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Classification of TOD Typologies Based on Pedestrian Behavior for Sustainable and Active Urban Growth in Seoul

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Abstract: Transit-oriented development (TOD) pursues sustainable urban development through compact growth, mixed-use zoning, and pedestrian-friendly neighborhood design in cooperation with transportation planning. Seoul has actively developed urban rail transit since the 1970s based on a TOD concept, and each station's areas have differently evolved throughout the history of urbanization in Seoul. In response to investigating the complications of current TOD, this paper evaluates TOD characteristics through accessibility and clustering analysis methods and categorizes TOD types using the targeted 246 subway station areas at the neighborhood level. As a result, subway TODs are grouped into the four distinct categories of (1) high-density: a form of mainly mixed-use with residential and retail development and good accessibility; (2) moderate-density: average accessibility and high-mixed use; (3) compact business district setting: highly accessible to offices and retail; and (4) compact housing: high-rise apartments with schools and retail. The results also find that Cluster 2 is the most common TOD type and redevelopment possibility in Seoul, with relatively lower ranks in the building floor area (GFA) and diversity in comparison to other TOD contexts. Cluster 3 has the most significant transit demand, generating an active transit environment in Seoul. Different urban development periods impact the characteristics of TOD types.

Keywords: subway station typology; active transit-oriented development (TOD); pedestrian accessibility; clustering analysis; urban sustainability

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1. Introduction

Urban railroads, as representative public transportation systems, have played an essential role in forming spatial structures and functional systems during industrialization in the development of the Seoul metropolitan area [1]. As the station area is where the population and logistics are concentrated, transit-oriented development (TOD) planning is implemented in many cities as a strategic tool for sustainable urban planning and management [2,3]. According to TOD planning, well-designed station development areas not only promote the ridership of public transportation among automobile users, but also operate as a center for organizing community development and restoring sluggish urban areas [4–6]. TOD planning achieves the main goals of ensuring location efficiency, a vibrant mix of choices, placemaking, and resolution of the tension between the node and place [2], which support sustainable urban growth.

TOD also generates more efficient business effects that positively influence the maintenance of existing urban areas [7]. The "livability" in urban life, according to high mobility and accessibility levels, generates more economic activities and benefits around station areas [5,8]. As Dittmar and Ohland (2004) defined the typical term of transit-oriented development (TOD) based on performances, TOD planning achieves five main goals, including location efficiency, a rich mix of choices, place making, and resolution of the tension between the node and place, which are closely related to the "livability" issue in urban life [9]. Urban livability considers the overall factors that create a better quality of life, including built and natural environments, economic prosperity, social stability, educational opportunity, culture, entertainment, and recreational possibilities in TOD areas [10]. A higher density of population and jobs in station areas also creates a better opportunity to improve subway ridership, increasing transit investment returns and managing the transit operation [7]. The location of transit stations supports land-use development to increase ridership through better pedestrian accessibility [11]. The benefit of integrated TOD and land use planning can be related to the urban land value [12]. As the awareness of the critical role of TODs in urban spaces is rising, it is necessary to closely look at the urban development patterns around TOD areas. A typical TOD planning setting promotes well mixed-use environments, integrated land-use and transportation systems, and walking and cycling friendly neighborhoods. The basic principle of TOD is similar; however, implementations of TOD planning are not the same in every station development area across the transit networks [13,14].

This research focuses on the urban types and characteristics of TODs in the Seoul subway system and classifies diverse TOD contexts based on urban factors of pedestrian accessibility at the neighborhood scale. This paper shows the complexity of the urban development situation in the subway station areas and uses a cluster analysis method to conduct intuitive grouping for Seoul's TOD. Typologies cannot judge the urban value of what is good or bad, but they can explain priorities regarding what a type is expected to achieve [15]. Cluster analysis enables the classification of TOD urban contexts through the evaluation of large amounts of urban data and separates them into the desirable number of categories to explain different scenarios. A clustering analysis also investigates the similarities and differences between groups in terms of their urban morphology, road connectivity, land use, building use, urban density, demographics, and travel behavior. After the clustering process, this research highlights the similar urban characteristics of station development areas.

The novelty of this research is that it contributes to understanding the complex TOD performance in terms of urban sustainability and active station environments by exploring actual TOD types in Seoul. Developing TOD typologies can be a useful tool for policy improvement to support transit development [16]. This study helps to investigate the ideal model for policy implementation and planning practice in future TOD. This paper clarifies the heterogeneity of TOD built environment characteristics and assesses the general characters of existing transit station areas or normative assessment for TOD potentials. This set of classifications shows various aspects of land use and transportation interactions in different urban areas that help urban planners and policymakers better understand the complexity of subway station environments and provide guidelines for future TOD planning and design for sustainable and active (re)development of subway station areas at the neighborhood level. It is useful for the decision-making process to develop new subway station planning in Seoul and evaluations of various transportation integrated land-use planning scenarios based on comparative studies between the cluster types, which consider the similarities and differences of station environments across the city.

This paper comprises five sections. Section 1 reviews the research background through the extant literature on TOD planning and types. Section 2 introduces the study area, dataset, and methodologies employed to evaluate TOD characteristics. Section 3 explains the main results, while Section 4 discusses these results. Section 5 summarizes the main findings and describes the conclusions and future studies.

2. Background

2.1. Development of TOD Planning and Types

TOD pursues a high-density, mixed land use, and walking-friendly neighborhood environment [2,9,17]. Calthorpe (1993) thought that TOD was "a neo-traditional guide to sustainable community design" that became a community design theory that promised to redefine The American Dream [18]. He developed TOD to address community ecologies and a comprehensive solution for regional growth. Calthorpe noted that the urban types related to the concepts of TODs are pedestrian pockets, traditional neighborhood developments, urban villages, and compact communities. The New Transit Town: Best Practices in Transit-Oriented Development (2003) summarizes the key components of TOD planning from Calthorpe's guidelines: To organize compact and transit-supportive growth on a regional level; locate retail, housing, office, park, and community uses within walking distance of transit stations; build pedestrian-friendly streets directly linking to local destinations; design a mixed use of housing types, densities, and costs; preserve nature and sensitive habitats zones, and exclusive open space; and make public spaces focusing on building orientation and neighborhood activity [9]. The book explains the potential benefits of TODs: To provide residents with a high quality of life; reduce household transportation expenses through the development of mixed-income neighborhoods; diminish environmental impacts on the region; and provide alternative traffic solutions.

Cervero (1998) explains that the Transit-Oriented Constellation Plan (TOCP) is a mixed-use new town around many suburban mass rapid transit (MRT) stations in Singapore. It embraces Scandinavian planning principles called radial corridors, which link the centers with master-planned new cities [6]. It is called a constellation of satellite 'planets,' or new towns, that circuit the central core, distributed by protective greenbelts through highly performing rail transit.

Some scholars have defined the ideal design and planning of TOD as a neighborhood development model and a conceptual urban development plan associated with a combination of nodes (e.g., transit stations) and places (e.g., neighborhoods) with a high density [2,19–21]. The TOD area is covered by public transport services at the nodes and facilitates urban activities. Well-connected street networks can be integrated with active transport [22,23]. A TOD area is not just a transit station, but it is an extraordinary place to live, socialize, recreate, and shop [2].

In the late 1980s, metropolitan transit agencies developed design guidelines for station areas similar to the neo-traditional environmental designers in the U.S. [24]. In the late 1990s, the metropolitan scale of TOD projects, including Copenhagen's 1947 Finger Plan, Stockholm's 1952 plan, and Paris' 1965 plan, was re-defined as a Transit-Oriented Metropolis (TOM) [6]. Belzer (2011) developed the concept of TOD extending along a corridor, which he called a Transit-Oriented Corridor (TOC) [25,26]. In the early 2010s, TOD's definition became a sustainable form of urban development: It features high-density and mixed-use urban design along with transit stops or stations; promotes public transit usage; and establishes pedestrian-friendly and slow traffic environments. To achieve a more sustainable urban future, the two concepts of Green Urbanism and TOD are combined into a new concept called Green TOD [27]. While TOD prevents urban sprawl and car-dependent lifestyles, green urbanism promotes a reduction in energy use, emissions, water pollution, and waste, which forms green architecture and sustainable community designs [28]. The following synergies are created when each strategy is merged: Higher densities; mixed land uses; reduced surface parking and associated impervious surfaces; and solar energy production at stations that result in self-sufficiency, zero-waste living, sustainable mobility, a vibrant street life, and higher land prices.

2.2. Development of Subway TOD Planning in Seoul

Seoul is the capital city of South Korea, which is a large and fast-paced city. The area of the city is approximately 605.25 km^2. It had a population of roughly 10 million as of 2018, where about twenty percent of Korean people live. Seoul has developed very actively and experienced rapid growth since the 1970s, strongly tied to the nation's economic development [29]. As urban growth, new transportation planning has been required to support sustainable urban development and the first subway line one opened in 1974. Following this, subway networks extended to nine subway lines, covering about 332.6 km, with 301 stations in 2018. Moreover, there are additional lines, such as Sinbundang Line, Gyeongchun Line, Gyeongui-Jungang Line, Ever Line, and Uisinseol Line, that operate across Seoul's metropolitan areas. The subway system carried approximately 7.5 million daily passengers in 2018.

Byong-Kee Kahng proposed the 1980s Comprehensive Plan in 1980 [30]. The concept is a combination of the Transit-Oriented Metropolis (TOM), transit and housing schemes, and Calthorpe's neighborhood TOD concepts (Figure 1a). His integrated metropolitan spatial planning and the station area prototype provided benefits for better rapid transit systems, more housing supplies, and self-sustaining public transportation [26]. The plan carefully considered making a self-sufficient public transportation environment by developing high-density accommodation around the subway station—50,000 people/km^2 within a 500-m radius from subway stations. Figure 1b illustrates that the land-use diversity of the subway station areas was carefully considered in the plan. The plan placed commercial facilities on the first and underground floors and office spaces on the buildings' lower and middle levels, as shown in Figure 1c. By locating residents and employees with high-density mixed-use housing around new subway stations, the city could redistribute the population density along with the subway networks. Therefore, the plan satisfied both urban diversity and the density around station areas [30]. The project also pointed to the design of a pedestrian-friendly environment in station areas and limited car traffic by speed control in inner streets. The plan became a valuable example of TOD planning and its implementation strategies in Seoul in the 1980s. The project provided many solutions to overcome city problems caused by rapid urbanization and growth [26].

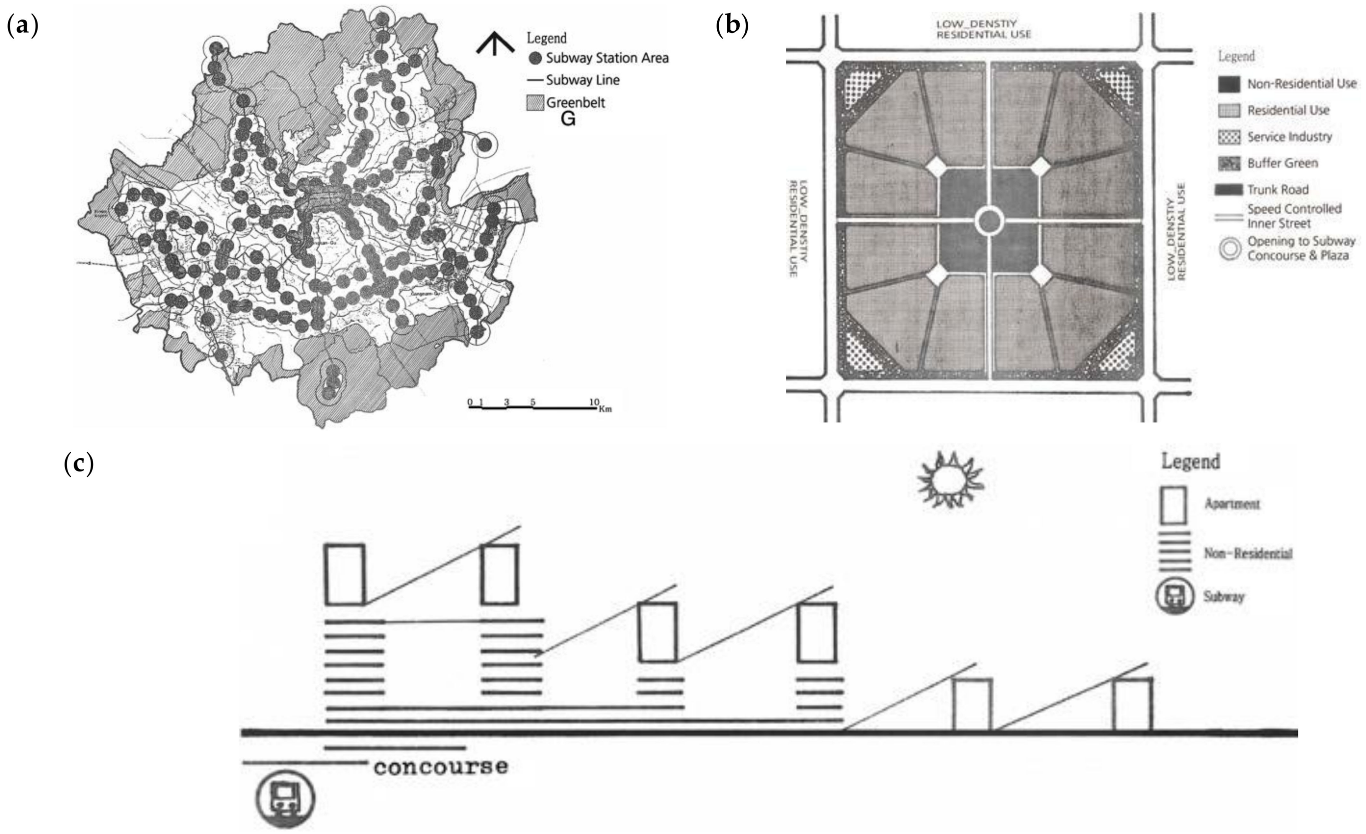


Figure 1. (**a**) Schematic image of the 1980s Comprehensive Plan for Seoul; (**b**) prototype of station areas; (**c**) section diagram of mixed land uses building near the station (source: Sung and Choi, 2017; Kahng, 1980 [26,31]).

Seoul has been a Transit-Oriented Metropolis (TOM) since the 2000s, when many high-density and mixed-use developments were completed, along with the public transportation networks [31]. The continuous efforts of TOD planning have been executed by integrating station area developments with transit networks, the housing supply, other facilities, and land-use patterns since the Comprehensive Plan. Some station nodes where more than two subway lines overlapped became important district centers by enhancing the land density and diversity [26]. According to the 10-Year Urban Railway Master Plan of Seoul (2014), the city aims to balance growth and improve urban rail connections to access insufficient subway service areas in sustainable ways [32]. In order to overcome the problem of stagnation in the existing metropolitan area, the development of an ideal station TOD type is also being discussed for urban improvement purposes.

3. Methodology

3.1. Description of the Study Area and Dataset

This research collected the average daily ridership counted by Smart Card Taps obtained from the Seoul Metropolitan Government (SMG) Big Data Campus. The study gathered land use data managed by the Ministry of the Interior and Safety (MIS) and Korea Local Information Research and Development Institute (KLID) to investigate the built environment characteristics and their relationship with transit development in Seoul. This research also collected geospatial data, including information on buildings (program, area, and floor), roads, subway stations, and bus stops from MIS and KLID, in order to perform pedestrian accessibility analysis. The research areas are set actual pedestrian network coverages within 500 m of the 246 targeted stations in Seoul. The usual range of walkable distance to stations is 600 to 1000 m [33]; however, many Korean scholars use 500 m as the ideal walking distance to stations due to the usual travel time of 10 min [31]. The designated 500 m walkshed is defined as a subway TOD area focusing on pedestrian accessibility in this research. Figure 2 shows a 500 m pedestrian network coverage of the 246 subway stations computed by the Service Area tool in Rhino's Urban Network Analysis (UNA). The UNA tool has been developed by the City form Lab at MIT and offers assessment tools for spatial accessibilities between people or places along with networks.

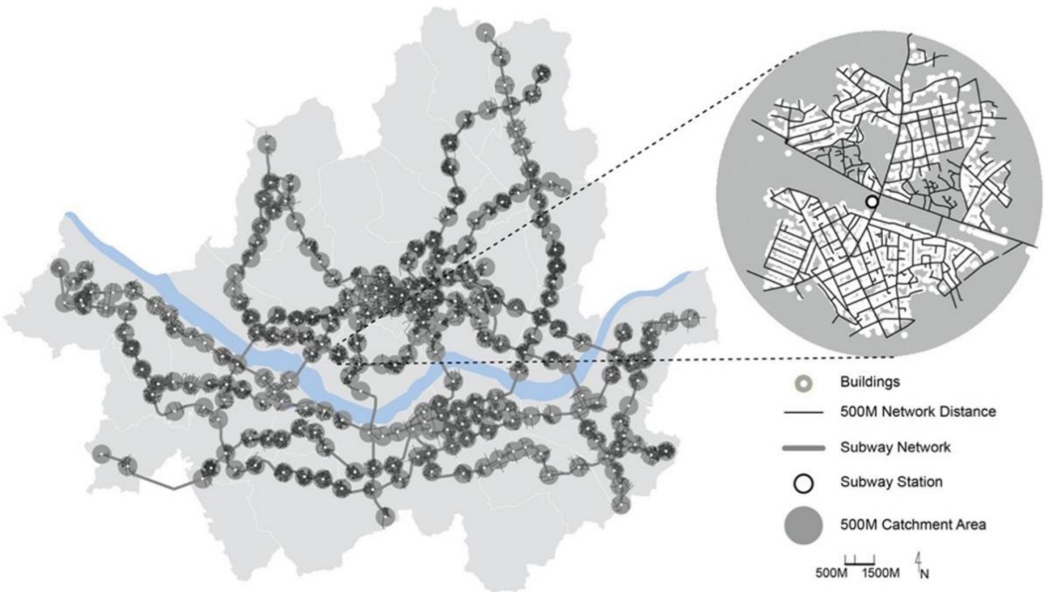


Figure 2. 500 m pedestrian walkshed of subway stations (source: drawn by author).

3.2. Pedestrian Accessibility Analysis for Measuring the TOD Characteristics

This paper investigates TOD planning principles based on pedestrian accessibility in current urban contexts to evaluate the characteristics of the subway station areas in Seoul. Accessibility is a critical tool for measuring TOD environments considering the urban Density, Diversity, and Design of the Cervero's 3Ds theory [22]. Transportation and land use theory refers to increased accessibility resulting in a higher land value and higher density regarding land use along with transportation linkages [34,35]. Sung and Oh (2011) also identified that denser and more mixed development tends to encourage people to walk and take subways more than drive cars in their residential areas around subway stations in Seoul [36]. Accessibility can measure the reachable value to desire places, services, activities, or other opportunities [37,38] that pedestrian accessibility utilizes as a critical tool to evaluate the quality of the transportation system and its service integrated with land-use planning [39]. Accessibility can expand the range of urban performance evaluation to reveal land use patterns to minimize the travel distance within service areas.

In this study, pedestrian accessibility is the critical method employed to ascertain the station development types for cities. This study explores concerns about the accessibility impacts on subway development areas and classifies the characteristics of built environments to investigate more sustainable urban development strategies for transportation planning. Sustainable urban planning for TOD areas pursues high-density, mixed land use, proximity to multi-modal public transportation, and walkable neighborhoods. Many TOD studies have focused on land use contexts and their relationships with the transit demand in station catchment areas. This paper focuses on processing the urban data to obtain pedestrian accessibility values. The benefit of the pedestrian accessibility method is that it can capture the urban density, diversity, and design factors reflecting the travel distance at the neighborhood scale. The accessibility includes road network configurations, accessible building uses and gross floor areas, and the travel distance to stations. The accessibility also explains whether and how the station's built environments are related to local pedestrian walkability. Therefore, measuring pedestrian accessibility is an essential tool for studying TOD planning and characteristics.

Reach analysis measures cumulative opportunities of the accessibility index using the weight value in a search radius [40]. The UNA tool allows testing with diverse weight types, depending on the site's contexts and research questions. Giving weights results in a more accurate outcome, which reflects specific urban contexts at a site. Applying a higher weight value more strongly affects the accessibility to the destination. The α (destination attractiveness) value is utilized to adjust the amount of travel at the site. In this study, Reach analysis captures the accessible value of destinations within the given radius of 500 m, representing a distance equivalent to 10 min of walking. The weight is the building floor area (GFA), reflecting the reachable total amount of building areas to the destinations. The mathematical formula of the Reach method is defined as follows:

$$Reach[i]^r = \sum_{j \in G-\{i\}, d[i,j] \leq r} W[j] \tag{1}$$

where:

i = origin
j = destination
G = number of destinations
r = a shortest path distance within a search radius
d[i, j] = the shortest distance between i and j
W[j] = weight of a destination j

3.3. Building Use Index for the TOD Areas' Diversity

The Building Use Index (BUI) for the subway station areas is applied to compare the building mixed-use ratio between city-wide and station areas, in order to investigate the station TOD areas' urban diversity index. The Match Index (MI) reveals the difference between a station's ratio and city-wide ratio for every building use class. The final Building Use Mix Index (BUI_i) shows how a mixed proportion of building uses within a station area corresponds to its city-wide distribution ratio. The BUI for each station was calculated by multiplying all MI values for the given building-use classes. This study follows the method of Sevsuk and Amindarbari (2012) to calculate the land use mix diversity and the mathematical formulae for the research are as follows [41]:

$$R_{B_{n:i}} = \frac{B_{n:i}}{\sum_{n=1}^{6} B_{n:i}} \tag{2}$$

$$MI_{B_{n:i}} = 1 - \left| R_{B_{n:i}} - CR_{B_{n:i}} \right| \tag{3}$$

$$BUI_i = \prod_{n=1}^{6} MI_{B_{n:i}} \quad (0 \le BUI_i \le 1) \tag{4}$$

where:

B_1 = total GFA of housing
B_2 = total GFA of office
B_3 = total GFA of retail
B_4 = total GFA of entertainment
B_5 = total GFA of community
B_6 = total GFA of industry
i = station

3.4. Clustering Analysis for Classification of the TOD Areas

This study employed combined two-step and K-mean cluster analysis to classify heterogeneous station areas' characteristics empirically. In the urban planning field, cluster analysis is applied to classify urban areas based on urban structure and land-use patterns [13]. A method using seven urban variables was selected as it produces the logical clustering of subways station areas. Implementations of TOD planning are not the same in every station catchment area across Seoul's subway networks. Cluster analysis reveals the complexity of TOD contexts, creates intuitive groupings for large amounts of urban data, and separates them into the desired number of categories based on the urban density and land-use diversity. After the clustering, this research investigates and presents the similarities and differences between the groups in terms of their urban form, building use, density, demographics, and travel behavior.

Two-step cluster analysis automatically defines an appropriate number of clusters based on input attributes according to Akaike's information criterion (AIC) and the Bayesian information criterion (BIC). The maximum number of clusters is equal to the number of clusters where the ratio BIC_k/BIC_1 is smaller than C_1 = 0.04 [42,43].

A prototype-based (center-based) clustering technique was used in this study, and the most prominent one is K-means. K-mean clustering finds a centroid for each group, which is the mean value of all points by group. The attributes (input variables) are populated in a continuous n-dimensional space. K-mean defines the most representative point for each group, but has a centroid meaning. To assign a point (object) to the closest centroid, it needs to proximately measure the notion of the center of gravity for a cluster using the Euclidean distance method. The Euclidean distance is often used for points in an Euclidean space and minimizes the sum of the squared distance of an object to its cluster centroid, which is known as a scatter [44]. The K-mean algorithm initially requires the specific number of groups when it begins the clustering to specify initial cluster centers. Therefore, K-mean analysis applies the determined number of clusters following the outcome of two-step analysis.

4. Results

4.1. Pedestrian Accessibility of the TOD Areas

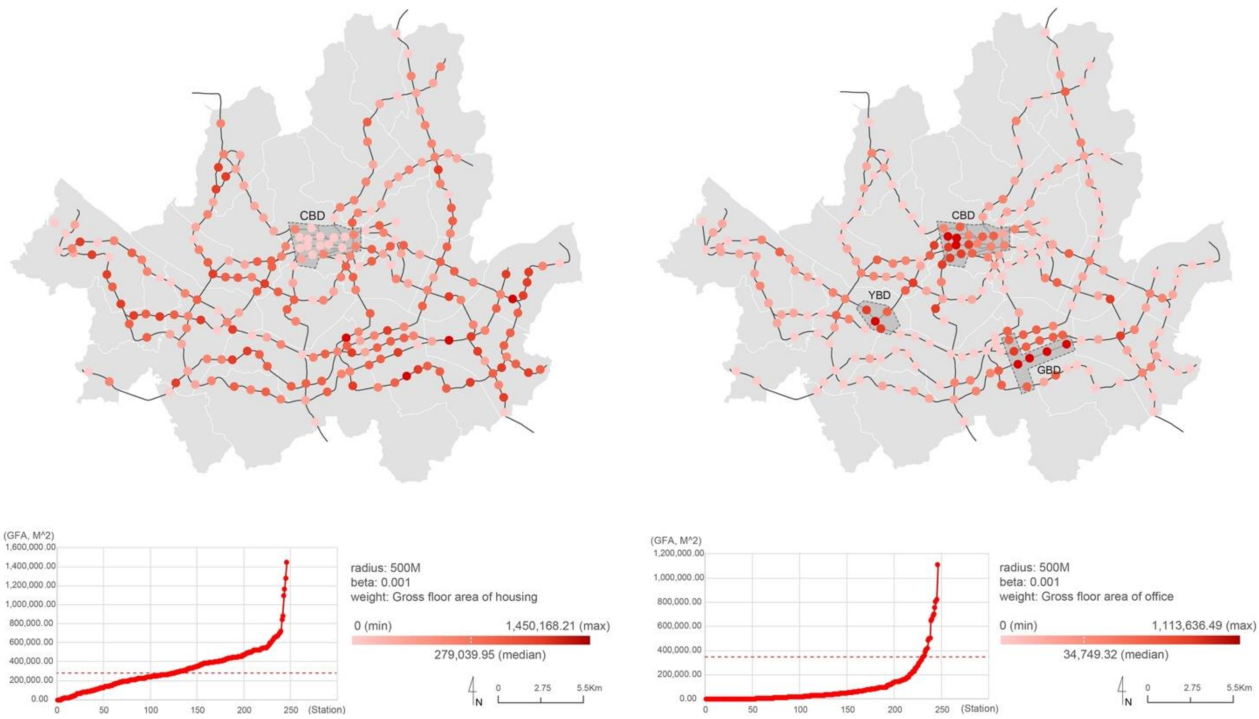
Figure 3a–f illustrates how large areas of building GFAs can be accessible to subway stations (destination) within a 500 m walkshed using the Reach analysis method of UNA—the higher the value of the weights, the more influential the impact on the station area. The darker red stations have more extensive GFA access than the lighter red ones. The unit is square meters. The input setting of the Reach analysis for building GFA within the station catchment areas is:

Origin = subway stations
Destination = buildings
Search radius = 500 m
Weights of a destination = gross floor area of buildings

Figure 3a illustrates that most stations have a high pedestrian accessibility to housing, except in the Central Business District (CBD) area of Seoul. The pedestrian accessibility to office buildings is shown in Figure 3b, where it can be seen that the stations in the three business districts of Seoul (Central Business District, Yeouido Business District, and Gangnam Business District) have vital pedestrian accessibility generated from office buildings. Figure 3f shows the pedestrian accessibility to industrial buildings, displaying limited station areas actively generating pedestrians from industrial buildings to the stations.

4.2. Building Use Index of the TOD Areas

The city-wide building-use balance for the 246 stations' TOD areas is shown in Table 1. On average, the housing of fifty-two percent, the offices of fifteen percent, the retail of nineteen percent, the entertainment of four percent, the community of six percent, and the industry of three percent occupy the station catchment area in Seoul. $CR_{B_{n:i}}$ is the city-wide average ratio of each building use (building use $= B_n$) within a station (station $= i$) area shown in Table 1. The BUI value ranges from 0 to 1, where a value of 1 indicates a perfect match with the city-wide balance. The higher the value, the closer the proportion to the city-wide distribution. Figure 4 illustrates the BUI outcome for each station, where a lighter colors mean a weaker match with the city-wide land-use mix ratio. Most stations with a lighter color located in the CBD area have a different proportion of building mixed-use from the city-wide land use mix balance.



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

Figure 3. *Cont.*

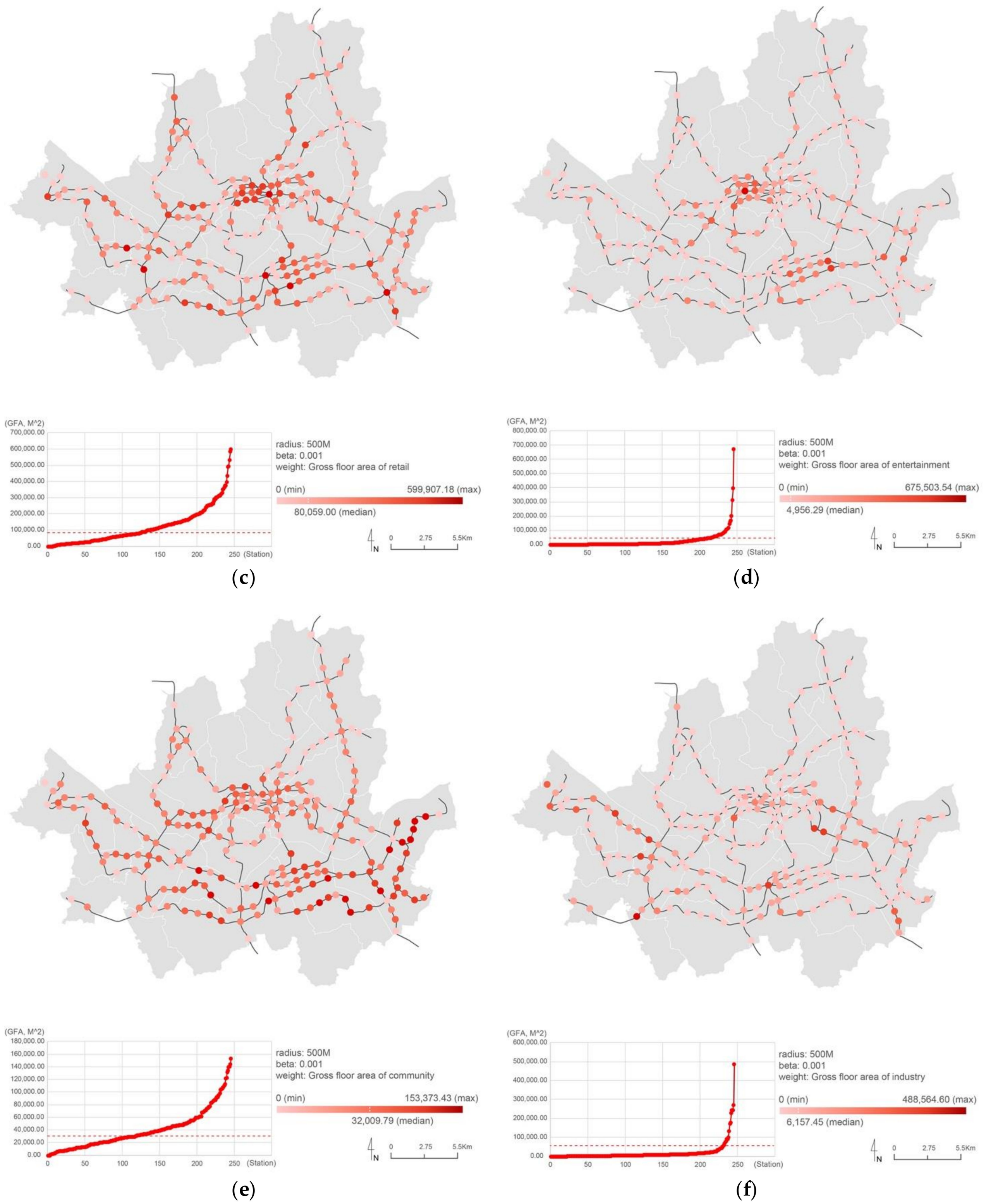


Figure 3. (**a**) Reach analysis of housing GFA; (**b**) office GFA; (**c**) retail GFA; (**d**) entertainment GFA; (**e**) community GFA; (**f**) industry GFA (source: Figure modified from [45]).

Table 1. City-wide balance of building uses for the subway station TOD areas.

Building Use Class (B_n)	Building Use Type	Building GFA (m^2)	Average Ratio $(CR_{B_{n:i}})$
Housings	Apt, housing, villa	77,967,240	0.52
Office buildings	Business	22,791,925	0.15
Retail facilities	Shop, restaurant	16,669,476.25	0.19
Entertainment facilities	Hotel, museum, theater, bar, gym, gathering places	5,798,521	0.04
Community facilities	Community center, library, hospital, educational, religious, cemetery, institutions	9,716,228	0.06
Industrial buildings	Farming, industrial infrastructures	4,426,314	0.03

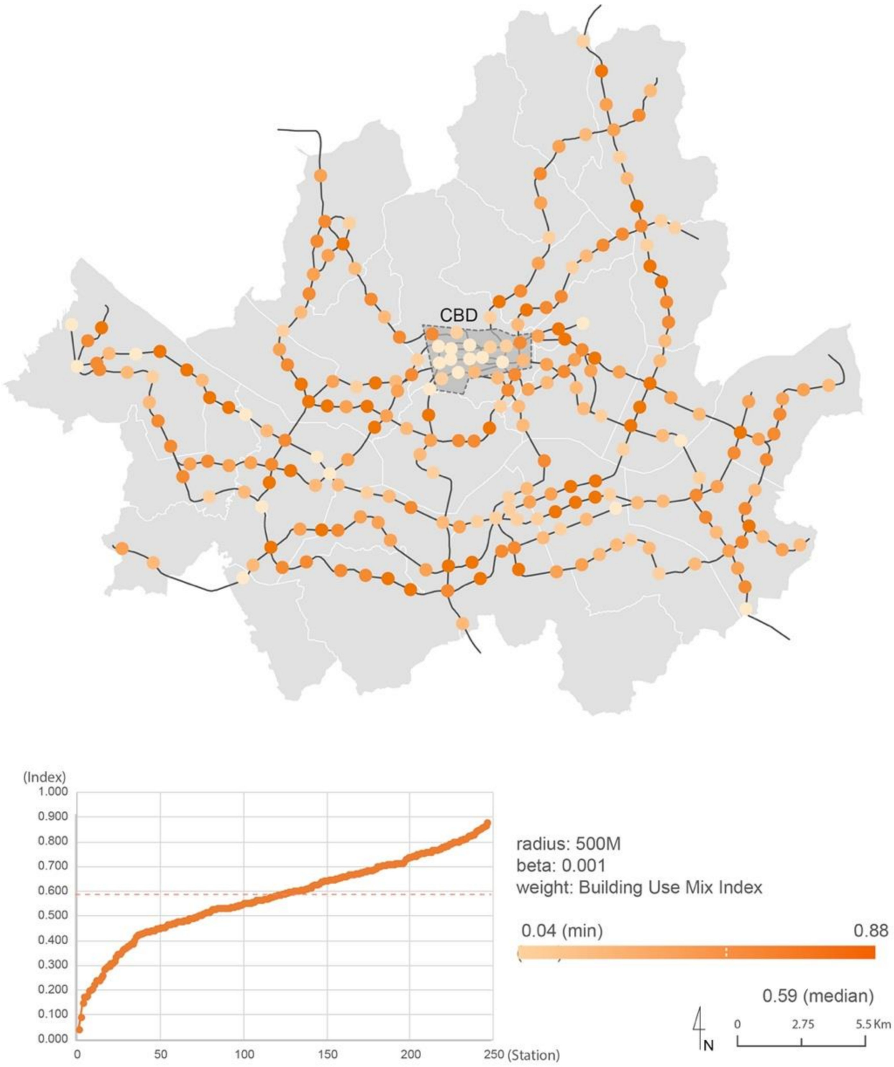


Figure 4. BUI for each subway station (source: Figure modified from [45]).

In sum, the statistics of pedestrian accessibility assessments and BUI for the station catchment areas are shown in Table 2. The largest mean value among accessibility variables is that for housing as housing is the most accessible building to subway stations within the subway catchment areas in Seoul. The smallest average accessibility value is that for industrial buildings as industrial buildings exhibit the smallest opportunity to access subway station areas, on average. The minimum BUI is 0.041 and the maximum BUI is 0.880.

Table 2. Statistics of accessibility measures.

Variables	Mean	Std. Deviation	Minimum	Maximum
Accessibility to housing	316,939.999	216,769.821	0	1,450,168.210
Accessibility to office	92,650.101	160,289.041	0	1,113,636.490
Accessibility to retail	117,860.181	112,097.504	0	599,907.180
Accessibility to entertainment	23,571.222	60,297.021	0	675,503.540
Accessibility to community	39,496.862	30,914.982	0	153,373.430
Accessibility to industry	17,993.147	48,127.593	0	488,564.600
BUI	0.579	0.168	0.041	0.880

4.3. Clustering the TOD Areas

The clustering process reveals the complexity of urban contexts and assembles similar urban characteristics of the station catchment areas. The result shows four distinct urban typologies across subway station areas in Seoul. The seven variables used to conduct a cluster analysis included the accessibility to housing, accessibility to offices, accessibility to retail facilities, accessibility to entertainment facilities, accessibility to community facilities, accessibility to industrial buildings, and BUI. The variables contain the attributes of road connectivity, building-use diversity, building density, and pedestrian walkability, reflecting the TOD contexts of the unique subway station areas.

This study selected four groups to classify the variables following the result of a two-step analysis. Four-cluster is the most meaningful type shown in Table 3 due to the lowest BIC value of 1073.432.

Table 3. Auto-clustering table.

Number of Clusters	Schwarz's Bayesian Criterion (BIC)	BIC Change [a]	Ratio of BIC Changes [b]	Ratio of Distance Measures [c]
1	1448.195			
2	1208.260	−239.935	1.000	1.770
3	1111.003	−97.258	0.405	1.475
4	1073.432	−37.571	0.157	1.623
5	1084.087	10.655	−0.044	1.384
6	1116.220	32.132	−0.134	1.157
7	1155.944	39.725	−0.166	1.292
8	1206.594	50.650	−0.211	1.437
9	1268.627	62.033	−0.259	1.049
10	1331.873	63.246	−0.264	1.059

[a] The changes are from the previous number of clusters in the table. [b] The ratios of changes are relative to the change for the two-cluster solution. [c] The ratios of distance measures are based on the current number of clusters against the previous number of clusters.

After the two-step analysis, K-mean analysis was conducted through iterating a dialog table process that compared several different variations of cluster centers and verified the stability of the given solution of K = 4 clusters shown in Table 4. The value of cluster centers tended to decrease over each iteration until finding the optimal central points. After the seventh iteration process, the value for all clusters reached zero, which means that the value was stabilized for the K = 4 that identifies the most meaningful centroid location for each cluster.

Table 4. Changes in cluster centers.

Iteration	Cluster 1	Cluster 2	Cluster 3	Cluster 4
1	480,266.973	512,131.535	267,551.234	348,559.639
2	60,339.013	20,585.272	257,442.763	0.000
3	72,546.404	28,103.617	204,545.365	0.000
4	24,871.068	14,171.449	86,899.304	0.000
5	6374.619	5991.824	51,335.438	0.000
6	1861.897	1401.185	0.000	0.000
7	0.000	0.000	0.000	0.000

Convergence achieved due to no or small change in cluster centers. The maximum absolute coordinate change for any center is 0.000. The current iteration is 7.

The cluster centers determined by the K-mean analysis demonstrate the central tendency and size of each group. In Table 5, Cluster 1 consists of 96 stations (39%), Cluster 2 has 129 (52%), Cluster 3 has 15 (6%), and Cluster 4 has 6 (3%). Each cluster has enough stations; although Cluster 4 only has six cases and is an under-representative station type among Seoul TODs, its results can still be meaningful. Cluster 2, which has the greatest number of stations, is the major case.

Table 5. Number of cluster cases.

Cluster	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Number of cases in each cluster	96 (39%)	129 (52%)	15 (6%)	6 (3%)

One of the results from K-mean clustering is the cluster membership assignment applied to determine the most relevant cluster for each variable according to the Euclidean distance values. Table 6 lists the station ID, cluster membership, and distance information for each station. Distances were computed by the Euclidean distance to measure their similarity, where the closer the distance, the more similar it is to its cluster center value. As the grouping was conducted by similarity, there could be some cases assigned in-between the multiple groups. However, there should be a more substantial similarity to one group than the others. The distances are an appropriate measure of proximity between the cluster centers and observations (stations) that measures the similarity within a group.

Table 6. Cluster membership for each station.

Station ID (N = 246)	Cluster Membership	Distance to Its Centroid
150	3	236,026.013
151	2	312,073.260
152	3	194,747.806
153	2	262,302.898
154	2	278,168.204
...	...	...
2520	1	84,320.913
2521	1	41,809.056
2522	4	473,944.322
2523	1	184,600.506
2525	1	129,941.150
2527	3	316,747.317

Figure 5 illustrates the cluster membership for each station on a map. There are approximately two times as many Cluster 1 types in the Gangnam area (n = 60) as in the Gangbuk area (n = 36). There are slightly more Cluster 2 types located in the Gangbuk area (n = 77) than in the Gangnam area (n = 52). The Cluster 3 type is collectively found in the business district areas of Seoul. All Cluster 4 types are only located in the Gangnam area.

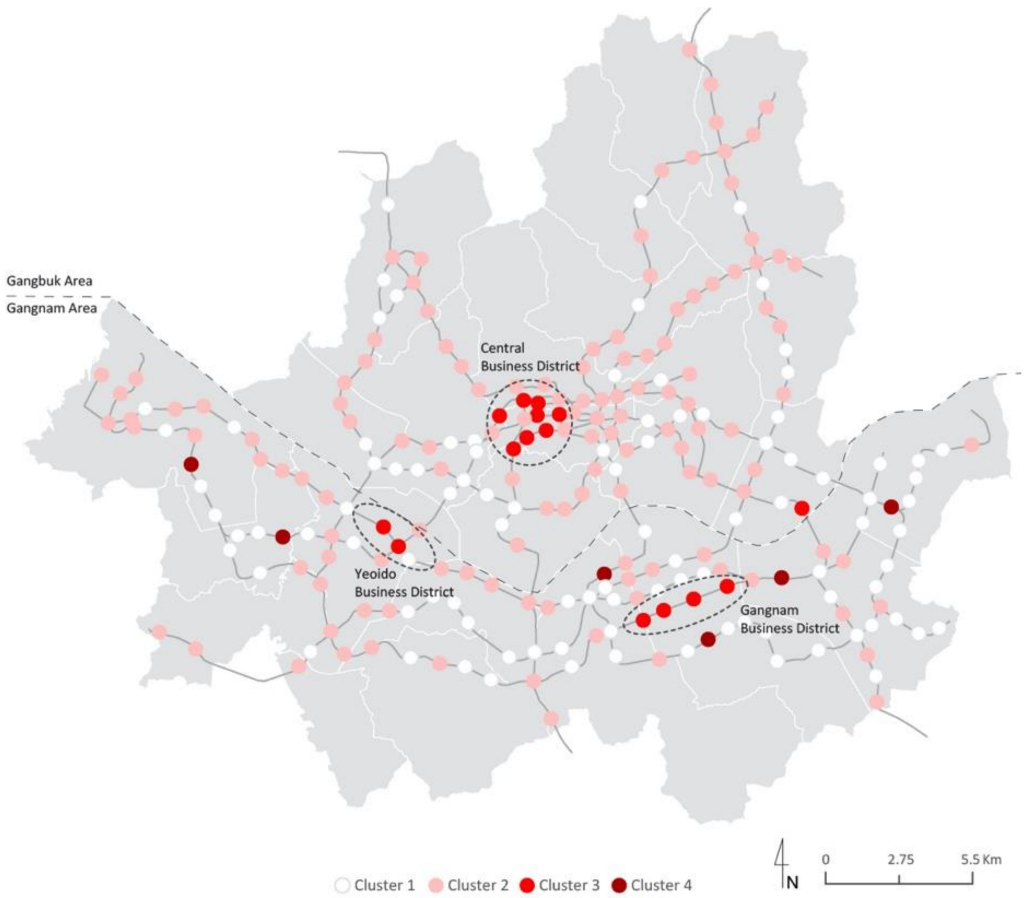


Figure 5. Cluster membership map (source: from [45]).

Additionally, Appendix A shows selected stations representing each cluster type. These were selected according to the results of the cluster membership (Table 6). If a station has a closer Euclidean distance to its centroid than other stations, then the station reflects the characteristics most similar to the center value. Therefore, the selected stations in Appendix A are the stations closest to the centroid for each cluster. The satellite image and Nolli map provide a two-dimensional understanding of roads and mass relationships, urban patterns, densities, and a clear distinction between public and private space using a plan view. Land-use explains the regulation of zoning uses. The 3D rendering image illustrates the building heights, volumes, and uses with different colors. The street pictures show actual urban contexts around station areas.

5. Discussion: Four Types of TOD Areas

Table 7 shows summary statistics for each cluster type to interpret the outcome of cluster analysis and understand each cluster's urban characteristics. The income class is the percentage distribution of the household's average monthly income in Seoul as of 2015. The 1st class represents the bottom 10% income bracket, and the 10th class represents the top 10% household income bracket. The residents and employees are the average number of people who live and work within the 500 m walkshed of subway station areas. The road degree index means the higher the value, the more complex the street pattern with a smaller urban block size. A smaller value means that the cluster has a more grid-like street pattern and a larger block size in the transit catchment areas. The accessibility index is the total average number of accessible buildings in relation to subway stations using the UNA's Reach analysis.

Table 7. Summary statistics of cluster type.

	Data (Average Value)	Cluster 1	Cluster 2	Cluster 3	Cluster 4
	Occupations	**39%**	**52%**	**6%**	**3%**
Demographic characteristics	Income class (1~10)	5.0	4.4	5.2	6.2
	Total resident (persons)	12,714.8	7354.6	2740.0	17,224.5
	Total employment (persons)	5194.7	4232.9	28,762.7	4068.0
	Resident density per housing (/GFA, m^2)	0.027	0.040	0.014	0.015
Built environment characteristics	Ground floor (floor)	4.0	3.5	5.2	5.7
	Underground floor (floor)	0.7	0.6	1.1	0.8
	BUI (0~1)	0.70	0.57	0.23	0.65
	Housing (GFA, m^2)	469,904	179,867	194,778	1,122,005
	Office (GFA, m^2)	63,836	55,049	614,705	56,970
	Retail (GFA, m^2)	124,436	102,441	194,156	153,413
	Entertainment (GFA, m^2)	14,577	18,378	131,854	8424
	Community (GFA, m^2)	50,785	28,923	44,050	74,838
	Industry (GFA, m^2)	13,564	22,096	15,659	6481
	Total building GFA (m^2)	738,140	407,242	1,199,645	1,422,703
	Road degree index (0~1)	0.050	0.056	0.043	0.033
Travel behavior characteristics	Accessibility Index for buildings (count)	530.2	408.6	336.4	240.3
	Daily subway ridership (passengers)	35,676.7	37,519.8	91,590.8	32,840.3

The radar chart (Figure 6) displays the clustering results comparing the quantitative variables of averages on axes starting from the same central point. This uncovers patterns across multiple values to identify dissimilarities of clusters. The chart helps to understand how the values of demographics, built environments, and travel behavior characteristics are different between cluster types through monitoring patterns. The four clusters are also ranked based on nine parameters on the chart. The color coding for each cluster helps to visually correlate and contrast the clusters regarding its diverse aspects. The chart gives an indication that Cluster 1 has higher ranks for accessible buildings and the land use index in comparison to other cluster types. Cluster 2 displays globally lower ranks for parameters than other clusters, except for the road degree index and daily ridership. Cluster 3 has the highest ranks for employment, ground floor, underground floor, and daily ridership, but shows lower ranks for residents and the land use mix index. Cluster 4 shows higher ranks for income class and residents, but lower ranks for employment, the road intersection density index, and daily ridership.

More specifically, Cluster 1 (urban residential neighborhood) is identified as high-density: A form of mixed land use with residential and retail development and a good accessibility to residential buildings and community facilities. The number of residents is, on average, more than twice as large as the number of employees. The average households in Cluster 1 are middle-income families. The land use mix index is 0.7, which indicates that the mixed proportion of land use diversity is relatively similar to the city-wide distribution. Cluster 2 (urban mixed neighborhood) is identified as a group of moderate-density (considerably less dense), high-mixed use with housing, offices, and retail, which is the most common station area type in Seoul (52%). Most urban areas in Cluster 2 developed in the 1970s–1980s and showcase early industrial development and urban expansion in Seoul. On average, this group has a low number of residents, but higher daily ridership than other clusters. Cluster 3 (CBD/compact urban commercial and offices) is identified as the recently (re)developed and densest urban type. It is a compact, high-density, high job, and high retail accessibility environment. There is a very high-density of employees and a retail center, which generates the largest daily ridership of all the cluster types. Cluster 4 (compact apartment complex) is identified as a predominately residential, high-density neighborhood with high-rise apartment complexes with a school and retailers and wealthier households. Residential blocks are prone to transformative change at the district scale. On average, the highest income class lives in this area, but it has the lowest number of employees who work in the area among clusters.

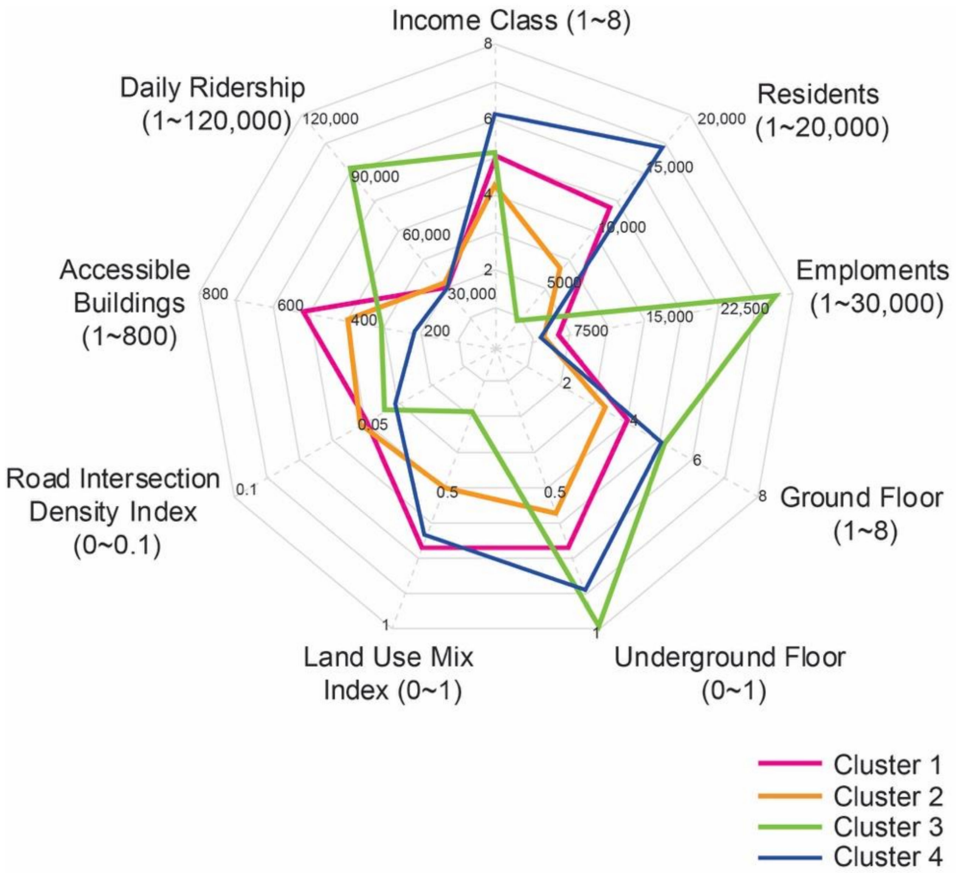


Figure 6. Radar chart of summary statistics for cluster types (source: Figure modified from [45]).

High mixed-used and denser urban renewal projects have recently been developed in some station areas in Cluster 3 and 4. The projects include high-rise residential towers, shopping malls, leisure and cultural spaces, and high-rise office towers that create mega-scale hubs in Seoul. Most subway stations were installed approximately 20–30 years ago and reflect urban growth and change over the period. The urban development period and speed were different between the Gangbuk district and the Gangnam district. The Gangnam area has developed since the 1970s, later than Gangbuk, when the Gangbuk area was already developed as the old city center. This urban development history impacts land use development and transit planning. Therefore, TOD types differ with regard to the urban development time and locations in the city.

6. Conclusions

Subway developments were integrated into urban planning and design throughout the industrialization and urbanization of Seoul in the 1970s. TOD planning worked as an urban generator and led the management of city development. As a result, Seoul became a dense, developed metropolitan city, which limits the potential to introduce a new urban structure in the city. In recent years, Seoul has focused on sustainable urban renewals incorporated within the station area's redevelopment projects. Therefore, government plans and policies require careful investigation of a sustainable urban development strategy for relatively less developed station areas to successfully execute future TOD planning.

For these reasons, this paper has investigated current TOD typologies to recognize potential types that ideally support redevelopments through integrated land use and transportation planning practices and policy implementation around the station areas at the neighborhood scale. Learning from Cervero's research [22], the research has emphasized the relationship between transit development and metropolitan growth and its relationship with urban density, diversity, and pedestrian-friendly design for serving TOD areas. In this research, the clustering outcome reveals the four distinct subway TOD types and gives insight into the unique characteristics of each TOD in Seoul based on urban density, diversity, and pedestrian connectivity.

The main conclusions can be summarized as follows: (1) This study offers considerable useful information and facilitates a meaningful comparison of TOD typologies in Seoul focused on the neighborhood scale. (2) The different urban development period between the Gangbuk and Gangnam areas shapes the characteristics of TOD types. (3) Although Cluster 2 is the most common TOD type in Seoul, it ranks lower in terms of building GFA and diversity parameters. Therefore, Cluster 2 has enough potential for future redevelopment of the TOD areas. (4) The CBD type of Cluster 3 has the most significant transit demand (approximately 2.6 times more daily ridership) in the city, which currently provides an active transit use environment in Seoul. (5) Both Cluster 1 and Cluster 4 have higher ranks for the total number of residents. However, housing building GFA and the resident's average income class of Cluster 4 are much greater than those of Cluster 1. This is because Cluster 4 is a more newly developed residential urban type.

This study's results confirm that the four TODs show distinct characteristics influenced by configurations of the urban density, diversity, pedestrian connectivity, and development period. In this regard, this paper suggests that the city's policy makers contribute to developing supportive policies regarding land use density and diversity patterns based on pedestrian accessibility to foster active and sustainable future TOD planning.

Future studies need to be conducted to further examine the effects of Cluster 3 as an active TOD environment and its sustainability. In fact, the CBD type of Cluster 3 has the most significant transit demand in the city, which provides an active transit use environment. In Cluster 3, non-residential buildings account for an average of 83% of all facilities in the station area. This result shows that non-residential land-use types have a greater influence on the public transportation demand than the residential type at the pedestrian scale. However, commuting between housing and jobs could still be an important factor for increasing the transit demand in cities. Future studies need to carefully review how and why non-residential facilities (e.g., restaurants, shopping malls, offices, etc.) affect the active transit environments and assess the transit supply and demand for a CBD TOD type and residential TOD type to understand active transit use by commuter travels and its effects on sustainable TOD environments in Seoul.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

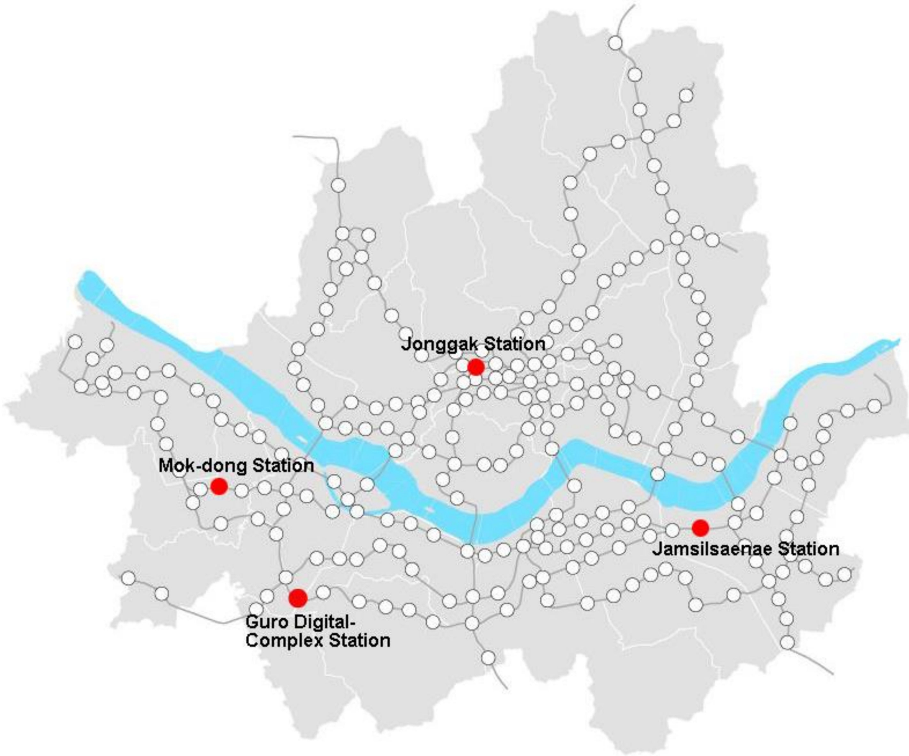


Figure A1. Key map for selected stations (source: from [45]).

Cluster 1 of the case study: Mok-dong Station (urban residential neighborhood).

Ha (2010) explains that, since the mid-1970s, high-rise apartments have been constructed and single-family housing has quickly been replaced by apartments [46]. In particular, 'Danji' became one of the popular apartment development types in Seoul. Mok-dong station opened in August of 1996. The station is near the large Mokdong Apartment Danji built in 1985. There are mixed commercial facilities and single-family houses located on the west side of the station.

Cluster 2 of the case study: Guro Digital Complex Station (urban mixed neighborhood).

Guro Digital Complex Station is a transit hub with approximately 124,300 daily riders transferring between a subway line and buses. It was opened in May of 1984 and called Gurogongdan, which means the Guro manufacturing industrial complex. Gurogongdan was the first industrial complex to promote national export industries in the 1960s. With the development of Information Technology (IT) in the early 2000s, IT offices began to move into this area and knowledge-based industries developed. The station area is mixed with office (Guro Digital Danji), residential, commercial, and entertainment areas.

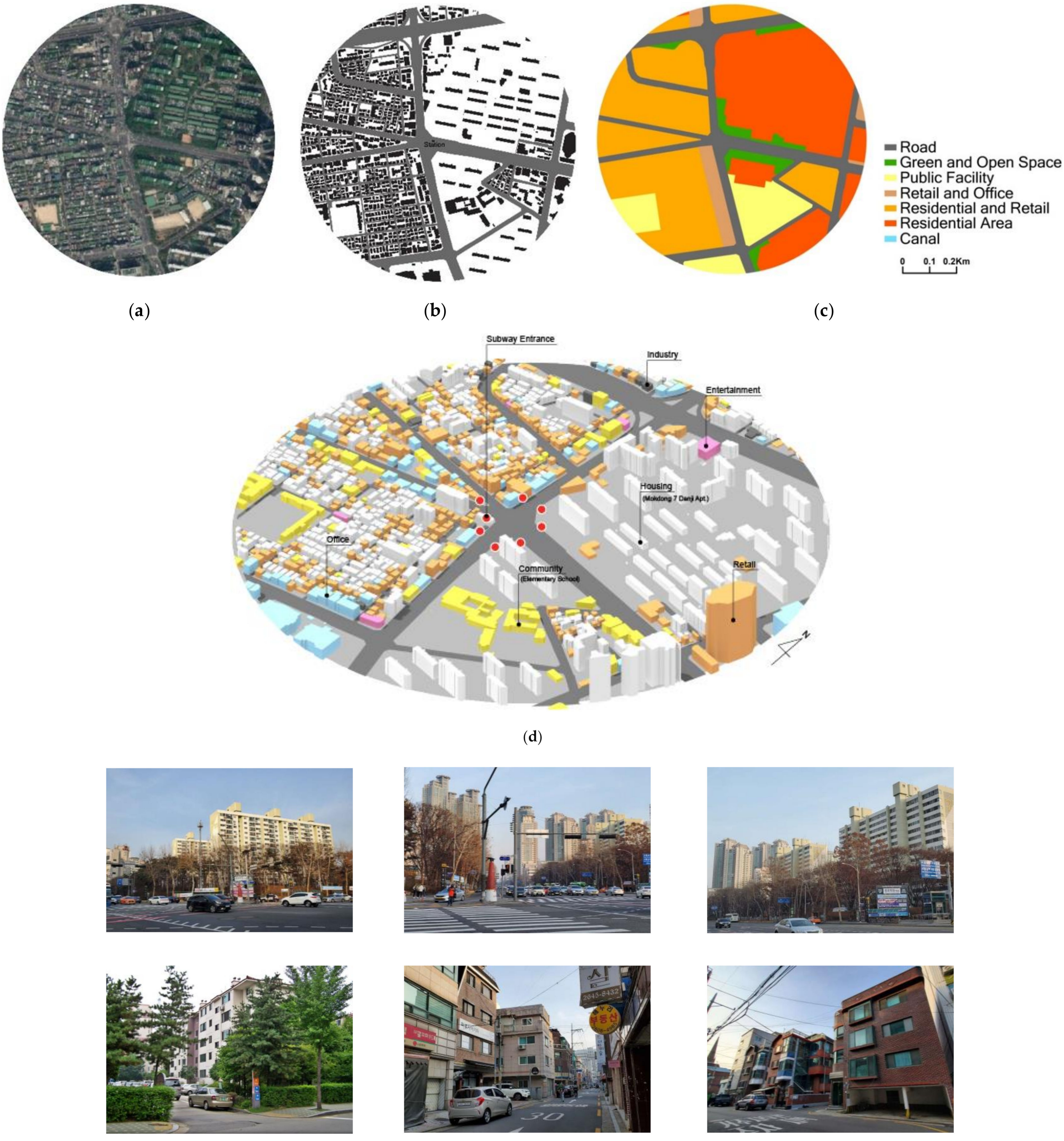
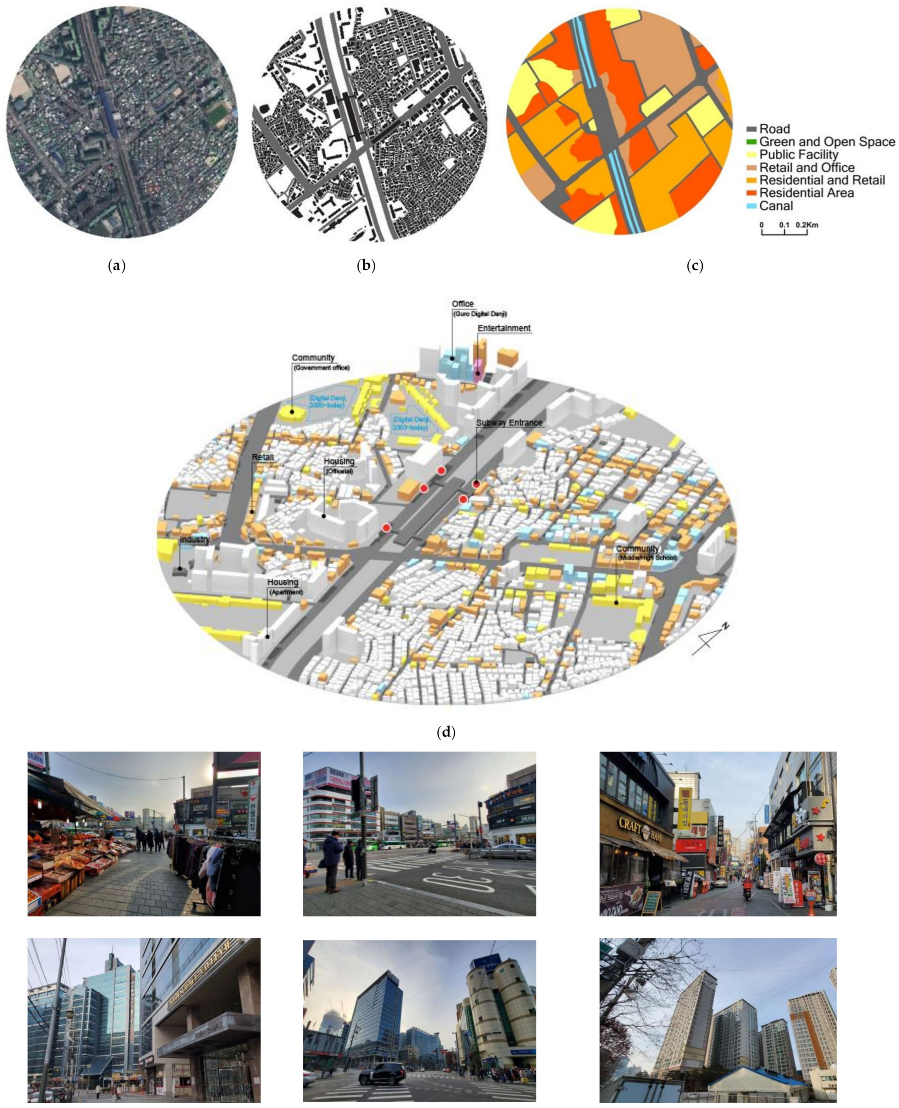


Figure A2. (**a**) Satellite image; (**b**) Nollie map; (**c**) land-use map; (**d**) 3D urban modeling (Bird's-eye view); (**e**) street view (source: Figure modified from [45]; photos by Kim, S.J.).



(**a**) (**b**) (**c**) (**d**) (**e**)

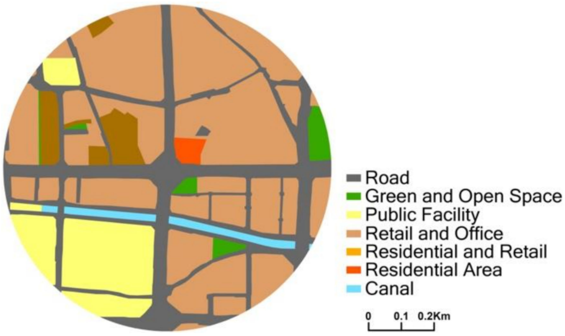
Figure A3. (**a**) Satellite image; (**b**) Nollie map; (**c**) land-use map; (**d**) 3D urban modeling (Bird's-eye view); (**e**) street view (source: Figure modified from [45]; photos by Kim, S.J.).

Cluster 3 of the case study: Jonggak Station (CBD/compact urban commercial and offices).

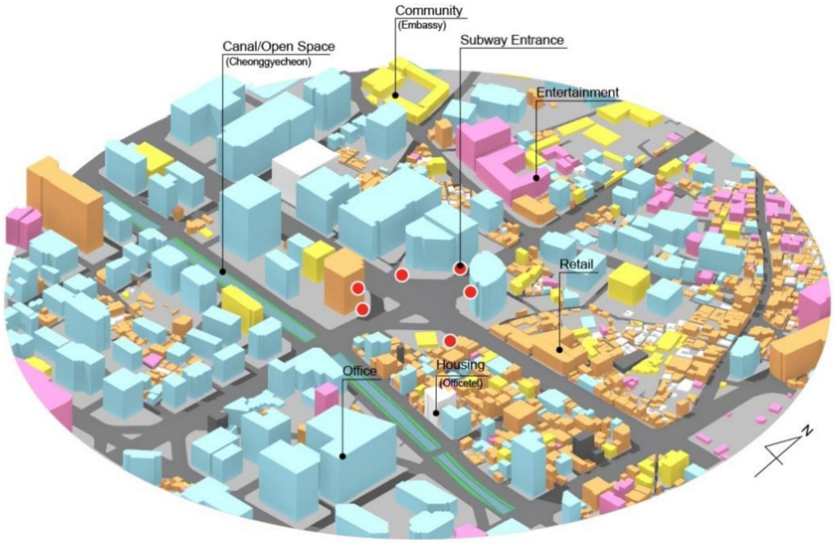
Jonggak Station is located in the Central Business District (CBD) in the center of Seoul. There are high-density and high-rise buildings of financial institutions, private and public offices, an officetel, underground shopping malls, and a commercial center. Over 88,000 passengers use the station every day, making it the third largest station in the subway network by ridership. Cheonggyecheon is easily accessible within the transit catchment area and provides an open and green space near the station.

(**a**)

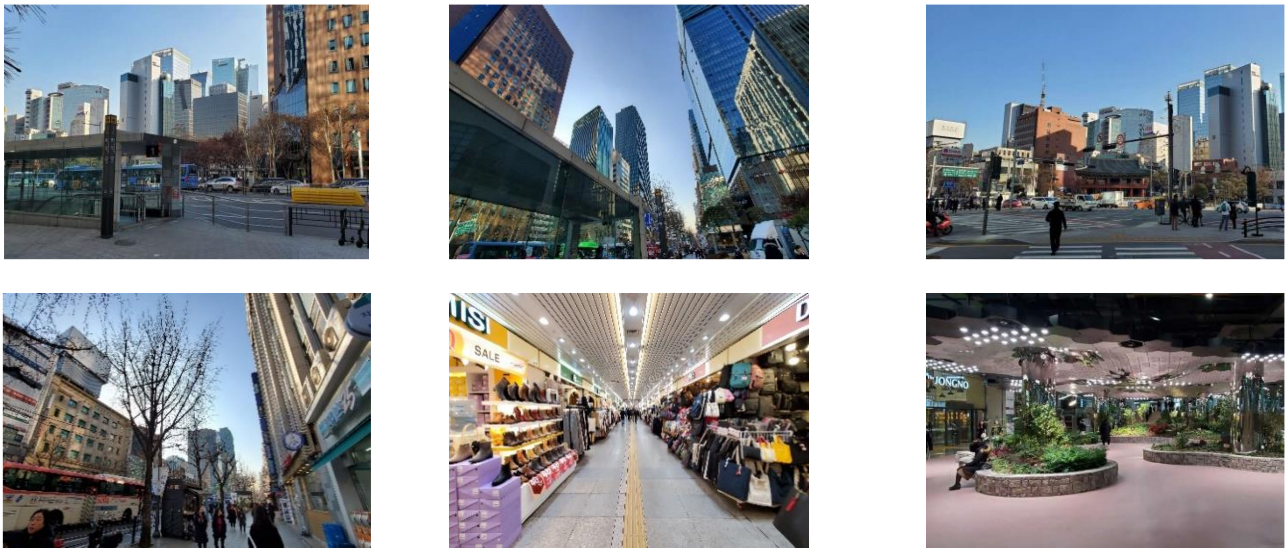
(**b**)



(**c**)



(**d**)



(**e**)

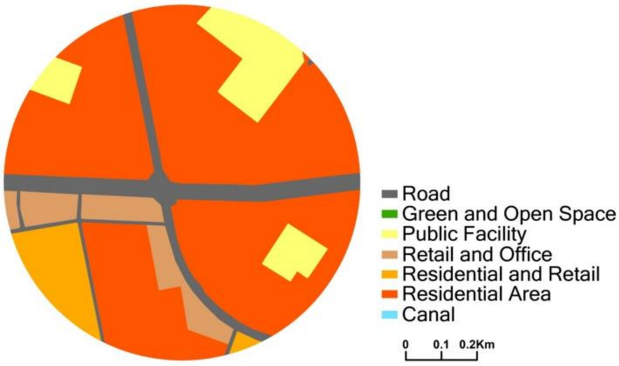
Figure A4. (**a**) Satellite image; (**b**) Nollie map; (**c**) land-use map; (**d**) 3D urban modeling (Bird's-eye view); (**e**) street view (source: Figure modified from [45]; photos by Kim, S.J.).

Cluster 4 of the case study: Jamsilsaenae Station (compact apartment complex).

Jamsilsaenae station is surrounded by Jamsil Apartment Complex, which is comprised of newly developed high-rise apartments reconstructed in 2007–2008. Each center of the apartment block has a school. The building sizes and urban fabric distinguish between old and renewal areas. The new development area has large blocks, high-rise apartment towers, and wide-open spaces between apartment buildings. The old urban area is an example of the urban village type, with narrow streets, small urban blocks, and villa-type housing. The retail area in an old market street, and entertainment spaces are developed at the southwest side of the station.

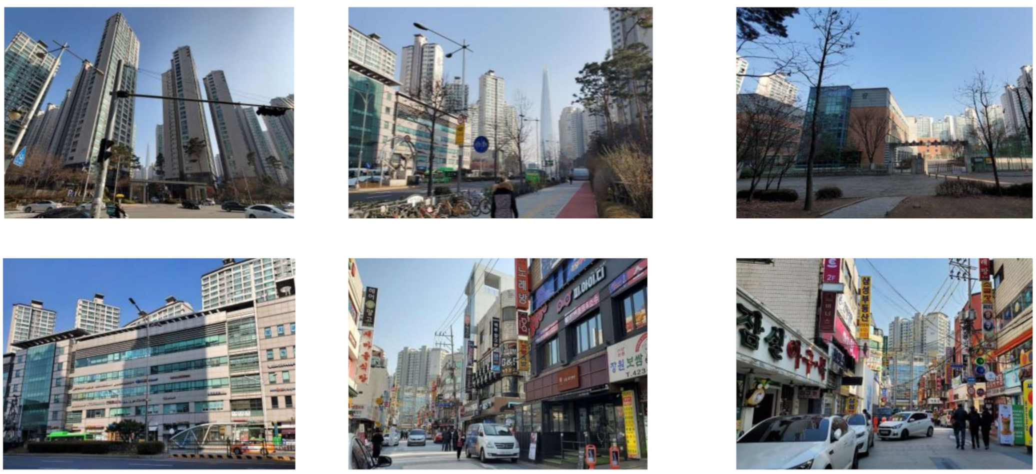
(**a**)

(**b**)



(**c**)

(**d**)



(e)

Figure A5. (**a**) Satellite image; (**b**) Nollie map; (**c**) land-use map; (**d**) 3D urban modeling (Bird's-eye view); (**e**) street view (source: Figure modified from [45]; photos by Kim, S.J.).

References

1. Kim, S. A Study on the Change of Spatial Structure in the Seoul Metropolitan Area between 1995 and 2010. 2014. Available online: https://dbpia.co.kr/journal/articleDetail?nodeId=NODE08786906&language=ko_KR (accessed on 12 January 2021).
2. Bertolini, L. Spatial Development Patterns and Public Transport: The Application of an Analytical Model in the Netherlands. *Plan. Pract. Res.* **1999**, *14*, 199–210. [CrossRef]
3. Li, Y.; Guo, H.L.; Li, H.; Xu, G.H. Transit-Oriented Land Planning Model Considering Sustainability of Mass Rail Transit. *J. Urban Plan. Dev.* **2010**, *136*, 243–248. [CrossRef]
4. Bardaka, E.; Hersey, J. Comparing the travel behavior of affordable and market-rate housing residents in the transit-rich neighborhoods of Denver, CO. *Travel Behav. Soc.* **2019**, *15*, 74–87. [CrossRef]
5. Furlan, R.; Zaina, S.; Patel, S. The urban regeneration's framework for transit villages in Qatar: The case of Al Sadd in Doha. *Environ. Dev. Sustain.* **2020**, 1–17. [CrossRef]
6. Cervero, R. *The Transit Metropolis: A Global Inquiry*; Island Press: Washington, DC, USA, 1998.
7. Berawi, M.A.; Saroji, G.; Iskandar, F.A.; Ibrahim, B.E.; Miraj, P.; Sari, M. Optimizing Land Use Allocation of Transit-Oriented Development (TOD) to Generate Maximum Ridership. *Sustainability* **2020**, *12*, 3798. [CrossRef]
8. Deatrick, J.F. Transit oriented development and sustainable cities: Economics, community and methods, edited by Richard D. Knowles and Fiona Ferbrache. *J. Urban Aff.* **2020**, *43*, 225–227. [CrossRef]
9. Dittmar, H.; Ohland, G. *The New Transit Town: Best Practices in Transit-Oriented Development*; Island Press: Washington, DC, USA, 2004.
10. Partners for Livable Communities. What Is Livability. 2021. Available online: http://livable.org/about-us/what-is-livability (accessed on 19 February 2021).
11. Cervero, R. Public Transport and Sustainable Urbanism: Global Lesson. 2006. Available online: https://escholarship.org/uc/item/4fp6x44f (accessed on 10 November 2020).
12. Bartholomew, K.; Ewing, R. Hedonic Price Effects of Pedestrian- and Transit-Oriented Development. *J. Plan. Lit.* **2011**, *26*, 18–34. [CrossRef]
13. Lyu, G.; Bertolini, L.; Pfeffer, K. Developing a TOD typology for Beijing metro station areas. *J. Transp. Geogr.* **2016**, *55*, 40–50. [CrossRef]
14. Higgins, D.H.; Kanaroglou, P. A latent class method for classifying and evaluating the performance of station area transit-oriented development in the Toronto region. *J. Transp. Geogr.* **2016**, *52*, 61–72. [CrossRef]
15. Center for Transit-Oriented Development. Performance-Based Transit-Oriented Development Typology Guidebook. 2010. Available online: https://trid.trb.org/view/1097129 (accessed on 19 February 2021).
16. Suzuki, H.; Cervero, R.; Iuchi, K. *Transforming Cities with Transit. Transit and Land-Use Integration for Sustainable Urban Development*; The World Bank: Washington, DC, USA, 2013.
17. Arrington, G.B.; Cervero, R. *Effects of TOD on Housing, Parking, and Travel*; Transportation Research Board: Washington, DC, USA, 2008.
18. Calthorpe, P.; Poticha, S. *The Next American Metropolis: Ecology, Community, and The American Dream*; Princeton Architectural Press: New York, NY, USA, 1993.
19. Renne, J.L. From transit-adjacent to transit-oriented development. *Local Environ.* **2008**, *14*. [CrossRef]
20. Reusser, D.E.; Loukopoulos, P.; Stauffacher, M.; Scholz, R.W. Classifying railway stations for sustainable transitions—Balancing node and place functions. *J. Transp. Geogr.* **2008**, *16*, 191–202. [CrossRef]
21. Zemp, S.; Stauffacher, M.; Lang, D.J.; Scholz, R.W. Classifying railway stations for strategic transport and land use planning: Context matters! *J. Transp. Geogr.* **2011**, *19*, 670–679. [CrossRef]
22. Cervero, R. Mixed land-uses and commuting: Evidence from the American Housing Survey. *Transp. Res. Part A Policy Pract.* **1996**, *30*, 361–377. [CrossRef]
23. Lin, J.; Gau, C. A TOD planning model to review the regulation of allowable development densities around subway stations. *Land Use Policy* **2006**, *23*, 353–360. [CrossRef]
24. Beimborn, E.; Rabinowitz, H.; Gugliotta, P.; Mrotek, C.; Yan, S. *Guidelines for Transit Sensitive Suburban Land Use Design*; U.S. Department of Transportation: Washington, DC, USA, 1991.
25. Belzer, D. *Corridor-Level Approaches to Creating Transit-Oriented Districts*; Strategic Economics and Center for Transit-Oriented Development: Washington, DC, USA, 2011.
26. Sung, H.; Choi, C.G. The link between metropolitan planning and transit-oriented development: An examination of the Rosario Plan in 1980 for Seoul, South Korea. *Land Use Policy* **2017**, *63*, 514–522. [CrossRef]
27. Cervero, R.; Sullivan, C. Green TODs: Marrying transit-oriented development and green urbanism. *Int. J. Sustain. Dev. World Ecol.* **2011**, *18*, 210–218. [CrossRef]
28. Beatley, T. Green urbanism: Learning from European cities. *Choice Rev. Online* **2000**, *37*. [CrossRef]
29. Kim, J.; Choe, S. *Seoul: The Making of a Metropolis*; Chichester, J., Ed.; Wiley: Hoboken, NJ, USA, 1997.
30. Kahng, B. *The Year 2000: Urban Growth and Perspectives for Seoul*; Korea Planners Association: Seoul, Korea, 1980; pp. 492–511. (In Korean)
31. Lee, S.; Yi, C.; Hong, S. Urban structural hierarchy and the relationship between the ridership of the Seoul Metropolitan Subway and the land-use pattern of the station areas. *Cities* **2013**, *35*, 69–77. [CrossRef]

32. A Comprehensive Development Plan (Proposal) for Seoul's 10-year Urban Railway Master Plan (Rep.). (n.d.). Seoul City. Available online: http://news.seoul.go.kr/traffic/files/2015/11/5b8cc8d8df5332.97339662.pdf (accessed on 1 February 2021).
33. Halden, D.; McGuigan, D.; Nisbet, A.; McKinnon, A. *Accessibility: Review of Measuring Techniques and Their Application*; The Scottish Executive, Central Research Unit: Edinburgh, UK, 2000.
34. Goldberg, M.A. Transportation, Urban Land Values, and Rents: A Synthesis. *Land Econ.* **1970**, *46*, 153. [CrossRef]
35. Muth, R.F. *Cities and Housing the Spatial Pattern of Urban Residential Land Use*; University of Chicago Press: Chicago, IL, USA, 1970.
36. Sung, H.; Oh, J.T. Transit-oriented Development in a High-density City: Identifying Its Association with Transit Ridership in Seoul, Korea. *Cities* **2011**, *28*, 70–82. [CrossRef]
37. Hanson, S. *The context of urban travel: Concepts and recent trends in The Geography of Urban Transportation*; The Guilford Press: New York, NY, USA, 2004; pp. 3–27.
38. Litman, T. Evaluating Accessibility for Transportation Planning: Measuring People's Ability to Reach Desired Goods and Activities. 2012. Available online: https://www.vtpi.org/access.pdf (accessed on 19 February 2021).
39. Boisjoly, G.; El-Geneidy, A.M. How to get there? A critical assessment of accessibility objectives and indicators in metropolitan transportation plans. *Transp. Policy* **2017**, *55*, 38–50. [CrossRef]
40. Sevtsuk, A.; Mekonnen, M. Urban network analysis. A new toolbox for ArcGIS. *Rev. Int. Géomat.* **2012**, *22*, 287–305. [CrossRef]
41. Sevtsuk, A.; Amindarbari, R. Measuring Growth and Change in East-Asian Cities. *City Form Lab* **2012**, 48–50. Available online: http://cityform.mit.edu/projects/measuring-urban-expansion (accessed on 10 November 2020).
42. Bacher, J.; Wenzig, K.; Vogler, M. SPSS Twostep Cluster—A First Evaluation. Available online: https://www.statisticalinnovations.com/wp-content/uploads/Bacher2004.pdf (accessed on 19 February 2021).
43. Bacher, J.; Wenzig, K.; Vogler, M. *TwoStep Cluster Analysis*; Technical Report; SPSS Inc.: Chicago, IL, USA, 2004; Available online: https://www.ssoar.info/ssoar/handle/document/32715 (accessed on 15 January 2021).
44. Jain, A.K.; Richard, C.D. Algorithms for Clustering Data. In *Prentice Hall Advanced Reference Series*; Prentice Hall: Englewood Cliffs, NJ, USA, 1988.
45. Woo, J.H. Accessibility impacts of Transit Development Areas in Seoul. Harvard University Graduate School of Design. Unpublished Doctoral Dissertation. 2020.
46. Ha, S.K. Housing, Social Capital and Community Development in Seoul. *Cities* **2010**, *27*, 35–42. [CrossRef]