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Exploring the Role of Transit Ridership as a Proxy for Regional Centrality in Moderating the Relationship between the 3Ds and Street-Level Pedestrian Volume: Evidence from Seoul, Korea

Seung-Nam Kim [1,*], Juwon Chung [2] and Junseung Lee [3]

[1] Department of Urban Design and Studies (209-707), Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Korea
[2] Department of Urban Planning and Design Research, The Seoul Institute, 57 Nambusunhwan-ro, 340-gil, Seocho-gu, Seoul 06756, Korea
[3] Department of Urban Design and Studies (207-737), Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Korea
* Correspondence: snkim@cau.ac.kr; Tel.: +82-2-82-5377

Abstract: The preference for walking and the resulting pedestrian activities have been considered key success factors for streets, neighborhoods, and cities alike. Although micro- and meso-scale built environment factors that encourage walking have been investigated, the role of macroscopic factors such as regional centrality in explaining street-level pedestrian volume is often neglected. Against this backdrop, this study examines the relationship between built environments and street-level pedestrian volume using Smart Card and pedestrian volume survey data from Seoul after controlling for transport ridership as a proxy for regional centrality. As a preliminary study, we analyzed 36 regression models applying different sets of transit ridership variables and found that the combination of bus ridership within 400 m and subway ridership within 300 m best explained the variation in pedestrian volume on a street. Then, the effects of the 3D variables (density, diversity, and design) on pedestrian volume were compared before and after controlling for ridership within this spatial range. The results demonstrated that, after taking transit ridership into account, the influence of built environment variables is generally reduced, and the decrease is more pronounced among walkshed-level 3D variables than street-level variables. Particularly, while the effect of "design" (street connectivity) on pedestrian volume appeared to be negatively significant in the constrained model, it was found to be insignificant in the unconstrained model which controlled for transit ridership. This suggests that the degree of street connectivity is influenced by regional centrality, and accordingly, the coefficient of the "design" variable in our constrained model might be biased. Thus, to accurately understand the effect of the meso-scale 3D variables on pedestrian volume, both micro- and macro-scale built environmental factors should be controlled.

Keywords: walking; pedestrian volume; built environment; land use; transit ridership; regional centrality; Seoul

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1. Introduction

Walking has received significant attention in urban and transportation planning as the most traditional, universal, affordable, sustainable, inclusive, and even irreplaceable mode of travel [1–3]. As the reckless spread of urban sprawl increases car dependencies and human-made greenhouse gas emissions accelerate climate change, researchers have further emphasized the importance of walking as a means of transportation [4–7]. Furthermore, walking determines various outcomes for individuals and cities. It affects individual health and social networks, and determines street safety and attractiveness, neighborhood livability and vitality, and even the prosperity of regional and state economies [8–16]. Preference for walking and the resulting pedestrian volume in public spaces is undoubtedly a crucial success factor for streets, neighborhoods, and cities [8,17].

Accordingly, urban design and transportation researchers have actively examined the physical conditions that encourage walking. For example, Jacobs [8] emphasized the importance of sidewalks, parks, land use mix, small urban blocks, and old buildings as prerequisites for walking and street vitalization. Ewing and Handy [18] suggested a conceptual framework explaining the link between the built environment and how an individual feels about the environment as a place to walk. From a more empirical point of view, studies have analyzed the relationship between the built environment and street-level pedestrian volume [19,20].

However, previous studies have seldom deliberated on the macroscopic mechanism that determines the pedestrian volume at a specific street segment and have mainly focused on the influences of the microscopic built environment alone. The pedestrian volume measured on a particular street includes the number of people that happen to be just passing by that point; the number is likely to be determined by the regional centrality and resulting background floating population before the microscopic built environment of that place. The effect of the built environment on the number of pedestrians may vary greatly depending on whether such regional centrality is controlled for, but previous studies have rarely considered this factor. This research gap has been derived from the absence of appropriate methods to control for regional centrality or the resulting background floating population. Here, the transit ridership data would be a reliable alternative to fill this gap in a city such as Seoul, Korea, where public transportation serves a wide range of metropolitan areas and almost everyone uses a Smart Card for payment on that service.

Against this backdrop, using Smart Card and pedestrian volume survey (PVS) data from Seoul, this study aims to analyze the relationship between the built environment and street-level pedestrian volume after controlling for transit ridership as a proxy for regional centrality. Specifically, this study compares the effect of traditional 3D variables (density, diversity, and design) on pedestrian volume between the constrained (excluding transit ridership variables) and unconstrained models (including transit ridership variables). Since the amount of walking on a street determines an individual's perception of the street environment as well as the outcomes of surrounding areas, the results of this study are expected to contribute not only to more accurately estimating the pedestrian volume but also to predicting the success of the street, neighborhood, and city.

2. Theoretical Background and Literature Review

2.1. Pathways from Built Environment to Street-Level Pedestrian Volume: A Conceptual Framework

Traditional travel behavior studies regarding mode choice and trip frequency have focused on the role of the built environment in enhancing active transportation. In particular, Cervero and Kockelman [21] suggested the 3D variables: density, diversity, and design. Following this, Ewing and Cervero [22] included two additional D variables: destination accessibility and distance to public transit. Based on these variables, several studies empirically investigated the effect of 3D to 5D variables after controlling for other factors [21–29]. Studies have also examined the role of microscopic streetscape elements such as architectural details and aesthetics, street furniture, pavement design, microclimate, and safety [30–35].

However, the theoretical framework of pedestrian volume studies is distinct from individual-level walking behavior studies. Contrary to urban design theorists' hopeful belief that more people visit and stay in better places [33,36,37], the number of pedestrians measured on a street (i.e., pedestrian volume) is determined by a wide variety of environmental factors including the built form, weather conditions, and even socio-cultural background [16,29,30,38]. From the viewpoint of transportation planning, to explain the pedestrian volume on a specific street, it is necessary to understand all the factors influencing trip generation, mode choice, and even the route choice of people around that place. Specifically, it is important to consider not only the impact of neighborhood-level walkability and urban design quality but also the effect of regional accessibility and centrality [39]. According to Chung et al. [16], the built environment's role appears differently depending on the activity type of pedestrians. Here, we expand this framework and examine the role of the built environment as a determinant of each behavioral type by scale (Figure 1).

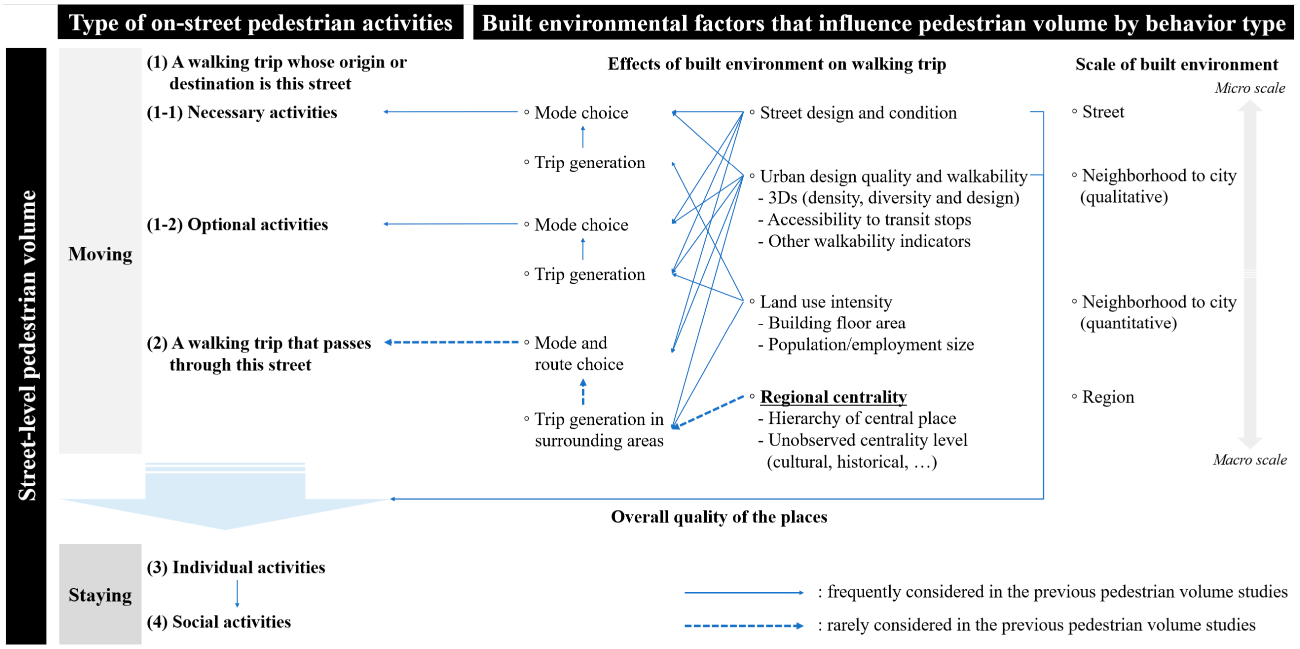

Figure 1. Pathways from built environment to street-level pedestrian volume: a conceptual framework.

Figure 1 illustrates a conceptual framework explaining the pathways from the built environment to street-level pedestrian volume. The pathways in this diagram are not only theoretically based, but also intuitively predictable. When studying pedestrian volume on a street, urban researchers tend to focus more on people who visit or stay at a place for a specific purpose [33,36,37,40]. However, when counting pedestrians on an actual street, a significant number of pedestrians that happen to be just passing by the place are also included regardless of the area's quality. Even though the number of people staying on the street is closely related to the quality of the place, many pedestrians may still pass by, in which case the connection to the built environment is relatively small [33]. Therefore, it is necessary to examine the determinants of walking in accordance with the type of pedestrian activities.

First, the pedestrian activities are divided into "moving" and "staying." For pedestrians on the "move", the activity can be classified broadly into two types: (1) the walking trip whose origin or destination is this street, and (2) the walking trip that passes through this street. Here, type (1) is classified again according to whether the purpose of the walking activity is necessary (1-1) or optional (1-2), and the built environmental factors affecting the activities also change accordingly. Necessary activities (1-1), such as commuting to work or school, are not greatly affected by the quality of the place [33]. Hence, trip generation of necessary activities is directly determined by land use intensity (i.e., employment size or building floor area) rather than the microscopic street environment [41]. However, the proportion of *walking* trips among the total necessary trips generated (mode choice) is affected by the street's design and condition and the urban design quality and walkability of surrounding areas. On the other hand, optional activities occurring in a desired place are more influenced by the built environment at the stage of trip generation (1-2) [33]. Land use intensity is a key driver, but the street- and neighborhood-level environment also matters. The factors determining the proportion of walking trips among the total generated trips are the same as those of necessary activities.

The number of walking trips passing through a specific street segment, type (2), is proportional to the amount of the floating population in the surrounding areas. We therefore need to consider the amount of trips generated in its surrounding areas rather than just that street segment [42]. The floating population is influenced not only by land use intensity and urban design quality, but also by more macroscopic physical aspects such as regional centrality by determining the total number of potential activities [39]. Even if the microscopic conditions of a specific area are the same, the number of trips generated in that area may vary depending on its historical, cultural, and economic centrality and status. Of course, how many of those trips are walking trips and how many of those walking trips will pass through the street (i.e., the internal capture of trips) are influenced by the urban design quality/walkability of surrounding areas and the design/condition of street segments [39].

The number of pedestrians performing "staying" activities (types 3 and 4), such as sitting on a bench or waiting for someone, is undoubtedly proportional to the total number of pedestrians moving in the area. Since only pedestrians on the move can stay, more moving activities cause more staying activities. Therefore, all the built environmental factors that generate moving activities indirectly generate staying activities at the same time. In addition, Gehl [33] argued that when there is a desirable place to stay, people who were passing by may also remain in that place; in a good built environment, these individual activities can develop into social activities, such as conversations and group activities. Thus, the conversion rate of moving activities to staying activities is closely related to the overall quality of the place [37,43].

Despite the above mechanism, the pedestrian volume on the street is just a single value, and the type of activity comprising that value cannot be known. Thereby, when explaining the variance in pedestrian volume using an econometric approach, all built environments ranging from the street (micro) to regional (macro) scales should be comprehensively considered. The next sub-section reviews the empirical evidence on this issue.

2.2. Empirical Evidence on the Relationship between Built Environment and Pedestrian Volume

Studies have empirically analyzed the relationship between the built environment and street-level pedestrian volume using data from diverse cities worldwide. Based on the conceptual framework explained in Figure 1, key findings of previous studies are summarized as follows.

Regarding the street-level built environment, Ewing et al. [25] examined the role of streetscape features to explain pedestrian volume using pedestrian count data from 588 blocks in New York City. They revealed that the design and use of adjacent buildings (i.e., proportion of first floor with windows, proportion of retail frontage, and proportion of active-use buildings) and street furniture encouraged pedestrian activities. In terms of specific street conditions, Rodríguez et al. [44] showed that sidewalk width was positively associated with pedestrian count in 338 street segments in Bogota. Using PVS data from Seoul, several studies also found that wider sidewalks and roadways, the existence of street furniture and crosswalks, and the absence of slopes and parked vehicles were crucial predictors of pedestrian volume [16,19,20,45–50].

The role of the 3D variables (density, diversity, and design) has also been the focus of previous studies. To measure those variables, studies have applied 50 to 500 m buffers from the survey spots, most frequently using 400 m (quarter mile). Although the specific type of measure is different (population density, job density, commercial density, floor area ratio, etc.), most studies confirmed that the higher the "density", the greater the pedestrian volume [25,26,44–46,50,51]. However, when two or more density variables were included in the model at the same time, as in Kang [20], conflicting signs of coefficients were also drawn. Here, when the spatial range for variable measurement is constant (e.g., 500 m buffer), both density and size (both population and employment) variables have the same meaning. Therefore, a couple of studies additionally controlled for the land use intensity using the building floor area variable [48]. Next, Lee et al. [45], Lee et al. [48], and Hajrasouliha and Yin [26] showed that a higher land use mix ("diversity") generates more walking activities. Lastly, studies also revealed a strong association between good street connectivity ("design") and pedestrian volume on the street by applying diverse forms of measures: road density [44], intersection density [26], intersection type (number of ways) [47,51], and average street length [51]. By contrast, the proportion of major arterials was found to be negatively associated with pedestrian volume [51].

In addition to the 3Ds, studies have also demonstrated that good public transit accessibility could be a key explanatory factor of pedestrian volume. Because people may walk a few blocks before boarding or alighting transport, pedestrian volume on the street is closely related to public transportation facilities in the surrounding areas [42]. While most studies have applied transit accessibility in the form of "existence/number of transit stops/stations within certain areas" or "distance to the nearest stops/stations" [20,25,45,47–49,51,52], Jang et al. [50] additionally considered the number of subway station entrances and subway/bus lines, daily service frequencies, and the distance decay effect.

Compared to the street- or neighborhood-level built environment, regional centrality has been rarely considered. Using PVS data from Seoul, Kang [20] investigated the effects of land-use accessibility and centrality on pedestrian count. His series of multilevel models showed that residential-, commercial-, and office-use accessibility and centrality, which were measured in terms of betweenness, straightness, and a gravity index, were positively associated with both weekday and Saturday pedestrian volume. However, regional centrality indicators using built environmental attributes are not a suitable variable to explain the variance in pedestrian volume as measured at different times. This is because the former is static, whereas the latter is day-dependent.

Thus, the surrounding area's transit ridership corresponding to the day when the PVS was taken has been considered as an alternative way to control for regional centrality. For instance, Rodríguez et al. [44] used the bus rapid transit (BRT) ridership to control for the BRT station demand itself in a model that explained the variation in pedestrian volume around the BRT stops. Using Smart Card data from Seoul, Chung et al. [16] attempted to control for the regional centrality of PVS spots by employing the bus and subway ridership of the surrounding areas to explain pedestrian volume. In both studies, transit ridership was identified as a robust estimator of walking activity. However, neither study tested how much spatial range should be considered when measuring the variable. Despite their different influences, Chung et al. [16] used a 400 m (1/4 mile) buffer for bus and subway en bloc. Unlike this, the present study firstly identifies the size of the influential area of transit stops/stations and then measures ridership within those identified areas as a proxy for regional centrality and the resulting floating population. Afterward, the study compares the effects of the traditional built environment factors (i.e., 3D variables) on pedestrian volume before and after controlling for transit ridership.

3. Empirical Setting

3.1. Study Area

The study area covers Seoul, the capital of South Korea, with a population of approximately 10 million (approximately 19.4% of the national population) over an area of 605 km^2 (0.6% of the national territory) as of 2019 [53]. As per the *2030 Seoul Master Plan* [54], Seoul pursues a polycentric spatial structure consisting of three central business districts (CBDs), seven regional centers, and twelve local centers. However, most employment is concentrated in the triangle-shaped area connecting the three CBDs, as can be illustrated through a regional job accessibility (RA) measure (Figure 2). (The RA measure was conceptually proposed by Hansen [55]. Since the RA of a given Transportation Analysis Zone (TAZ) is defined as the sum of jobs inversely weighted by their distance from the TAZ, TAZs with higher RAs represent the employment centers of the region [56]. To measure the RAs of 424 TAZs in Seoul, we used employment data from 1,138 TAZs not only in Seoul but also in its surrounding areas (i.e., Incheon and Gyeonggi Province) in 2015. Term $RA_i = \sum_j E_j \times e^{(\beta d_{ij})}$, where RA_i is regional job accessibility in TAZ i; E_j is total employees of TAZ j, β is the distance resistance coefficient = 0.280 [57], and d_{ij} is the distance between TAZ i and j [56].)

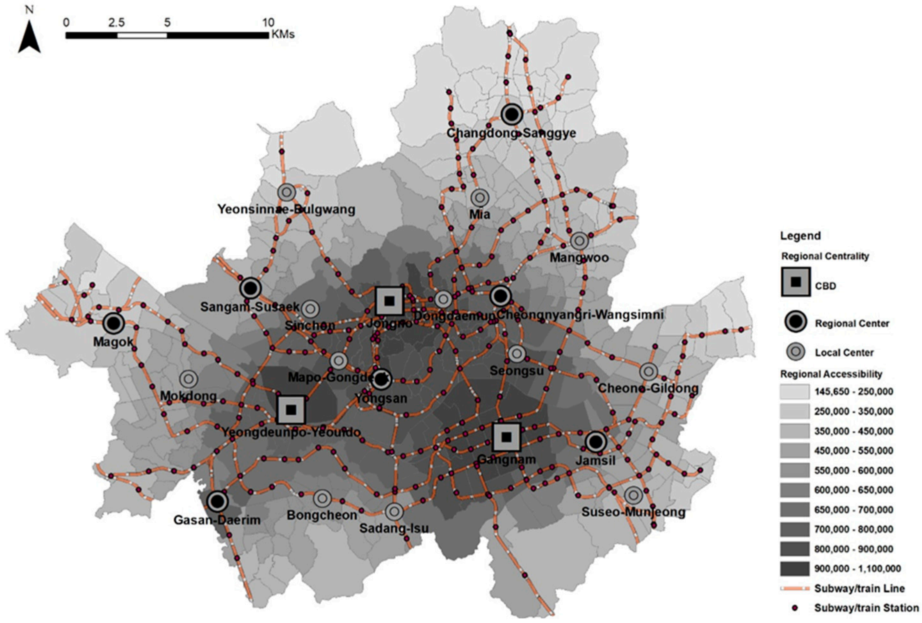

Figure 2. Map of Seoul: Location of central places suggested in the *2030 Seoul Master Plan* [54], regional job accessibility of 424 *Dong* (literally means a neighborhood in Korean, and it is the smallest administrative unit in Seoul. This spatial unit, *Dong*, is used as the TAZ in Korea) in 2015, and location of subway lines and stations in 2015.

Seoul's sizable population density (17,013 people/km^2) makes public transportation feasible [15,54]. In 2019, Seoul had 10 subway lines supporting 329 stations and 354 bus lines with 6254 stops [58–60] (Figure 2). The collective commuting modal share of public transport, walking, and cycling was relatively high at 77.8% in 2019 [61]. Seoul also has a very convenient and advanced payment system called "Smart Card" [48,62]. According to Lee [63], as of 2014, 99.02% of transit users paid for their fares with a Smart Card. Thus, transit ridership data collected through Smart Card usage information can be one of the most suitable proxies for the floating population and regional centrality in Seoul.

In addition, from 2009 to 2015, the Seoul Metropolitan Government investigated and provided quality data to the public for pedestrian volume studies. Since the data (i.e., PVS data) contain quite large samples covering almost all built-up areas of Seoul, which is one of the largest metropolitan cities, it has a variety of advantages over other research data worldwide [16]. Accordingly, the data have been widely used for pedestrian volume studies [16,19,20,45–50]. We believe that Seoul, which has a quality Smart Card system as well as transit ridership and PVS data, is a most suitable study area for this study.

3.2. Data and Variables

To explore the relationship between the built environment and street-level pedestrian volume, this study used the following data from Seoul, 2015: (1) PVS data, (2) transit ridership data, and (3) various spatial data for measuring the built environments. Specific measurements were selected based on the literature review previously provided (Section 2; Figure 1). The following sub-sections describe the study's data, measurements, and analysis method and model specifications.

3.2.1. Pedestrian Volume (Dependent Variable)

To measure street-level pedestrian volume (the dependent variable), we used the 2015 PVS data from Seoul. The Seoul City Government and National Information Society Agency had jointly launched this survey in 2009, and it was conducted annually until 2015. Namely, the data used in this study were the most recent. The survey was conducted by trained investigators who employed manual counting in the field. As Chung et al. [16] argued, this approach has various advantages over self-report surveys or automated counting using GPS, sensors, and computer vision techniques.

In the 2015 survey, 1223 spots (street segments) were investigated. The spots were officially selected from an initial 10,000 representative spots selected by the Seoul Metropolitan Government in 2009, including (1) arterial roads, (2) streets in CBDs, regional centers, and local centers, (3) streets in low-rise residential and mixed-use areas, and (4) roads along the Han River [64]. Using cluster analysis, the 10,000 spots were clustered so that 5 to 20 spots were included in one cluster based on land use and location (longitude and latitude coordinates) [65]. Then, in each annual survey, at least one survey spot candidate was randomly selected from each cluster, and the spots were finalized after confirming both the possibility of securing a view and the presence of a place to avoid sunlight through a preliminary field survey [64,65]. As a result, the survey spots covered a considerable portion of built-up urban areas in Seoul, as shown in Figure 3. Each street segment was investigated three times a week (either Tuesday or Thursday; Friday; and Saturday) from 2–31 October 31. On each day, every pedestrian was counted from 07:30 to 19:30. Because the survey was not conducted on a single day, it is necessary to consider factors that might vary depending on the survey date in the model specification process.

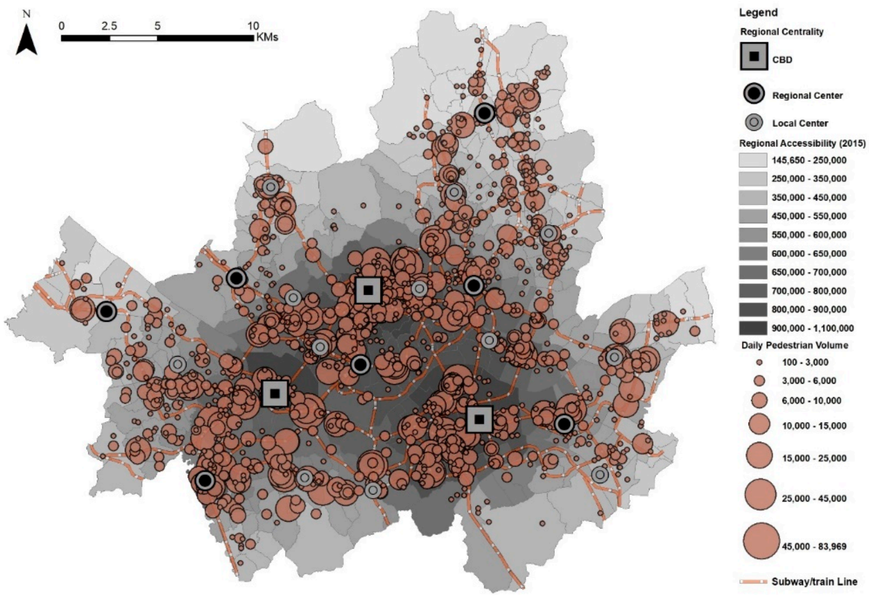

Figure 3. Central places in 2014 [54], regional job accessibility in 2015 (authors' calculation), and 2015 PVS spots and their results (2015 PVS data).

The data cleaning procedures followed those of Chung et al. [16]. First, we excluded the data gathered on Thursdays as the survey was conducted on only two days (15–22 October) as a supplementary survey for the Tuesday survey, and the number of spots included was quite small (one and three spots, respectively). Second, we also excluded the data surveyed from 28–31 October, which were not provided by the Seoul Open Data Plaza due to data processing errors. Finally, to render the distribution closer to normality, we used the log-transformed daily pedestrian volume of 2889 observations counted at 1162 survey spots as a dependent variable. Since the data contained the exact X- and Y-coordinates and various physical conditions of the survey spots, we were able to analyze the effect of the specific built environment on street-level pedestrian volume.

3.2.2. Transit Ridership (Proxy for Regional Centrality)

As discussed in Section 2, using Smart Card data, we controlled for daily transit ridership of the PVS days as a proxy for regional centrality. The transit ridership variable is expected to contribute in two major ways to explaining the variation in street-level pedestrian volume. First, because people may walk before boarding and after getting off a transit [42], transit riders of surrounding areas naturally/directly become pedestrians on the street. Second, transit ridership can be a proxy variable representing the level of centrality of that area. In other words, in Seoul, a large number of transit users in an area means that there is a larger floating population in the surrounding areas. Either way, transit ridership is inevitably closely related to the floating population, and as explained in Figure 1, the floating population can potentially be connected to the amount of walking trips that pass through a certain street, alongside the consequent staying activities.

Figure 4 shows that subway stations and their ridership are concentrated in the CBD triangle area. Bus stops are relatively more distributed, but major stops with the highest ridership are populated in major central places, particularly Gangnam CBD area (Figure 5). These support our premise that transit ridership can be a useful proxy for regional centrality. In addition, given the characteristic of the dependent variable being composed of non-single survey days, transit ridership, which is a time-dependent variable, is more suitable for controlling for regional centrality than other static variables such as regional job accessibility and central place hierarchy, and thereby addresses the limitations of prior studies using PVS data.

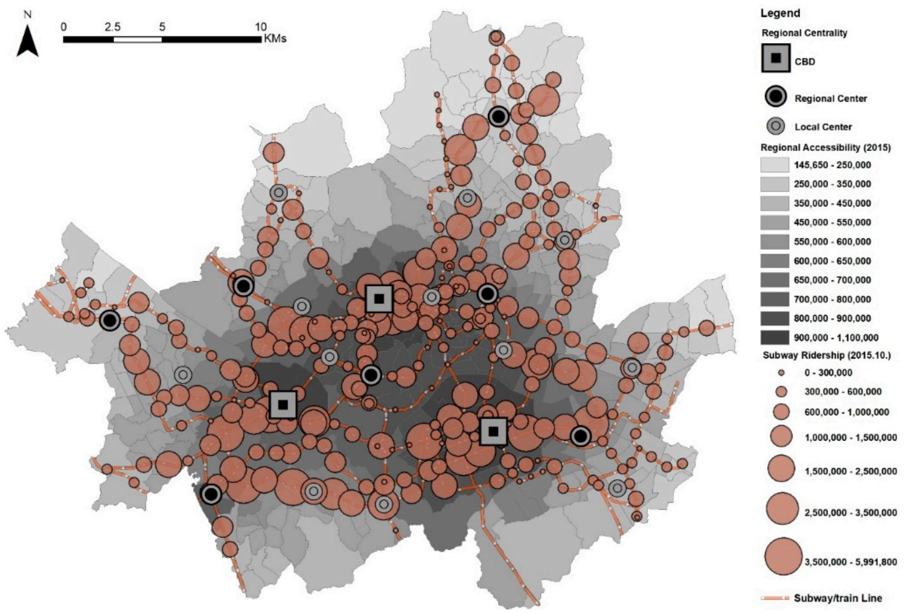

Figure 4. Central places in 2014 [54], regional job accessibility in 2015 (authors' calculation), and total subway ridership in October 2015 (2015 subway ridership data).

Specifically, the log-transformed daily total number of passengers boarding and alighting at all bus stops and subway stations within certain areas of the survey spot on the survey day was measured as an independent variable in the model. Here, it is important to determine the transit stops' influential area from the PVS spot. In contrast to the conventionally used 400 m to 500 m walkshed in previous walkability studies when measuring the built environment, there is little empirical guidance regarding the spatial extent of transit ridership that best explains the pedestrian volume on a street. Accordingly, in Section 4.1, we identify the size of the influential areas of bus stops and subway stations, respectively, by successively applying 100 to 600 m buffers at 100 m intervals for measuring each transit's ridership, and finding the ridership set with the highest explanatory power for a preliminary regression model among the 36 possible combinations.

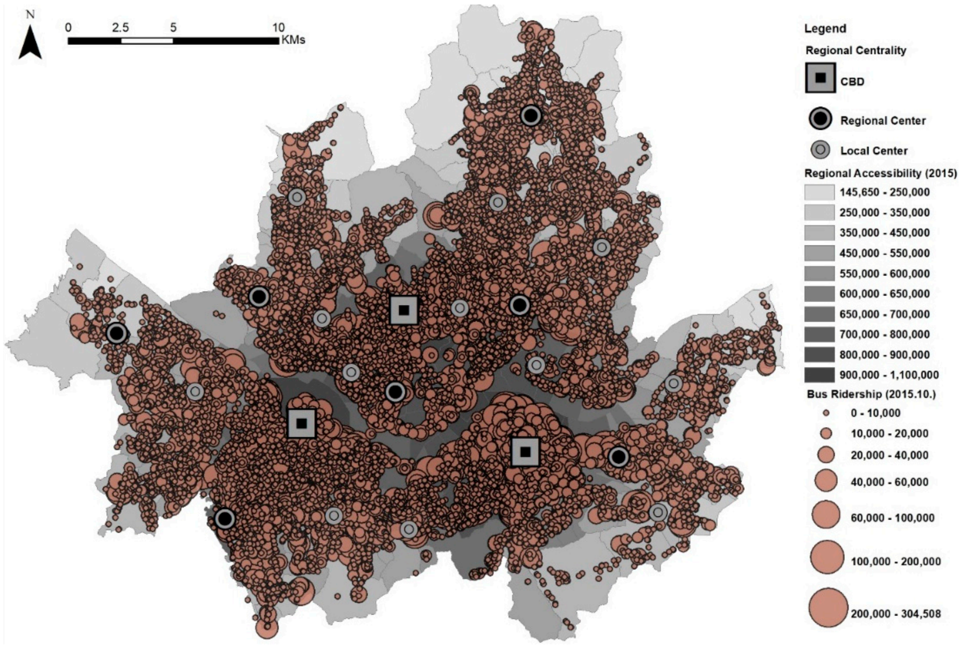

Figure 5. Central places in 2014 [54], regional job accessibility in 2015 (authors' calculation), and total bus ridership in October 2015 (2015 bus ridership data, only 12 PVS days included).

3.2.3. Walkshed-Level Built Environment (3D) Variables

As for walkshed-level built environment variables, we measured and employed the 3D variables within 500 m of the survey spot. Unlike the size of the transit stations' influential areas, the size of the walkshed is generally agreed in previous studies to be approximately a 400 m to 500 m buffer [20,66,67].

First, for the "density" measure, we controlled for both population and job density (the number of residents and workers in the 500 m walkshed). Since the area of the walkshed is constant, this measure has the same meaning as controlling a fixed population (i.e., population and employment size). As explained in Section 2, density variables are applied in almost all previous studies (e.g., [15]). They are mainly expected to affect trip generation and mode choice, thereby explaining the variation in pedestrian volume.

Second, for the "diversity" measure, while previous studies mostly applied the extent of land use mix such as the entropy index [68], we employed the facility accessibility index, borrowing the core concept of WalkScore™ [69]. This covers not only land use diversity but also proximity to pedestrian-friendly facilities. As Frank et al. [70] revealed, the higher the mixed land use, the closer the convenience facilities such as grocery stores, shops, and restaurants, and the more walking activities occur in the specified areas. Lee and Moudon [27] also argued that distance to routine daily destinations can be simple and effective alternatives to a complicated land use mix index. Using data from the Ministry of Security and Public Administration, Korea, this study categorized pedestrian-friendly facilities into (a) restaurants and cafes, (b) shopping facilities, (c) cultural and leisure facilities, (d) educational facilities, and (e) public transportation facilities (Table 1). We then estimated the weight of each category using the analytic hierarchy process (AHP) method developed by Saaty [71] by surveying 73 experts in the urban and transportation fields via email. Of the 53 experts who responded (53/73 = 72.6%), only responses of 43 experts (43/53 = 81.1%) whose consistency index was less than 0.2 were used for analysis. They averaged 13.6 years of professional experience, and 82% were either professors or researchers with either a master's or doctoral degree. Table 1 shows the result of AHP analysis. Finally, we calculated each PVS spot's facility accessibility index considering whether each facility was located within walkable distance from the spot. Specifically, we awarded 2 points if the facility was located within 250 m and 1 point for 500 m, similar to those of WalkScore™. Then, we summed all the points after multiplying their weights.

Table 1. Type and weight of pedestrian-friendly facilities.

Category		Specific Type of Facility	Weight
(a)	Restaurants and cafés	General restaurant, café	0.164
(b)	Shopping facilities	Market, department store, shopping center, outlet, mall, general store	0.161
(c)	Cultural and leisure facilities	Theater, exhibition hall, museum, auditorium, concert hall, zoo, botanical garden, gym, swimming pool	0.141
(c)	Educational facilities	Library, kindergarten, elementary/middle/high school, university	0.177
(e)	Public transportation facilities	Bus stop, bus terminal, subway station, train station	0.357

Third, regarding the "design" measure, we applied the connectivity index (i.e., link/node ratio), which is a widely used indicator in previous studies and urban design guidelines [72–74]. As Jacobs [8] emphasized the importance of small blocks, the more connected the pedestrian path, the more walking activities people complete. The link/node ratio reflects at least three characteristics of street networks: whether the block size is small, whether the pedestrian path is properly connected, and whether the networks provide shorter and more varied routes. We measured the ratio using the pedestrian path network map in Seoul provided by the National Geographic Information Institute in Korea and following Steiner and Butler's [72] guideline. Along with the pedestrian volume and transit ridership variables, the 3D variables explained so far were also log-transformed to convert their distribution closer to normality. Resultantly, we could interpret the coefficients of key built environment variables as the elasticity of pedestrian volume.

3.2.4. Street-Level Built Environment Variables

We also controlled for street-level built environment variables including adjacent land use, street type, and specific street conditions of the survey spot. Because the information was included in the PVS data, most previous papers have also controlled for them [16,19,20,49]. As Gehl [33] suggested, the quality of the microscopic urban spaces can also affect the number of people on a street.

First, to control for land use of the surrounding area, two land use dummy variables—commercial and residential—were used, with other uses as the reference group. In general, we can expect that people would be more likely to walk and stay in commercial streets with higher diversity and vitality [33,37,50]. Second, we employed the street type of the survey spot. This was defined as dummy variables for "street with a sidewalk" and "street without a sidewalk (i.e., shared street)", where "street with a sidewalk, but shared with bicycles" functioned as the reference group. Third, regarding specific street conditions, we controlled for the sidewalk width, number of traffic lanes, and various dummy variables assessing the presences of road centerlines, sloping road segments, pedestrian protection fences, nearby crosswalks, and obstacles to walking. Here, note that these dummy variables were measured based on their presence within 50 m from the survey spot, and the presence of a sloping road segment was entirely determined by the trained investigator's perception [16]. Definitions and descriptive statistics of all variables explained so far are provided in Table 2.

Table 2. Definitions and descriptive statistics.

Variables	Definition (Unit)	Mean	S.D.	Min.	Max.
Dependent variable					
Pedestrian volume	Total daily pedestrian counts	7121	9615	57	103,437
	Ln (pedestrian volume)	8.247	1.164	4.043	11.547
Transit ridership (proxy for regional centrality): macro-scale variables					
Bus ridership	Daily bus ridership within 400 m buffer	23,494	21,326	0	127,236
	Ln (bus ridership + 1)	9.696	0.953	0.000	11.750
Subway ridership	Daily subway ridership within 300 m buffer	27,020	43,941	0	247,209
	Ln (subway ridership + 1)	4.512	5.350	0.000	12.420
Walkshed-level variables (within 500 m buffer): meso-scale variables					
Density (population)	Population density of census tracks within 500 m (capita/m^2)	0.016	0.010	>0.001	0.041
	Ln (population density)	−4.467	0.936	−9.520	−3.190
Density (job)	Job density of census tracks within 500 m (capita/m^2)	0.019	0.022	>0.001	0.124
	Ln (job density)	−4.570	1.133	−9.440	−2.090
Diversity	Facility accessibility index (see Section 3.2.3)	0.406	0.118	0.050	0.710
	Ln (facility accessibility index)	0.277	0.170	−0.528	0.837
Design	Connectivity index (link/node ratio)	1.338	0.221	0.590	2.310
	Ln (connectivity index)	−0.951	0.334	−2.996	−0.342
Street-level variables (mostly within 50 m buffer): micro-scale variables					
Land use					
Residential	Residential use (yes = 1)	0.694	0.461		
Commercial	Commercial use (yes = 1)	0.222	0.415		
Other land use (ref.)	Other land use (yes = 1)	0.085	0.218		
Street type					
With sidewalk	Street with a sidewalk (yes = 1)	0.711	0.454		
Without sidewalk	Street without a sidewalk shared with pedestrians and vehicles (yes = 1)	0.084	0.278		
With shared sidewalk (ref.)	Sidewalk is shared with pedestrian and bicycle (yes = 1)	0.205	0.404		
Street condition					
Sidewalk width	Width of sidewalk or fringe of the road for pedestrian passage (m)	4.198	2.221	1.000	24.000
# of traffic lanes	Number of traffic lanes (count)	4.182	2.731	1.000	18.000
Presence of centerline	Dummy (yes = 1, *within 50 m buffer*)	0.730	0.444		
Presence of sloping road	Dummy (yes = 1, *within 50 m buffer*)	0.213	0.409		
Presence of fence	Dummy (yes = 1, *within 50 m buffer*)	0.225	0.417		
Presence of crosswalk	Dummy (yes = 1, *within 50 m buffer*)	0.616	0.486		
Presence of obstacle	Dummy (yes = 1, *within 50 m buffer*)	0.917	0.276		

Number of observations = 2889.

3.3. Analysis Method and Model Specification

We employed a multiple regression approach to test the effects of the built environment variables explained above. Although we conceptually categorized them into three levels (street-, walkshed-, and regional-level), the variables had no actual hierarchical structure in the data, so there was no need to apply multi-level analysis. However, we applied spatial regression analysis methods to consider a potential spatial autocorrelation issue.

The analysis consisted of two steps. As a preliminary analysis, we identified the size of the influential areas of bus stops and subway stations that best explain the variation in pedestrian volume. We first ran 36 ordinary least squares (OLS) regression models by applying different sets of bus and subway transit riderships that were measured based on different sizes of influential areas (100 m to 600 m at 100 m intervals). Then, we conducted a spatial regression analysis including the transit riderships within the specific influential areas identified above and identified a more suitable model between the spatial lag and spatial error models. Lastly, we ran 36 spatial lag or spatial error models again by applying different sets of transit riderships and identified the final size of the bus stops' and subway stations' influential areas.

In the second step, we conducted two spatial regression analyses: constrained and unconstrained models. While the constrained model excluded the transit ridership variables, the unconstrained model included transit ridership measured within the specific influential areas identified in the first step. Then, we compared the results of the two differentiated models depending on whether or not transit ridership was controlled for. Except transit ridership, the same set of independent variables were applied in all regression models explained so far.

4. Results of Analysis

4.1. Preliminary Analysis: Determining the Size of the Transit Stops' Influential Area

Through the process described in Section 3.3., we found that the spatial error model had a better goodness of fit than the OLS and spatial lag models (see Appendices A and B). Then, we ran 36 spatial error models applying different sets of bus and subway transit riderships and found that the ridership variables in all 36 models had statistically and positively significant associations with street-level pedestrian volume at the 1% probability level (Table 3). Therefore, we determined the size of the transit stops' influential areas that best explain the variation in pedestrian volume based on the model fit measures. Table 3 illustrates that the model applying a bus ridership within 400 m and a subway ridership within 300 m shows the highest explanatory power (Pseudo R^2 = 0.5232). Log-likelihood statistics also show exactly the same pattern (see Appendix C).

Table 3. The explanatory power (Pseudo-R^2) of the spatial error models by the transit stop/station's influential area size.

		Subway Ridership Within					
		100 m	**200 m**	**300 m**	**400 m**	**500 m**	**600 m**
Bus ridership within	100 m	0.492	0.509	0.518	0.513	0.511	0.495
	200 m	0.493	0.509	0.516	0.511	0.510	0.497
	300 m	0.504	0.518	0.5227	0.516	0.516	0.506
	400 m	0.504	0.519	**0.5232**	0.514	0.512	0.503
	500 m	0.496	0.515	0.519	0.509	0.504	0.494
	600 m	0.480	0.500	0.508	0.500	0.496	0.481

Note: All models' bus and subway riderships had statistically positive associations with street-level pedestrian volume at $p = 0.01$. Other built environmental factors suggested in Table 2 were applied as control variables in all regression models.

These spatial ranges are not substantially different from other similar empirical studies ([75], light-rail station 326 m; [66], BART (Bay Area Rapid Transit) station 548 m; [76], transit stops 494 m) or the general walking distance (400 m to 500 m) conventionally adopted in previous studies [16,20,66,67]. This reflects the general tendency that people are willing to walk before boarding or after alighting from transit [42]. This result also supports the persisting claim that values the link between walking and public transportation [76–78]. Reflecting this result, we applied both the 400 m buffer bus and 300 m buffer subway transit riderships in the unconstrained model as a proxy for regional centrality.

4.2. Impact of Built Environment on Pedestrian Volume: Transit Ridership Controlled vs. Not Controlled

Appendix A (constrained models) and Appendix B (unconstrained models) present the results of OLS, spatial lag, and spatial error models of the log-transformed street-level pedestrian volume. In all models, the variance inflation factor (VIF) values were quite small; accordingly, no multicollinearity was found. Moran's I, Rho (ρ), and Lambda (λ) values in the models were statistically significant, indicating the presence of spatial autocorrelation. The results of the Lagrange Multiplier (LM) lag and error test demonstrated that the spatial error model had better goodness of fit than the spatial lag model. The improvement of fit measured by Log likelihood, Akaike Info Criterion (AIC), and Schwarz Criterion (SC) was also greater in the spatial error model than in the spatial lag model.

Table 4 summarizes the results of both the constrained (not controlled for transit ridership) and unconstrained (controlled for transit ridership) spatial error models. As expected, due to the strong significance of both ridership variables (coefficient: 0.267, 0.043; Z: 10.760, 11.775), the unconstrained model showed higher explanatory power (Pseudo-R^2: 0.523) than the constrained model (Pseudo-R^2: 0.475) and those of previous studies using the same dataset [19,20,45–50,79], although R^2 and Pseudo-R^2 are not statistically comparable. This implies that the area-wide floating population captured by transit ridership, which represents regional centrality, can explain street-level pedestrian volume well. Conversely, it would mean that, as previously explained, it is difficult to accurately grasp the impact of the built environments on street-level pedestrian volume when the macroscopic centrality and resulting floating population are not controlled for. The unconstrained model produces less biased coefficients than the constrained model. Thus, we interpret the following results by focusing on how the coefficients of the built environment variables change after controlling for transit ridership.

Table 4. Spatial regression (spatial error) models of log-transformed street-level pedestrian volume.

Variables	**Constrained Model**		**Unconstrained Model**	
	Coef.	**z**	**Coef.**	**z**
Lambda (λ)	0.744 ***	32.652	0.706 ***	28.370
Constant	8.409 ***	35.374	4.860 ***	13.465
Transit ridership (proxy for regional centrality)				
log_bus ridership (400 m buff.)			0.267 ***	10.760
log_subway ridership (300 m buff.)			0.043 ***	11.775
Walkshed-level 3D variables				
Density (log_population density)	−0.025	−0.682	−0.069 **	−2.074
Density (log_job density)	0.191 ***	5.623	0.126 ***	4.028
Diversity (log_facility accessibility index)	0.495 ***	7.292	0.200 ***	3.009
Design (log_connectivity index)	−0.343 ***	−2.783	−0.144	−1.229
Street-level variables				
Land use				
Residential	0.376 ***	4.464	0.296 ***	3.702
Commercial	0.665 ***	7.208	0.433 ***	4.889
Other land use (ref.)				
Street type				
Street with a sidewalk	0.663 ***	10.936	0.647 ***	11.199
Street without a sidewalk	0.550 ***	6.896	0.558 ***	7.342
Street with a shared sidewalk (ref.)				
Street condition				
Sidewalk width	0.080 ***	9.562	0.065 ***	8.180
Number of traffic lanes	0.022 **	2.414	0.016	1.836
Presence of centerline	−0.242 ***	−3.986	−0.169 ***	−2.910
Presence of sloping road	−0.369 ***	−8.584	−0.317 ***	−7.734
Presence of fence	0.127 ***	3.078	0.144 ***	3.647
Presence of crosswalk	0.185 ***	4.599	0.192 ***	5.025
Presence of obstacle	−0.026	−0.427	0.024	0.414
Summary Statistics				
N	2,889		2,889	
Pseudo-R^2	0.475		0.523	
Moran's I	41.182 ***		36.238 ***	
Robust LM (error)	388.289 ***		398.931 ***	

** $p < 0.05$, *** $p < 0.01$.

First, with regard to walkshed-level 3D variables, the coefficient size and significance level showed quite substantial differences between both models. Of the two density variables, only job density was significant in the constrained model, while the unconstrained model showed significant but conflicting signs of coefficients for both variables (coefficient: −0.069, 0.126; Z: −2.074, 4.028). Although this appears to be a somewhat contradictory result, a reasonable interpretation is possible if both density variables are considered at the same time. As Chung et al. [16] asserted, areas with high job density would represent an inner-city area in Seoul, and more people walk in those areas than in the populated, outlying residential areas. Kang [20], who demonstrated the same results as our study, argued that previous studies showing a positive coefficient for the population density variable did not include job density in the model.

Next, the results demonstrated that "diversity" (facility accessibility index) was positively associated with pedestrian volume in both models. However, the coefficient size was dramatically reduced after controlling for transit ridership (coefficient: 0.495 to 0.200; Z: 7.292 to 3.009). This implies that the coefficient of "diversity" in the constrained model may be a combination of the direct influence of the variable on street-level pedestrian volume and the indirect influence via the generation of a floating population (transit ridership) in the surrounding area, as explained in Figure 1.

The results regarding "design" were distinctive between the two models. While the "design" variable (connectivity index) was significantly and negatively associated with street-level pedestrian volume in the constrained model (coefficient: −0.343; Z: −2.783), the relationship was not statistically significant in the unconstrained model (coefficient: −0.144; Z: −1.229). This suggests that there may be an unobserved relationship between regional centrality and street network design. In Section 5.1, we discuss this possibility through comparison with other empirical studies.

Lastly, the coefficient size and significance level of street-level built environment variables also tended to decrease after taking transit ridership into account. However, the tendency was not noticeable compared to the walkshed-level variables. This is considered to be so because the street-level environment has a weaker association with regional centrality than the neighborhood-level environment. In other words, microscopic street elements can affect walking independently of macroscopic factors. In the unconstrained model, significant variables generally showed the same results as previous studies [19,20,49,50,79] as well as the constrained model. The only variable whose results have changed is the number of traffic lanes. While this was positively associated with pedestrian volume in the constrained model (coefficient: 0.022; Z: 2.414), it appeared insignificant in the unconstrained model (coefficient: 0.016; Z: 1.836). This seems to be derived from the intervention of the regional centrality (transit ridership) variable in the "design" (street connectivity) variable. In fact, it is more likely that roads with more lanes are formed in places with greater regional centrality (where there are many transit users) [45].

5. Discussion

In Section 4, the analysis results were interpreted and discussed focusing on the effects of the 3D variables. Section 5 extends our discussion, focusing on the following two derivative issues.

5.1. Does "Design" Matter?

The constrained model demonstrated that the street connectivity ("design") variable had a negative and significant effect on pedestrian volume, in contrast to general urban design theory [72]. This relationship was also identified in Kang's study [20] using the same data set as our study. In the study, he revealed that street intersection density, which is another representative variable measuring "design," had a negative relationship with pedestrian volume [20]. This result may be interpreted as follows: in the case of Seoul, where old and complex urban fabric and street network pattern extensively remains throughout the city, the higher the street connectivity, the smaller the pedestrian volume, unlike in Western cities.

However, this conclusion is still arguable. Although the specific measurements and study areas were different from the above studies, some studies have shown contradictory results. Using path analysis, Hajrasouliha and Yin [26] demonstrated that street network connectivity (intersection density variable) not only had a direct positive effect but also an indirect positive effect via the job density variable on pedestrian volume. Miranda-Moreno et al. [51] and Lee et al. [46] also showed that the number of roads at an intersection was positively associated with pedestrian volume.

Moreover, the relationship was insignificant in the unconstrained model, which controlled for regional centrality. This tendency also appeared in other studies. In Lee and Koo's [45] analysis model that controlled for regional centrality by employing street-level integration measured with space syntax, the association between the block-level street network density (street length/block area) and pedestrian volume was insignificant. What both studies had in common was that they controlled for regional centrality in any form. This suggests that regional centrality and the street network design variables are strongly associated. Hajrasouliha and Yin [26] also argued that street connectivity might have an indirect impact on pedestrian volume by influencing other built environment characteristics. In addition, in reality, a higher street network connectivity can be expected in urban areas with higher centrality than in peripheral areas. Therefore, we can interpret that, in the models where the required built environment variables (such as regional centrality) are not controlled for, street-connectivity-related variables function as proxy variables, having no conclusive effect on pedestrian volume.

This offers two more implications. First, in a model that does not control for regional centrality, the effect (coefficient value) of the street connectivity variable on pedestrian volume may not actually be a net effect of "design." Second, to reveal the net effect of "design" (whether "design" matters), regional centrality needs to be controlled for in the model as in the present study. In conclusion, after examining our results alone, unlike previous studies, "design" may not directly matter in terms of street-level pedestrian volume.

5.2. Which Is a Better Explanatory Variable, Accessibility to Transit or Transit Ridership?

Walking and public transportation usage are complementary activities [76–78]. Accordingly, studies that analyzed the determinants of pedestrian volume reflected the factors indicating the degree of public transit use in their econometric models. Here, the methods fall into two main approaches. While the first approach measures and reflects "accessibility to public transit" using variables such as the distance to the stop/station, the existence of the stop/station, or stop/station density [20,49,50,52], the second approach reflects it more directly through utilizing "transit ridership" itself [16,44]. Although both approaches empirically revealed that the variables were significantly associated with pedestrian volume [16,20,25,47,49], the meaning of the results was different.

Studies that used accessibility to transit stop/station generally intended to test hypotheses that suggest: (1) more pedestrian traffic may occur in places with more transit stops/stations that generally have good accessibility to various urban services; and (2) if there is a transit stop/station nearby, some of the transit users flowing out may flow into the PVS point. Most studies used the accessibility variables to test the first hypothesis. However, rather than simple accessibility variables (distance to stop/station or density), "how many people *actually* use public transportation" can more accurately indicate the centrality of an area. This is because transit ridership is determined by regional centrality rather than the micro-scale built environment. At the same time, without controlling for regional centrality or the floating population, it is difficult to ascertain the net effect of the micro-level transit accessibility variable on pedestrian volume. Moreover, when testing the second hypothesis, the transit accessibility variable was only a proxy. It is reasonable to use a more straightforward variable, the number of transit users, which directly explains the variation of pedestrian volume.

Thus, researchers can choose from either form of variables according to the purpose of the analysis. If the goal of modeling is to better reflect the determinants of pedestrian volume, it is desirable to directly control for the transit ridership as in the present study. If the goal is to derive policy implications for public transportation infrastructure (e.g., optimal transit stop density or interval), applying accessibility-type variables is more desirable. In addition, the desired form of a variable may vary depending on the type or availability of research data. When using cross-sectional data, it is desirable to employ an accessibility variable to represent the static built environment, and when using time series data, it is desirable to apply a day-dependent ridership variable. However, at this point, whether reliable transit ridership data are well established, as in Seoul, can also be an important consideration. In the case of Seoul, where almost all citizens use a Smart Card [63], transit ridership can be a good proxy for regional centrality and the resultant floating population. This is highly accurate and easily obtainable data, which greatly improves the explanatory power of the model for predicting pedestrian volume on a specific street, while street vitality and commercial performance can be determined accordingly. Being an obvious benefit of smart technology, it can be a more accurate method than the previous approach that utilized the distance from or existence of transit stops/stations.

6. Conclusions

This study examined the relationship between the built environment and street-level pedestrian volume after controlling for regional centrality (transit ridership) using 2015 PVS and Smart Card data from Seoul. As a preliminary study, we analyzed 36 spatial regression models by applying different sets of bus and subway transit riderships and found that the combination of a bus ridership within 400 m and a subway ridership within 300 m best explained the variation in street-level pedestrian volume. These are not substantially different from other empirical studies [66,75,76] or a general walking distance of 400 m to 500 m conventionally adopted in previous studies [16,20,66,67].

After controlling for both ridership variables as a proxy for regional centrality, we examined the effect of the 3D variables on street-level pedestrian volume and compared this with the result of the model that did not control for ridership. Key findings are as follows. First, both transit ridership variables explained the variance in pedestrian volume well, greatly improving the explanatory power of the models. Specifically, we found that if daily ridership at bus stops (subway stations) located within 400 m (300 m) from a specific street point increased by 1%, the daily pedestrian volume at that street point increased by 0.267% (0.043%). Second, after taking transit ridership into account, the influence of built environment variables was generally reduced, and the decrease was more pronounced in the walkshed-level variables (i.e., 3D variables) than in the street-level variables. In particular, the influence of the "design" variable (street connectivity index) was found to be insignificant in the unconstrained model. This means that the degree of street connectivity is influenced by regional centrality, and accordingly, the coefficient of the "design" variable in our constrained model (or even in other previous studies' pedestrian volume estimation models) might be biased. Thus, to accurately understand the effect of the meso-scale 3D variables on pedestrian volume, both micro- and macro-scale built environmental factors must be controlled.

As explained throughout, this study provided more precise empirical evidence on the effects of traditional 3D variables on pedestrian volume by controlling for regional centrality. This analytical framework and these analysis results can be transferred to many metropolitan cities around the world. Since a large number of pedestrians on the streets contribute to the attractiveness of public spaces and vitality of the urban economy in most cities around the world, with the exception of some cities with poor security [80], many urban researchers have been and will continue to examine the determinants of pedestrian volume. Thus, a more accurate analysis method as to which built environment attributes may encourage pedestrian activities would be meaningful not only in Seoul but also for all cities on earth.

In addition, even though this study focused on the theoretical and analytical frameworks to identify the physical factors influencing street-level pedestrian volume more accurately, it also suggested implications for planning policies and practices. Although 3D variables have been accepted as normative theories of urban planning and design in

North American cities [21–29], the effects of these variables may vary depending on the urban context. The present study confirmed once again that high job density and facility accessibility (i.e., "density" and "diversity") at the walkshed level were values that planners and policymakers should pursue. However, as explained above, in predicting the increase in pedestrian volume due to the physical environment and the consequent socioeconomic outcomes, it is necessary to sufficiently control for the centrality of the area and the resultant floating population. Furthermore, planners and policymakers must consider the negative externalities of agglomeration such as congestion, air pollution, and even the excessive complexity of landscape. As many studies have shown, compact development has more losses than benefits in high-density Asian cities [81–83].

In terms of "design", more thoughtful policies and plans are required. In contrast to previous studies, our analysis demonstrated that street connectivity (i.e., "design") was not directly associated with street-level pedestrian volume after controlling for regional centrality. This is derived from the distinctive urban context of Seoul, where few cul-de-sacs and loop-like street patterns exist. Thus, the practice of uncritically accepting Western theories centered on North American cities (e.g., planning principles of New Urbanism), as in Korea, is by no means desirable, which is a lesson to be kept in mind in other rapidly growing Asian metropolitan cities.

The city governments should identify the determinants of pedestrian volume and the corresponding urban design principles suitable for their urban context. In this process, to control for regional centrality, they can employ transit ridership data from the highly utilized Smart Card system of the city. Since public transportation in a particular city serves not only the city but also the metropolitan area surrounding the city, transit ridership can be reliable and easily obtainable data to represent regional centrality. Our approach will therefore also be applicable in other cities with similar systems and urban contexts.

Despite these contributions, this study has several limitations. First, as explained in Figure 1, the relationship between the built environment and pedestrian volume may vary depending on the purpose for walking. However, because it is difficult to determine in large-scale PVSs, we could not ascertain how the built environment specifically affects walking activities by purpose. Future studies can address this limitation by securing research data that incorporate a post hoc survey on the counted pedestrians. Alternatively, it would be possible to perform similar analyses using data on the transit ridership and pedestrian volume by time, which narrows the time zone and corresponding travel purpose (e.g., commuting travel during peak hours). Second, we need to consider the endogeneity issue between key variables. That is, pedestrians observed on the street may also be transit riders in the surrounding area. Therefore, in future research, it is necessary to apply a multivariate analysis, such as path analysis, considering the two-way causal relationship. Third, when measuring the built environment variables, the airline distance buffer was used instead of the network distance buffer. Since the streets in Seoul are very dense, the difference between the two buffers is not expected to be relatively large, but this may cause bias in the analysis results. In addition, unlike the transit ridership variables, when measuring the 3D variable, the conventionally used 500 m buffer was uncritically used without testing the appropriate buffer size, which may also be a limitation of our study. The last shortcoming is that the analysis is yet only a single case study. Even though relatively large PVS data from a major metropolitan area were used, their generalizability is still limited due to the distinctive context of the single study area. Thus, key findings in this study would need to be reconfirmed through further research focusing on more diverse cities.

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Appendix A

Regression models of log-transformed street-level pedestrian volume (constrained model).

Variables	Constrained Model						
	OLS			**Spatial Lag**		**Spatial Error**	
	Coef.	**t**	**VIF**	**Coef.**	**z**	**Coef.**	**z**
Rho (ρ)				0.678 ***	30.416		
Lambda (λ)						0.744 ***	32.652
Constant	8.602 ***	47.084		2.657 ***	10.621	8.409 ***	35.374
Walkshed-level 3D variables							
Density (log_population density)	0.003	0.125	1.269	0.052 ***	2.725	−0.025	−0.682
Density (log_job density)	0.216 ***	10.885	1.527	0.071 ***	3.943	0.191 ***	5.623
Diversity (log_facility accessibility index)	0.563 ***	9.029	1.314	0.371 ***	6.694	0.495 ***	7.292
Design (log_connectivity index)	−0.232 **	−2.022	1.148	−0.277 ***	−2.756	−0.343 ***	−2.783
Street-level variables							
Land use							
Residential	0.355 ***	5.069	3.146	0.281 ***	4.572	0.376 ***	4.464
Commercial	0.763 ***	9.753	3.191	0.489 ***	7.014	0.665 ***	7.208
Other land use (ref.)							
Street type							
Street with a sidewalk	0.699 ***	10.745	2.627	0.575 ***	10.045	0.663 ***	10.936
Street without a sidewalk	0.514 ***	6.073	1.666	0.435 ***	5.860	0.550 ***	6.896
Street with a shared sidewalk (ref.)							
Street condition							
Sidewalk width	0.099 ***	10.867	1.235	0.077 ***	9.589	0.080 ***	9.562
Number of traffic lanes	0.021 **	2.291	1.974	0.018 **	2.237	0.022 **	2.414
Presence of centerline	−0.342 ***	−5.196	2.577	−0.234 ***	−4.059	−0.242 ***	−3.986
Presence of sloping road	−0.337 ***	−7.485	1.026	−0.304 ***	−7.662	−0.369 ***	−8.584
Presence of fence	0.123 ***	2.690	1.096	0.135 ***	3.390	0.127 ***	3.078
Presence of crosswalk	0.127 ***	2.914	1.353	0.147 ***	3.871	0.185 ***	4.599
Presence of obstacle	−0.000	−0.003	1.017	−0.036	−0.621	−0.026	−0.427
Model Summary							
N	2889			2889		2889	
R^2	0.298						
Adjusted R^2	0.294						
Pseudo-R^2				0.460		0.475	
Log likelihood	−4026			−3707		−3681	
Akaike Info Criterion (AIC)	8085			7448		7394	
Schwarz Criterion (SC)	8180			7549		7490	
Statistics							
Moran's I	41.182 ***						
Robust LM (lag)	10.278 ***						
Robust LM (error)	388.289 ***						

** $p < 0.05$, *** $p < 0.01$.

Appendix B

Regression models of log-transformed street-level pedestrian volume by the transit ridership (unconstrained model).

Variables	Unconstrained Model						
	OLS			Spatial Lag		Spatial Error	
	Coef.	t	VIF	Coef.	z	Coef.	z
Rho (ρ)				0.599 ***	25.151		
Lambda (λ)						0.706 ***	28.370
Constant	4.313 ***	14.441		0.466	1.528	4.860 ***	13.465
Transit ridership (proxy for regional centrality)							
log_bus ridership (400 m buff.)	0.331 ***	15.129	1.524	0.214 ***	10.492	0.267 ***	10.760
log_subway ridership (300 m buff.)	0.045 ***	12.769	1.259	0.039 ***	12.085	0.043 ***	11.775
Walkshed-level 3D variables							
Density (log_population density)	−0.061 ***	−2.955	1.306	0.003	0.151	−0.069 **	−2.074
Density (log_job density)	0.144 ***	7.643	1.597	0.039 **	2.250	0.126 ***	4.028
Diversity (log_facility accessibility index)	0.172 ***	2.829	1.451	0.097	1.760	0.200 ***	3.009
Design (log_connectivity index)	−0.107	−1.001	1.151	−0.179	−1.857	−0.144	−1.229
Street-level variables							
Land use							
Residential	0.201 ***	3.039	3.244	0.193 ***	3.245	0.296 ***	3.702
Commercial	0.360 ***	4.745	3.471	0.243 ***	3.527	0.433 ***	4.889
Other land use (ref.)							
Street type							
Street with a sidewalk	0.690 ***	11.412	2.631	0.579 ***	10.569	0.647 ***	11.199
Street without a sidewalk	0.603 ***	7.659	1.675	0.503 ***	7.065	0.558 ***	7.342
Street with a shared sidewalk (ref.)							
Street condition							
Sidewalk width	0.082 ***	9.634	1.246	0.067 ***	8.697	0.065 ***	8.180
Number of traffic lanes	0.007	0.795	1.990	0.009	1.103	0.016	1.836
Presence of centerline	−0.223 ***	−3.627	2.599	−0.159 ***	−2.865	−0.169 ***	−2.910
Presence of sloping road	−0.278 ***	−6.626	1.032	−0.267 ***	−7.044	−0.317 ***	−7.734
Presence of fence	0.155 ***	3.650	1.098	0.159 ***	4.151	0.144 ***	3.647
Presence of crosswalk	0.143 ***	3.525	1.356	0.161 ***	4.402	0.192 ***	5.025
Presence of obstacle	0.070	1.128	1.020	0.019	0.333	0.024	0.414
Model Summary							
N	2889			2889		2889	
R^2	0.394						
Adjusted R^2	0.391						
Pseudo-R^2				0.505		0.523	
Log likelihood	−3812			−3565		−3532	
Akaike Info Criterion (AIC)	7661			7168		7101	
Schwarz Criterion (SC)	7768			7282		7208	
Statistics							
Moran's I	36.238 ***						
Robust LM (lag)	14.415 ***						
Robust LM (error)	398.931 ***						

** $p < 0.05$, *** $p < 0.01$.

Appendix C

The log likelihood of the spatial error models by the transit stop/station's influential area size.

		Subway Ridership Within					
		100 m	200 m	300 m	400 m	500 m	600 m
Bus ridership within	100 m	−3631.534	−3582.570	−3554.960	−3566.286	−3574.785	−3619.577
	200 m	−3624.403	−3578.292	−3555.164	−3567.127	−3572.268	−3609.902
	300 m	−3590.634	−3552.466	−3535.724	−3553.718	−3557.134	−3582.928
	400 m	−3590.328	−3545.743	**−3532.321**	−3557.138	−3566.522	−3592.585
	500 m	−3614.468	−3558.104	−3542.730	−3572.256	−3589.259	−3619.456
	600 m	−3665.148	−3608.897	−3581.035	−3604.125	−3617.418	−3659.830

Note: All models' bus and subway riderships had statistically positive associations with street-level pedestrian volume at $p = 0.01$. Other built environmental factors suggested in Table 2 were applied as control variables in all regression models.

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