Indicators for the network category include public transit service frequency, density of transit nodes, various lane-type density, and bicycle parking density. In the activity category, indicators encompass different economic clusters (e.g., commerce, restaurant, education) density, land use mix, land value, and return on investment. The human category indicators are mainly focused on population, environment, and social and recreational consumption. It is worth mentioning that this method is adaptable to diverse sizes and any situation. Wey et al. [49] considered sustainability and developed three dimensions of evaluation criteria: economic, environmental, and social. The economic efficiency criteria include population density, business and retail facilities density, and design of pedestrian spaces with upward expansion of traffic volume. The environmental sustainability criteria are the environmental loading capacity of high-density development, externality due to land use mix, and open space. The social equity criteria involve the ability of building area incentives to dampen house prices, and equal residence and safety. Zhou et al. [13] defined the following indicators for the assessment: metro accessibility, intermediate stations, network directedness, time and distance to the central business district (CBD), all destination intensity, Simpson index, walkability, cyclability, and number of bus and metro stations. Zheng et al. [20] constructed a comprehensive three-level, five-dimensional index system. The primary indicators are land use, transportation, socioeconomic, environment, and social perception. The land use components are density, land mix, and community vitality. The travel indicators module encompasses active transit (walking and cycling), rail transit, and motor-related indicators. Economic indicators are housing and commercial ones. Environmental indicators focus on noise and air. Social indicators

are subjective public perceptions of satisfaction. Qiang et al. [50] evaluated transportation, accessibility, and development. Transportation criteria focus on the number of subway lines, service frequency, accessibility, and connectivity with buses and parking. Pedestrian accessibility considers pedestrian network density and accessibility, intersection density, etc. The development aspect considers point of interest (POI) density, FAR, population and employment density, and functional mix.

3.2 Weighting and Aggregation

Determining the weights of the indicators and aggregating them are an important part of the study. The indicator weights represent the significance of each dimension relative to the whole, and the aggregations represent the ability of each dimension to be substituted and integrated [42]. Indicators encompass both spatial factors, such as density and land use, and nonspatial factors such as passenger volume and frequency of transit services. Therefore, they are generally calculated based on ArcGIS. Since each indicator has a different scale and scale unit, it may affect the results of the data analysis and cannot be calculated directly. All indicators need to be standardized to realize the comparability among them. Once standardized, indicators can be weighted and aggregated. Singh et al. [41] used geographic information system (GIS)-based multiple criteria analysis (MCA) for calculation. Teklemariam and Shen [9] and Uddin et al. [16] adopted spatial multi-criteria analysis. The weighting methods involve manually ranking the indicators, aggregating them using Borda counting, and converting the final rankings into weights using the rank-sum method [14, 41]. Lukman [12] conducted a multi-criteria evaluation (MCE) of all criteria and indicators in the Integrated Land and Water Information System (ILWIS) and performed a sensitivity analysis. Zhang et al. [29] and Taki et al. [11] employed the hierarchical analysis method to ascertain indicator weights based on different measurement organizations. Galelo et al. [15] applied fuzzy hierarchical analysis, with the membership function using trigonometric functions. Wey et al. [49] and Huang and Wey [51] used the fuzzy Delphi method to select indicators based on the importance assigned by the expert panel to each indicator. The weights of the selected indicators are calculated using fuzzy network analysis (FANP). Rabiei et al. [14] utilized the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method to determine the weights and evaluate the objectives. Uddin et al. [48] presented an objective-weighted spatial multi-criteria analysis using the CRITIC (CRiteria Importance Through Inter-criteria Correlation) assignment method. In some studies, indicators are given equal weight [50]. Most studies use subjective weights, and fewer studies use objective weights.
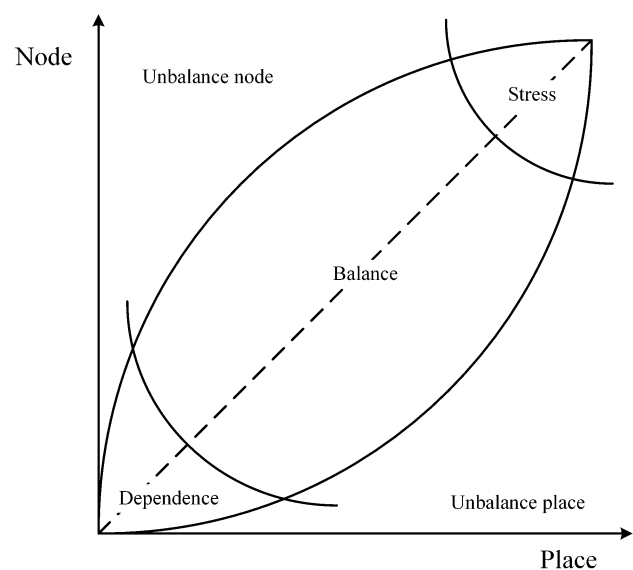
4 The Node-Place Model

4.1 TOD Indicators

The node-place (NP) model was proposed by Bertolini [52] to quantitatively assess the node value and place value of a station area. The model comprehensively evaluates the level of development and coordination between nodes and places. The author emphasized the significance of the integration and differentiation of nodes and places in the redevelopment of sites and their surroundings. In Fig. 2, the *y*-axis represents the node value, indicating the accessibility level of the site catchment. Higher values signify enhanced accessibility and more convenient transportation in the area. The *x*-axis represents the place value, which indicates the intensity of land use development and functional mixing within the catchment. Higher values indicate a greater variety of available functional sites and dynamic land development.

The relationship between nodes and places is categorized into five types. The area around the central diagonal line represents the equilibrium zone, further divided into three subtypes: dependence at the lower end, equilibrium in the middle, and stress at the upper end. The transportation and land use values of the equilibrium zone are approximately equal. The area above the central diagonal line is the unbalanced node type, indicating that the land use development of the site lags behind the accessibility of the node. The area below the central diagonal line is the unbalanced place type, indicating its place value is relatively better than the node value in the imbalance situation.

Based on Bertolini's study, numerous researchers have further investigated the node-place model. Within the node

Fig. 2 The node-place model by Bertolini

aspect, they consider other public transport and bicycle accessibility [22, 23, 53], and parking [23, 53]. Some studies consider betweenness and closeness, the presence of shared bicycles [53], and accessibility to CBD [22]. Regarding the place index dimension, the majority of research takes into account the number of inhabitants, the number of employees in different economic clusters (e.g., hospital, distribution, education, culture) within the catchment area, and the functional mix [22, 23, 53]. Some studies consider the pedestrian shed ratio [23, 53]. Vale [23] calculated the pedestrian shed ratio for each node-place, highlighting the morphological correlation between transit and land use. Additionally, Lyu et al. [31] defined this relationship as the orienting characteristic of the station. The node and place indicators are similar to those discussed earlier. The orienting indicators include the average distance from stations to different destinations, footpath length, crossing density, average block size, and walk score. Liao and Scheuer [54] developed three dimensions: transit, development, and connection. They introduced demand-related factors to obtain demand indicators and morphological indicators, exploring the alignment between demand and morphology of the sites.

Based on the classical node-place model, several studies have introduced a third dimension: design [17, 35, 55]. The node index includes the number of service directions and service frequency of public transport, accessibility of stations within 20 min, distance to the nearest highway entrance, and parking. The place index consists of the number of residents, the number of employees in each field, the functional mix, and the number and type of POIs. Meanwhile, the design dimension involves pedestrian shed ratio, crossing density, and accessibility network length. Zhang et al. [55] incorporated the city's 2035 Plan into their design criteria, placing greater emphasis on the topological connectivity of the pedestrian network.

Introducing a third dimension, connectivity, has also been undertaken by various scholars [4, 14, 56]. The node dimension focuses on the station transportation attributes, the place dimension concentrates on land use, and the connectivity dimension focuses on the link between transportation and land use. In the node dimension, Li et al. [4] considered carrying capacity, service capacity, and station connectivity. In the place dimension, diversity and land use combination indicators were selected. Land use diversity indicators include various types of sites within 15-min walking distance of the station. In the connectivity dimension, indicators such as accessibility to different kinds of places including workplaces, medical facilities, and bus stations, and walkability were selected. Rabiei et al. [14] used a node-place model in the first phase encompassing accessibility to public transport, private vehicles, and active transportation. The place indicators included passenger flow, travel origins,

and destinations. The tie indicators included pedestrian safety, walkability, cycling-friendliness, and pedestrian network connectivity. Tang et al. [56] presented a node-place-connection model. Node indicators include the number of station entrances and exits, frequency and direction of trips, station accessibility, and bicycle parking. Place indicators are vitality, area of various land use types, and land use diversity. Connectivity indicators centered on bus, cycling, and walking connectivity.

Ma et al. [18] introduced a new assessment dimension, system support, which quantitatively describes the relationship between stations and urban systems. The node index is defined as two components: transfer capacity and station design. The place index is subdivided into building density, functional integration level, and population scale. The system support index is composed of network centrality and core parcels. Dou et al. [26] developed a node-place-network model with a network dimension indicating the importance of stations in a metro network. The network indicators are categorized into two main aspects—degree centrality and betweenness centrality—which are calculated based on the passenger movement network rather than the infrastructure network. The node indicators primarily include rail accessibility and access to other transportation modes. The place indicators are composed of density, diversity, and design. Amini Pishro et al. [57] proposed a node-place-passenger-time model. The node values include the number of station facilities, station accessibility, destination accessibility, and network centrality. The place values are indicators in terms of design, density, and diversity. Ridership is divided into inbound and outbound ridership, while time is segmented into peak, off-peak, weekday, and weekend. The combination of ridership and time results in eight distinct scenarios. The model provides a more refined assessment of station balance.

4.2 Weighting and Clustering Methods

After calculating the individual indicators, the majority of node-place models also determine indicator weights, which are aggregated into a node index, a place index, an extended indicator index, and a composite index. Li et al. [4] applied hierarchical analysis to calculate the weights, and Zhang et al. [35] used principal component analysis, which reflects the contribution of each indicator and minimizes inter-indicator covariance. Ma et al. [18] combined indicators from different dimensions using the information entropy weighting method. The entropy method is used to calculate the relative importance of indicators [26]. Many researchers have set equal weights for indicators and summed them [23, 35, 53, 54]. Tang et al. [56] used the entropy weight-fuzzy comprehensive evaluation method, combining both subjective and objective factors for evaluation. Following the weighted calculation to

obtain the node, place, expansion dimension, and integrated index, the node-place model also conducts cluster analysis. Li et al. [4] used a self-organizing map (SOM) to classify TOD types, while most studies have adopted the K-means clustering method [17, 35, 54]. Dou et al. [26] utilized a modified version of K-means clustering, as K-means++ clustering. Lyu et al. [31] employed hierarchical clustering. Higgins and Kanaroglou [36] used latent class clustering with a probabilistic method for clustering. The advantages of latent class clustering include the generation of statistics that serve as a foundation for correcting the number of clusters, and the ability to accommodate non-standardized and continuous variables. In addition, some studies have used a two-stage clustering approach. The first stage determines the number of clusters by hierarchical clustering, and the second stage uses K-means clustering [49, 58].

5 Data Envelopment Analysis Model

DEA is a nonparametric tool with several inputs and outputs. It is not influenced by different units of measurement in the indicators and does not require weights for input and output indicators. It excludes many subjective factors, making it widely used for evaluation [59]. Ding et al. [60] used rail transit indicators as input and land use indicators as output. The rail transit indicators include average transfer time, average travel time to the station, transit station capacity utilization, segmentation of bus trips, vehicle kilometers traveled per capita, and trip distance per capita. The land use indicators are population density, jobs-housing ratio, FAR, ratio of non-motor lane area, and ratio of nonresidential area. The input variables for TOD planning factors include population, land use, and network centrality, while the output variables consist of bus, metro, and bike-share transit ridership [33]. Similarly, Guo et al. [30] adopted public transport ridership as an output variable, and density, diversity, and design indicators as input variables. One of the diversity indicators focuses on a rare indicator, high-building area. Tamakloe and Hong [34] employed network centrality indicators and pedestrian traffic as inputs and ridership as an output. Lee et al. [21] designed a two-stage approach. In the first phase, transit design is evaluated using socioeconomic and transportation facilities factors. In the second phase, transit efficiency is assessed by transportation facilities and transit trips. The weighted sum of the two phases is the overall TOD efficiency. Socioeconomic factors such as population density, land price, and the number of residential and commercial units serve as input variables. Transportation facilities, the number of metro and bus lines, the number of bus stations, and transfer distance of different public transport modes are intermediate variables. Transit trip factors including metro trips, bus trips, interchange ridership, and energy consumption are output variables.

6 Adaptation Analysis

To explore the adaptability of each method, the literature is summarized based on country type, city type, station type, assessment stage, and method, and the results are shown in Table 3. The current studies mainly focus on large cities in both developed and developing countries, with a high percentage of Chinese cities. The assessment methods used for different categories are enumerated and illustrated in Fig. 3. Developing countries usually use the TOD index and the node-place model for evaluation. Developed countries more frequently use the TOD index, and existing DEA study cases primarily focus on Seoul. The TOD index and node-place model are flat in large cities, and the DEA model is less frequently applied. Medium-sized cities basically adopt the TOD index assessment method. Among different station types, tram and light rail stations have received limited attention, resulting in analysis being conducted only on subway and light rail stations. The node-place model is more frequently used for metro stations, and the TOD index method is also commonly used. Commuter rail stations basically use the TOD index method. Post-evaluation cases slightly outnumber pre-evaluation cases. The TOD index is used more often in pre-evaluation and a similar proportion of the three methods in post-evaluation. In addition, by analyzing the application of the methods under the cross-cutting attributes in Table 3, we find that in the TOD level assessment of metro stations, the node-place model is more commonly used for pre-evaluation in large cities of developed countries, and both models are favorable for post-evaluation. In developing countries, the node-place model is commonly used for the pre-evaluation in medium-sized cities. In post-evaluation, the application of the first two evaluation methods remains consistent. In the TOD assessment of commuter rail stations, the TOD index method is usually used for post-evaluation in large cities of developed countries and for pre-evaluation in developing countries. The node-place model is commonly applied for post-evaluation in developing countries.

7 Conclusion

The focus of this study was to review the research methods for evaluating existing or potential TOD and solving various transportation and urban planning challenges. The scope of TOD research, namely the determination of the catchment area, is limited between 300 and 1500 m. Some studies directly select range circles such as 500, 800, and 1000 m, and others adjust the scope based on passenger survey results or urban density. For different city cases, suitable TOD catchment areas can be established according to the specific urban construction and the travel behavior of residents.

Table 3 Summary of literature characteristics for assessing TOD levels around stations

| Domain	Country		City		Station				Evaluation phase		Method		
TOD study case used in the reviewed studies	LDC	DC	BC	MC	MS	TS	LS	RS	PrE	PoE	TOD index	The node-place model	DEA
Abdi and Soltani [28]	√		√		√				√		√		
Chorus and Bertolini [22]		√	√					√		√		√	
Dou et al. [26]	√		√		√				√			√	
De Córdova et al. [44]	√			√		√			√		√		
Guo et al. [30]		√	√					√	√	√			√
Ke et al. [27]		√	√		√					√	√		
Lukman [12]		√		√				√	√		√		
Lyu et al. [31]	√		√		√				√			√	
Lee et al. [21]		√	√		√					√			√
Li et al. [4]	√		√		√					√		√	
Liao and Scheuer [54]	√		√		√					√		√	
Ma et al. [18]	√		√		√				√			√	
Niu et al. [19]		√	√					√	√		√		
Qiang et al. [50]	√		√		√					√	√		
Rabiei et al. [14]		√		√	√					√	√	√	
Singh et al. [41]		√		√				√	√		√		
Sulistyaningrum and Sumabrata [8]		√		√				√	√		√		
Taki et al. [11]	√		√					√		√	√		
Tamakloe and Hong [34]		√	√		√					√			√
Teklemariam and Shen [9]	√			√			√		√		√		
Tamakloe et al. [33]		√	√		√					√			√
Tang et al. [56]	√		√		√					√		√	
Uddin et al. [16]	√			√	√				√		√		
Uddin et al. [48]	√			√				√	√		√		
Vale et al. [17]		√		√	√				√			√	
Wey et al. [49]	√		√				√		√		√		
Zhou et al. [47]	√		√		√					√	√		
Zhang et al. [35]		√	√		√					√		√	
Zhou et al. [13]	√		√		√					√	√		
Zheng et al. [20]	√		√		√					√	√		
Zhang et al. [55]	√		√		√					√		√	

Abbreviations: LDC: developing country; DC: developed country; BC: big city; MC: medium-sized city; MS: metro station; TS: tram station; LS: Light rail transit station; CS: commuter rail station; PrE: pre-evaluation; PoE: post-evaluation

Many methods and techniques have been adopted to evaluate the level of TOD. This paper reviews the three most widely used methods: the TOD index, the node-place model, and the DEA model. The TOD index proposes indicators from various dimensions, including transportation efficiency, land use, and development potential, ultimately providing a comprehensive assessment of TOD levels. On the other hand, the node-place model aims to evaluate both transportation and land use, as well as the synergy and balance between these two aspects. However, the index weights of the TOD index and the node-place model are mainly determined through expert scoring, which can be highly subjective. The DEA model does not need manual weight assignment and avoids many subjective factors. However, the efficient and objective weights it generates might not match the actual situation.

Different evaluation methods have their own focuses and characteristics. Thus, for the TOD assessment at the station level of urban rail transit, the choice of a specific assessment method should be tailored to each case. If the decision-maker is more concerned about the overall level of each station's composite index, the TOD index is recommended. If the

Fig. 3 Percentage of assessment methods under different classifications
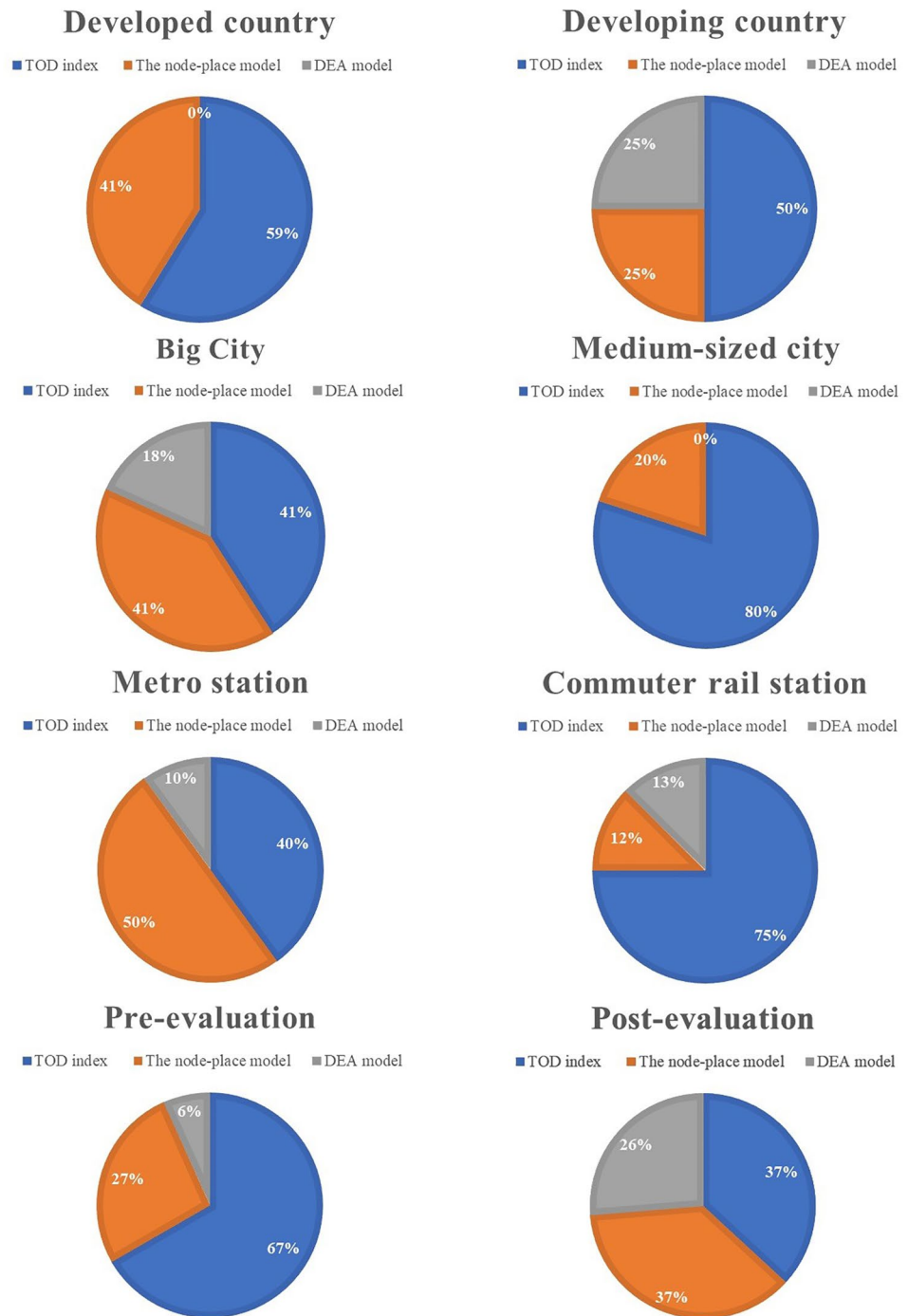
decision-maker is more interested in examining the coordination between the station and the surrounding development, the node-place model is suggested. If the decision-maker does not want to process the data in multiple steps and prefers the weights to be data-driven, the DEA model can be used. Furthermore, within each method, it is possible to conduct horizontal comparisons among different indicators to discern the aspects where a station excels and those where improvement is needed. Regarding the selection of indicators, many

studies have provided good examples. We can choose some broader indicators, such as population, transportation, economy, and land use, and then add more detailed considerations such as happiness experience and safety. The choice of assessment methodology can also be based on available statistical data, taking into account the specific country, city, and station, as well as the stage and purpose of the assessment.

Therefore, combining subjective and objective weights for evaluation indicators, integrating multiple assessment

indicators, and conducting pre-evaluations for the implementation of TOD at sites under construction or planned rail stations may represent future directions for improvement. Meanwhile, considering that some indicators vary over the long term, it could be considered in subsequent research to categorize indicators into two types, namely dynamic indicators and fixed indicators.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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