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Research Article

Efficiency Assessment of Transit-Oriented Development by Data Envelopment Analysis: Case Study on the Den-en Toshi Line in Japan

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Transit-Oriented Development (TOD) is an urban planning approach that encourages a modal shift from private to public transportation. This shift can generate additional benefits from a sustainability perspective. This study aims to assess the efficiency of TOD by applying the data envelopment analysis (DEA) method. The ridership of public transportation is considered as the direct output characteristic of TOD efficiency, and nine indicators of ridership are selected as inputs on the basis of the core concepts of TOD. These concepts include density, diversity, and design (3Ds). The Tokyu Den-en Toshi Line in Japan is presented as a typical case of TOD because this line includes TOD and non-TOD stations. Assessing and comparing the results of all railway stations reveal that almost all indicator values of non-TOD stations are higher than those of TOD stations. The results suggest that TOD planning and programs are inefficient in terms of ridership generation. This implication, however, may be attributed to the inadequacy of the selected indicators for TOD assessment. The results obtained after adding operation year as input indicators and removing transfer station show that TOD stations perform efficiently and in accordance with expectations. This response indicates that the inclusion of influential factors is necessary for equitable TOD assessment. Therefore, other influential factors must be considered when evaluating the efficiency of TOD-based stations with different inherent attributes. In addition, the design input with the largest impact on all inefficient units was identified, suggesting that management of bus service and railway system should be well enhanced.

1. Introduction

Transportation infrastructure is one of the most important components of urban development. The efficient development and implementation of a transportation infrastructure plan are necessary to solve traffic congestion, greenhouse gas emissions, and other environmental consequences that accompany rapid urbanization and motorization [1]. From the perspective of sustainable and integrated urban development, the imbalance between land use and transportation systems is the most critical factor that affects the efficiency of transportation infrastructure. Transit-Oriented Development (TOD) strategy has been proposed as an efficient approach to solve this imbalance [2, 3].

TOD aims to encourage the use of public transportation [4] by increasing population density and mixed land use in areas surrounding transportation hubs and by promoting connectivity between stations and trip origins/destinations. Although the formal term of TOD was not introduced until 1993 [5], its underlying principle has been applied and implemented as a solution to urban growth challenges since the late 19th and early 20th centuries, mainly in the United States and Europe [6]. Later, in 1997, the density, diversity, and design (3D) framework of TOD was proposed and explained [7]. In several American cities, the 3D-based TOD plan has increased the ridership and modal shares of public transport and has decreased vehicle mileage by 3%–5% [8, 9]. Accordingly, the TOD concept has been applied with an emphasis on the 3D framework in urban and transport planning worldwide. However, its efficiency in practical applications may sometimes not meet expectations [10]. The low utilization of public transport cannot achieve the sustainable cycle of land–people–transport [11]. In other words, whether or not the TOD strategy can play its due role in urban planning and management is inconclusive. Therefore, evaluating the efficiency of TOD is a necessary challenge faced by urban administrators and policy makers who aim to successfully implement, enhance, and improve TOD.

To respond to such a demand, this study selects the appropriate indicators that reflect the 3D concept of TOD in practice. This study assesses the efficiency of a railway system that was developed on the basis of the 3D framework of TOD. Furthermore, it provides advice to improve the factors that most significantly influence the efficiency of TOD. In this study, data envelopment analysis (DEA), which was first proposed by Charnes et al. in 1978, is applied [12, 13]. Since its introduction, DEA has been widely used to measure the relative efficiency of various organizations, referred to as decision-making units (DMU), with multiple inputs and outputs [14–17]. DEA can identify the input with the largest impact on an inefficient unit. Such input can provide guidelines to policy makers. One line of the Japanese railway system is presented as a case study. In Japan, the integration of the transport system and land use has been practiced since the 1910s. This practice is consistent with the concept of TOD. After more than a century, the country has recognized advancements in railway operation and management. The efficiency evaluation of TOD cases in Japan can provide essential guidance or experiences for future transport and urban planning in other countries, especially in developing countries experiencing rapid urbanization.

2. Literature Review

The integration of transportation and land use dates back to the post-World War II era, when planners in Europe, most notably in Stockholm [18] and Copenhagen [19], led suburban development into satellite areas along transit corridors. Since the 1990s, a series of new concepts and approaches, such as the Smart Growth concept [20, 21] and New Urbanism approach [22], for the integration of transportation and land use have emerged to combat uncontrolled urban sprawl [6]. TOD is also gaining popularity as an approach to promote smart growth and sustainable development in the metropolitan areas of many developed and developing countries [23–26] where mass transit systems have been implemented to relieve traffic congestion.

A common definition or criterion remains to be established for TOD despite the substantial body of research that has discussed the concept. For example, Cervero et al. stressed the contributions of the 3Ds to the TOD concept; furthermore, they explained the 3D concept as density in the form of residence and jobs, diversity in the form of mixed land-use development, and design in the form of good street connectivity for pedestrians [25]. Other scholars interpreted TOD by borrowing words from its original explanation and providing new empirical additions. The various definitions for TOD generally state that TOD should promote compact and highly mixed-use development around transit hubs and should include accessible and walkable neighborhoods [18, 19].

Existing studies have demonstrated that TOD provides numerous advantages, such as facilitating polycentric cities and regions, mitigating urban sprawl, boosting public transport ridership, increasing bike usage and walkability, accommodating economic growth, and creating sustainable neighborhoods [6]. The most important function of TOD is to reduce traffic congestion and increase public transit use in areas experiencing accelerated urban development [25, 27, 28]. TOD has attracted increasing attention as a solution to the challenges of urban growth given its widely recognized benefits. TOD implementation, however, is not always successful. Thus, several studies have evaluated the efficiency of TOD (e.g., [9, 21]). Most existing research applied single and several indicators to measure the outcomes or benefits that TOD provides in terms of travel behavior, economics, and environment [28, 29]. Ridership is one of most representative indicators of TOD outcome [25]. Renne and Wells monitored the success of TOD through a survey that included and summarized the various indicators of the influences and the most useful indicators of TOD [3]. However, this study quantified TOD in the form of a single indicator and provided a limited explanation for the ridership efficiency of TOD. In addition, it lost meaningful information for the aspects that contribute to the success or failure of TOD. The multi-indicator evaluation method involves weight setting for each indicator. However, weight setting in existing studies is often empirical or less objective and could provide biased results.

In the past decade, DEA has been widely used to measure the efficiency of different models of transportation system operations or management [30]. The most significant advantage of DEA over traditional weight-based methods is that DEA does not require weight parameters to measure efficiency. Researchers have employed DEA to address two main research topics. One topic is the analysis and comparison of the efficiency of firms, networks, or nations in the field of economics and management science [31–33]. Only a small part of related works has focused on the evaluation of the operational performance and management of railways [30]. The other topic is the selection of the optimal solution for actual operations in vehicle dispatching and route planning [34, 35]. Up to now, DEA has not been applied in the assessment of transportation strategy, at least in terms of TOD.

2.1. DEA. As mentioned above, DEA identifies the frontier (envelopment surface), which is determined directly from data, and quantifies the relative efficiency of a set of comparable DMUs with several inputs and outputs. It solves a linear programming model to detect the efficient inputs and outputs that form the frontier and the inefficient inputs and outputs that form nonfrontier units. In addition to providing the efficiency level, DEA can identify the sources of inefficiency and the projection path to the frontier. The projection path to the envelope surface is determined by whether the model

Table 1: Indicators for DEA method.

		Indicators	Unit	Explanation
Density	x_1	Population density	Person/km^2	Population per square kilometer
	x_2	Land-use diversity	-	Shannon–Wiener Index
Diversity	x_3	Functional land area	km^2	Total residential, commercial, official, public service land area per catchment
	x_4	High-building area	km^2	Area with high buildings (over 4 floors) per catchment
	x_5	Bus stops	-	Bus stops per unit catchment area
	x_6	Daily bus operation length	km	Bus operation length per day in each catchment
Design	x_7	Bus routes	-	Number of routes to and from railway station
	x_8	Road length	km	Road length per catchment
	x_9	Number of station exits	-	Number of exits per railway station
	y	Ridership	Person	Average daily commuters per station

is output-oriented or input-oriented, the choice of which depends on the production process that characterizes the units (i.e., the process minimizes the use of inputs to produce a given output level or maximizes output level given an input level). A large output (i.e., ridership) is preferred in the evaluation of TOD efficiency given several certain inputs. Therefore, output-oriented DEA was selected in this study.

The CCR model, which was first proposed by Charnes et al. in 1978, is the basic DEA model. It functions under the assumption of constant returns to scale and reflects the fact that outputs change proportionally with inputs [12]. Assume that n DMUs ($j = 1, \ldots, n$), m inputs x_{ij} ($i = 1, \ldots, m$), and s outputs y_{rj} ($r = 1, \ldots, s$) exist for each DMU$_j$. The output-oriented CCR model can be formulated as follows:

$$\begin{aligned} \max \quad & \theta + \varepsilon \left(\sum_{i=1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+ \right) \\ \text{s.t.} \quad & \sum_{j=1}^{n} \lambda_j x_{ij} + s_i^- = x_{i0} \\ & \sum_{j=1}^{n} \lambda_j y_{rj} - s_i^+ = \theta y_{r0} \\ & s_i^-, s_r^+ \geq 0 \\ & \lambda_j \geq 0, \end{aligned} \tag{1}$$

where θ is the efficiency score limited to less than 1, ε is the non-Archimedean infinitesimal, and x_{i0} and y_{r0} refer to the input and output of one certain unit DMU$_0$. s_i^- and s_r^+ are the input and output slack, which refers to the excess input or missing output that exists after the proportional change in the input or the output has reached the efficiency frontier. λ_j is the weight given to the DMU$_j$ to achieve its optimal performance. It is calculated automatically during the model-solving process.

The improvement target (projection) of each inefficient unit is the result of respective slack values added to proportional reduction amounts (formula (2) and (3) for the output-oriented DEA model). The improvement target provides alternative ways to improve the performance of each inefficient unit. The difference between x_{i0} and x'_{i0}, y_{r0} and y'_{r0} should receive focus when changing the input and output.

$$x'_{i0} = x_{i0} - s_i^- \tag{2}$$

$$y'_{r0} = \theta y_{r0} + s_r^+. \tag{3}$$

2.2. Indicator Selection. As the output variable, ridership (y) is the number of passengers who ride a public transport system and directly reflects the efficiency of transportation policy and urban planning, such as TOD strategy. Populations living around transport hubs provide the trip demand and have the potential to use the transportation infrastructure; mixed land use in the catchment area helps generate trips by providing different services; and convenient design encourages high numbers of people to use public transportation. All of these effects promote modal shift and increase ridership. Therefore, from the core concept of TOD, that is, density, diversity, and design, nine indicators were selected as the input variables of ridership output (Table 1).

First, density is defined as the number of buildings or population per area. Here, population density (x_1) in a catchment, that is, population per unit area, is the primary indicator that directly determines trip demand and economic activity. The residential population tends to generate the boarding ridership, whereas the commercial and office population is related to the alighting ridership via commercial or employment attractiveness.

Second, diversity is reflected by land use and primarily represents the level of mixed land-use development. This indicator is obtained through the Shannon–Wiener index, which is widely applied to calculate species diversity in the field of ecology. It has been successfully applied in land-use research to estimate the number of land-use types and evenness [16]. Given that residential land, commercial land, official land, and public service land are the primary types of urban functional land areas, the functional land area will affect ridership by providing for the different needs or demands of passengers and other interested people. Furthermore, areas with high buildings (over 4 floors) surrounding transportation hubs affect trip demand generation and represent the basic characteristic of regional development level. Therefore, land-use diversity (x_2), functional land-use area

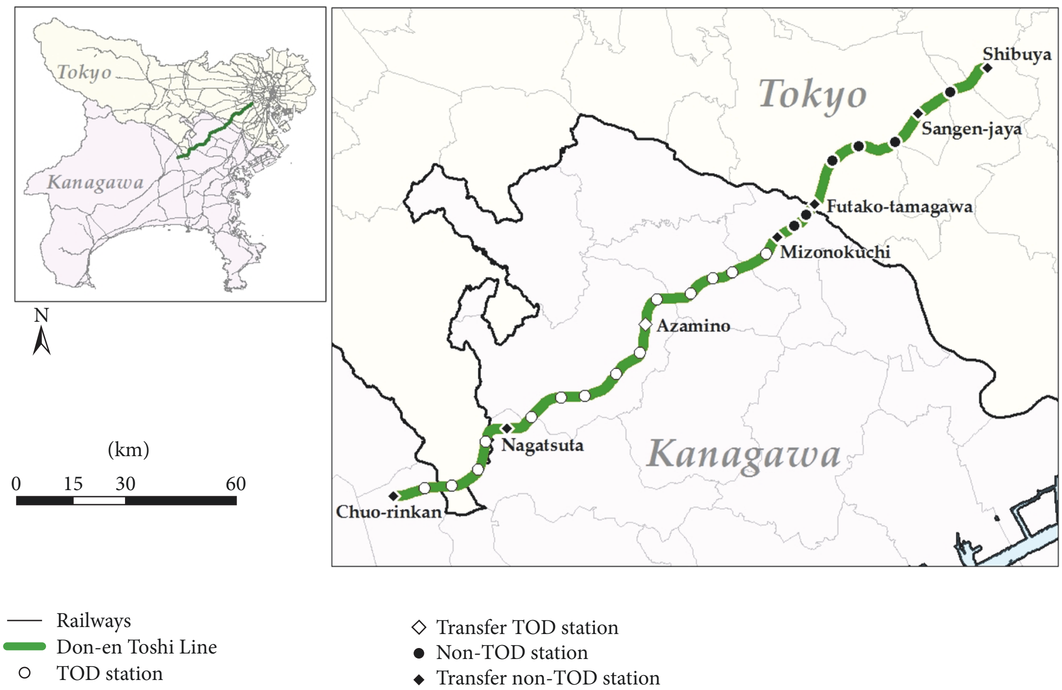

Figure 1: Tokyu Den-en Toshi Line.

(x_3), and high-building area (x_4) were selected as the three indicators of diversity input.

Third, design schemes can influence travel demand by increasing the accessibility of destinations by foot or by other public transportation systems [6]. It contains different implications from the micro to macro level, including the presence of shade trees and overhead lighting, design of on-site stores and services, and connections between work sites and worker residences. In this study, the design points to a basic transit infrastructure around rail stations that shortens the distance or time required to reach a destination. A highly advanced design would have the potential to facilitate public transit use and walking, as well as promote efficient energy use. Therefore, the number of bus stops (x_5), daily bus operation length (x_6), and bus routes (x_7) were selected to represent the connectivity between the rail station and passenger destinations. Connectivity eventually affects ridership choice and mode split. With respect to the total road length (x_8), we hypothesized that long roads in a certain area would increase road density and facilitate passenger access to railway stations. Finally, the number of railway station exits (x_9) also provides passengers with convenient access to aboveground roads or buses and underground stores or supermarkets.

3. Case Study

3.1. Tokyu Den-en Toshi Line. Japan's urban transportation system is famous for its excellent accessibility, efficiency, and punctuality. These characteristics resulted from advanced and reasonable transportation/urban planning. Moreover, in Japan, cities are commonly planned on the basis of TOD because the country has centered its land and city development along railroad construction for more than a century. *Ensenkaihatsu* (or "railway corridor development") was proposed by as early as 1910 and has a longer history than TOD. This urban development concept focused on residential district development along railways.

The Tokyu Den-en Toshi (DT) Line is a major commuter line that connects Shibuya in Tokyo and the Chuo-Rinkanin terminal in the neighboring Kanagawa Prefecture (Figure 1). The earliest interval, which is known as the Mizonokuchi Line, was opened in 1927 and connects the Futako-Tamagawa and Mizonokuchi Stations. In the mid-20th century, economic activity and employment rapidly concentrated in the central area of Tokyo, thus drastically increasing land and real estate prices and promoting ex-urban settlement. In response to this situation, the Japanese government adopted a new TOD plan. The DT Line was born at the right moment, and Tama New Town was subsequently developed. In 1966, the DT Line began operating from the Mizonokuchi Station to the Nagatsuta Station. An expansion was built as an access route to Tama Garden City [36]. The DT Line, which spans Shibuya Station to Futako-Tamagawa Station, was completed in 1977. In 1984, the line was extended from Nagatsuta Station to Chuo-Rinkan Station. Stations between the Mizonokuchi and Chuo-Rinkan Stations, except for Nagatsuta Station (Figure 1), were developed on the basis of TOD. To enable comparison in this study, the earlier/older stations are identified as non-TODs (12 stations), and the latter/newer stations are considered as TODs (15 stations).

The DT Line was selected as a case study in this work for two reasons. First, the DT Line and the Tama New Town that it traverses provide examples of transportation and land-use integration that are intended to stimulate population concentration and ridership growth. Second, this line has a relatively long history and was constructed under previous and new urban development policies (i.e., some of its stations were originally built with the birth of the line, whereas others are relatively new and were constructed through the TOD project). Therefore, earlier and later/newer stations can be compared to identify the factors that affect ridership.

3.2. Catchment Definition and Data Collection. Station catchment areas, which influence indicator values, need to be determined. In the transportation research field, the catchment area where local residents potentially use the railway is identified through (1) placing a buffer circle around a station (e.g., buffers with a radius of 400, 800, or 1200 m to define walkability to the public transportation facility) [37]; (2) network analysis [38] based on path networks, wherein a catchment area can be an area with a fixed walking or driving distance or travel time; (3) the boundary method, which is based on geo-code trip survey data (in this method, however, only 90% of the trip data are used within the study to remove the outliers) [39]; and (4) statistical modeling based on spatial theory, such as location and allocation method [40]. Among these methods, the boundary method is the most objective method that does not require intensive expert experience.

In this study, the Japanese Nationwide Person Trip Survey was used to identify station catchments through the boundary method. This survey is the most fundamental transportation questionnaire survey and is conducted every 10 years by the Ministry of Land, Infrastructure, Transport, and Tourism to investigate the actual travel behaviors of people in certain regions in Japan. In the Tokyo Metropolitan Area, approximately 730,000 individual questionnaires are collected. Survey items include individual trips, personal attributes, and travel behaviors. The origin collected for the survey was recorded by a small zone geo-code, and the survey results showed the station choices in each zone.

An origin–destination matrix from the zones of passenger residence (origin) to rail stations (destination) was constructed in accordance with the survey results and is shown in the flow map in Figure 2(a). Then, zones that generated few demands were removed on the basis of the rule that a catchment area should cover at least 90% of the ridership around the station (Figure 2(b)). A single catchment area nearly covers the buffer area with a 1,500 m radius around the railway. Given that individuals from the same small zone may select different rail stations, the catchment areas of two or more adjacent rail stations may overlap. Overlapped zones were divided into different stations by the number of station choices and distances to different stations (Figure 2(c)). Finally, the catchment area for each rail station was identified. Following the identification of catchment boundaries, all data for selected indicators (e.g., bus stop data, as an example shown in Figure 2(d)) were collected from the website of the Official Statistics of Japan and National Land Numerical Information. The collected data were then masked, reorganized, and standardized.

4. Results

4.1. Basic Statistical Characteristics. The initial analysis provided the basic statistical characteristics of all selected indicators for the 27 stations. All of the indicator values of non-TODs are higher than those of TOD stations. Therefore, TOD stations do not provide any obvious advantages. In detail, the mean population density of TOD stations is considerably lower than that of older stations. This result may be attributed to the different development histories of non-TOD and TOD stations. The higher land-use diversity of non-TODs than that of TOD stations can be attributed to the main function of the Tama New Town Station along the DT Line. The catchment of the Tama New Town Station mainly functions to relieve housing problems in Tokyo. Thus, this area contains vast tracts of residential land. By contrast, the catchment areas of older stations contain relatively more commercial and office areas than those of the Tama New Town Station. Non-TOD stations have higher functional land areas and numbers of high buildings per unit area than TOD stations, indicating that land use around old stations is better developed than that around new stations. TOD stations consistently have lower values for the five design indicators than non-TOD stations. This result suggested that infrastructure with less accessibility may not serve a high proportion of riders. Compared with non-TOD stations, TOD stations have lower average daily ridership, which is the direct output of transportation operation and management and land use. However, low ridership and indicator values do not necessarily indicate low efficiency and vice versa. Thus, an in-depth assessment is necessary to identify the efficiency of TOD stations.

4.2. TOD Efficiency. To explain whether different 3D patterns can generate correspondingly different ridership patterns, the DEA method was applied to calculate the efficiency of each station pattern. The results are shown in Table 3. Nine stations with E equal to 1 are considered as relatively efficient. However, seven of these stations are non-TOD stations, and only two are TOD stations. The mean efficiency score of TOD stations is lower than that of non-TOD stations, indicating that the 3D-based TOD strategy does not generate sufficient ridership as initially expected.

This finding can be partly explained by the individual attributes of each station. Station attributes include designation as a transfer station, opening date, and operating history. For example, the Shibuya Station is a transfer station with a long operating history in a catchment area with high population density. Accordingly, its corresponding land use is well developed, and its accessibility attracts high numbers of riders. Furthermore, non-TOD stations may achieve TOD goals given their specific attributes. For example, among non-TOD stations, the Azamino Station is highly efficient despite its lack of a long operating history because of its transfer function. The above result suggests that considering only 3D-related indicators cannot provide an adequately comprehensive assessment of TOD efficiency. The inherent attributes of each station cannot be ignored because they constrain the comparability of stations.

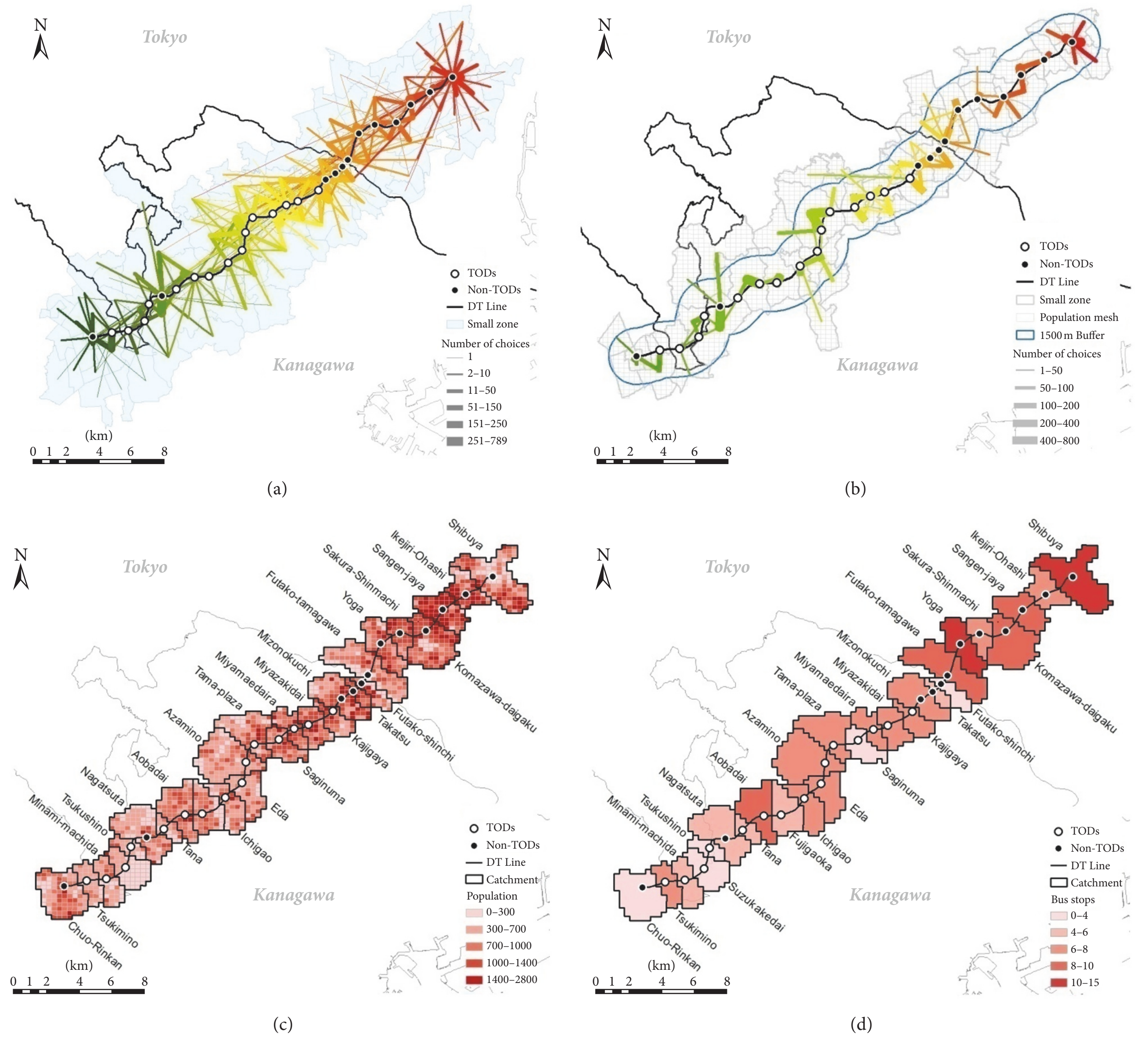

Figure 2: Generation of catchment area and distribution of a selected indicator for each catchment. (a) Original flow map; (b) deletion of extra zones and magnification; (c) finished catchment area; (d) bus stops for each catchment. *Note.* In (a) and (b), the flow color is used to distinguish the populations of different stations. The width of gray bar in legend represents the number of choices of separate stations.

4.3. TOD Efficiency considering Inherent Station Attributes. The inherent attributes of each station may affect its ridership proportion and efficiency. Inherent station attributes include the number of operation years, designation as a transfer station, number of trains running per day, and duration between trips. The former two attributes have been discussed above to account for the relatively inefficient performance of TOD stations. To avoid the biases resulting from operating history and transfer function, operation year was added to the DEA model. At the same time, seven transfer stations were removed from the DMU list to improve the comparability of stations. Hence, the DEA model was recalculated with 20 stations (6 non-TOD and 14 TOD stations) with 10 input indicators, including operation year.

After removing transfer station as an input (Table 4), the differences between the input indicator values of TOD and non-TOD stations have drastically decreased compared with those shown in Table 2. As shown in Table 2, the average ridership of non-TOD stations is almost three times larger than that of TOD stations. However, the average ridership of non-TODs is approximately 20% higher than that of TOD stations when only nontransfer stations are considered. Given that ridership is the output indicator of the DEA model, changes in ridership will inevitably lead to the different efficiency results shown in Table 5. Most TOD stations are relatively efficient, and the mean values of efficiency E for TODs and non-TODs are not considerably different. Yoga Station, a non-TOD station, performed relatively inefficiently

Table 2: Means of the indicators of non-TOD and TOD stations.

	Indicators	Non-TODs	TODs	Difference
Density	Population density	14.21	10.39	3.82
Diversity	Land-use diversity	0.97	0.64	0.33
	Functional land area	0.87	0.86	0.01
	High-building area	0.06	0.03	0.03
Design	Number of bus stops	7.37	6.05	1.32
	Daily bus operation length	575.44	423.51	151.93
	Bus routes	4.50	1.73	2.77
	Road length	19.36	21.37	−2.01
	Number of station exits	12.08	7.87	4.21
Daily ridership		130459	46747	83712

Table 3: Efficiency of each station.

Non-TOD stations			TOD stations		
Station	E	Operation years	Station	E	Operation years
			Kajigaya	0.824	51
Shibuya*	1	132	Miyazakidai	0.536	51
Ikejiri-Ohashi	0.364	40	Miyamaedaira	0.496	51
Sangen-Jaya*	0.739	110	Saginuma	1	51
Komazawa-Daigaku	0.760	40	Tama-Plaza	0.644	51
Sakura-Shimmachi	0.730	110	Azamino*	1	40
Yoga	0.487	110	Eda	0.895	51
Futako-Tamagawa*	1	110	Ichigao	0.507	51
Futako-Shinchi	1	90	Fujigaoka	0.513	51
Takatsu	1	90	Aobadai	0.905	51
Mizonokuchi*	1	90	Tana	0.809	51
Nagatsuta*	1	109	Tsukushino	0.286	49
Chuo-Rinkan*	1	88	Suzukakedai	0.274	45
			Minami-Machida	0.573	41
			Tsukimino	0.257	41
Mean	0.840	93.25	Mean	0.635	48.4

Note. * denotes a transfer station.

Table 4: Means of indicators of nontransfer stations.

	Indicators	Non-TODs	TODs	Difference
Density	Population density	15.74	10.48	5.26
Diversity	Land-use diversity	0.93	0.64	0.29
	Functional land area	0.87	0.86	0.01
	High-building area	0.03	0.02	0.01
Design	Number of bus stops	7.02	6.01	1.01
	Daily bus operation length	542.05	430.90	111.15
	Bus routes	2.83	1.71	1.12
	Road length	22.99	21.71	1.28
	Number of station exits	10.67	7.29	3.38
Operation year		80	49	31
Daily ridership		52478	40566	11912

given its 110-year operation history. The efficiency values of 12 TOD stations with 40–50 years of operation history, except for Ichigao and Tana Stations, are all higher than those of Yoga Station. This result suggested that TOD stations tend to reach their current efficiency more rapidly than non-TOD stations.

4.4. Potential for Improving Efficiency. The frontier project reflects the improvement target that the inputs and outputs of each inefficient station should reach. The distance (difference) between the real point and its projection indicates the volume required for improvement. Then, the percentage

Table 5: Efficiencies of nontransfer stations considering operation year.

Non-TOD stations		TOD stations	
Station	E	Station	E
		Kajigaya	1
		Miyazakidai	1
		Miyamaedaira	1
		Saginuma	1
Ikejiri-Ohashi	0.702	Tama-Plaza	1
Komazawa-Daigaku	1	Eda	1
Sakura-Shimmachi	1	Ichigao	0.708
Yoga	0.881	Fujigaoka	0.958
Futako-Shinchi	1	Aobadai	1
Takatsu	1	Tana	0.809
		Tsukushino	1
		Suzukakedai	0.894
		Minami-Machida	0.928
		Tsukimino	0.999
Mean	0.981	Mean	0.955

Table 6: Difference between the average projected and real values of inefficient stations (%).

	Indicators	Non-TODs	TODs
Density	Population density	6.33	17.89
Diversity	Land-use diversity	20.39	20.14
	Functional land area	6.04	8.67
	High building area	9.46	27.89
Design	Number of bus stops	28.68	26.32
	Daily bus operation length	38.31	46.32
	Bus routes	36.38	28.08
	Road length	19.27	23.17
	Number of station exits	6.34	0.62
Operation year		27.03	13.84

of difference relative to the original input can be calculated to discover the excess input indicator that contributes most significantly to inefficiency. The average difference percentage of each input for non-TOD stations and TOD stations (only including inefficient stations) is listed in Table 6.

All inefficient railway stations have higher numbers of redundant design indicators than the other two types of stations. The results indicated that bus location and services do not increase the corresponding ridership proportion of the railway. One possible reason is that passengers' daily transportation needs cannot be satisfied by the mutual independence of the railway and bus systems. Therefore, bus services and their feeder roles should be enhanced to improve the efficiency of the railway system. Moreover, diversity in the land use of areas surrounding inefficient stations does not generate adequate ridership, suggesting that the mixture of land-use types should be promoted despite requiring long-term effort. Population density is more redundant for inefficient TOD stations than for non-TOD stations. This result can be attributed to the number of serviced people and to age category (i.e., percentage of the elderly, adults, and children) and social level (i.e., percentage of unemployed, professionals, and managers) of the residents of a certain catchment area. For example, high-class workers and the elderly tend to use private transportation. Accordingly, increasing the density and optimizing the age and social category of the target population may help improve TOD efficiency. All aspects listed above should receive additional attention when planning future TOD stations.

5. Discussion and Conclusions

This study focused on measuring the efficiency of the TOD strategy implemented in the DT Line. TOD is a powerful urban planning approach and concept that is applied to resolve various urban problems. This study expounded on TOD assessment on the basis of the 3D framework. In this study, the assessment procedure included the identification of catchment areas and the selection of suitable indicators as input variables and ridership as output variables. The input variables are then subjected to the DEA method to validate the successful performance of the TOD strategy or program and to identify possible solutions to strengthen TOD implementation.

Existing TOD evaluations have failed to provide reliable conclusions regarding TOD performance. For example, a single-indicator assessment cannot adequately characterize the comprehensive efficiency level of a TOD strategy from the perspective of the 3D framework. Meanwhile, a simple weight-based method following the 3D concept is likely to be affected by weights with low objective values and may thus produce a biased result that may contradict reality. These situations suggest the necessity of designing a procedure for the comprehensive assessment of TOD strategies. By considering that density and diversity may generate transportation demand and that design must provide convenient service to satisfy such needs, we employed DEA to reflect the relative efficiency of TOD in accordance with 3D-based inputs and ridership output. Our DEA-derived results reflect the core principle of the TOD concept, which coordinates density, diversity, and design with ridership output.

Many TOD applications have demonstrated that TOD has a significant role in regional development. However, the present results suggested that TOD strategies cannot provide more positive effects than non-TOD strategies because, on the one hand, market power enables non-TOD strategies to achieve effects similar to those achieved by TOD strategies. More importantly, the current indicators selected for TOD assessment do not adequately reflect the 3D concept. In fact, the current indicators for TOD assessment only highlight aspects related to 3D, and some important factors that affect output are excluded from conventional TOD assessment. For example, operating history can also affect the output of TOD stations along the DT Line. Although TOD stations are comparable with non-TOD stations in general, development history results in the incomparable efficiency of new and old stations. Moreover, other factors, such as the age and social class of the catchment population, designation as transfer station, number of trains running per day, and duration between trips, have been overlooked. Adding operation year as an input indicator and removing transfer station revealed that the performance of TOD stations is relatively efficient and approaches expectations. This result indicated that the inclusion of other influential factors is necessary for equitable TOD assessment. Consequently, taking such factors into account is indispensable when evaluating the efficiency of TOD stations with different inherent attributes. In addition, the design input with the largest impact on all inefficient units was identified. Management of bus service and railway system should be well enhanced and encouragement for public transportation usage should be emphasized.

The applicability of the DEA-based TOD assessment approach is mainly dependent on indicator selection. The framework of the approach includes indicator selection from the perspective of 3Ds, catchment divisions, and the DEA model and is applicable to other public transportation systems (e.g., light rail, metro, bus, and bus rapid transit) and to other regions or countries. Nevertheless, the selected indicators may vary across different applications. Researchers and urban planners may have specific local or specialized priorities and knowledge that differ from those emphasized in the present case. Thus, other researchers should select indicators that are appropriate for their priorities and knowledge.

Nevertheless, the present study presents several critical issues that should be considered to improve the evaluation of TOD approaches. First, additional factors that affect the efficiency of TOD-based systems should be considered during the assessment and planning of a TOD project. These factors include the attributes of the target population (age structure, occupation, and income level) and the transportation system itself. Second, the design scheme should improve the convenience of accessing destinations by foot, bus, or bicycle. In this study, the selected indicators mainly characterized connectivity to railway stations by bus. However, such a characterization may be insufficient for design characterization. Other factors, such as plating strips, overhead lights, and bicycle path lengths, should be considered in future studies. Furthermore, the definition of the analytical unit is crucial for TOD assessment. In this study, the Nationwide Person Trip Survey in Japan was used to identify station catchment areas through the boundary method. When such data are unavailable, the effect of catchment size should be addressed by specifying a different buffer radius, travel distance, or travel time.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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