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Meso-Scale Urban Form Elements for Bus Transit-Oriented Development: Evidence from Seoul, Republic of Korea

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Received: 28 July 2017; Accepted: 21 August 2017; Published: 25 August 2017

Abstract: Rapid urbanization and the increased use of private vehicles have led to many urban problems. Transit-oriented development (TOD) has been proposed as a solution to these problems. The present study examined the relationship between meso-scale urban form and bus ridership, as well as the link between bus and subway use in Seoul, Republic of Korea. Spatial regression models identified the effects of TOD planning factors on bus ridership at 2300 target bus stops in Seoul. The analysis revealed that TOD planning factors have a significant positive impact on bus ridership. In addition, the result indicated a complementary relationship between bus and subway use, implying that transportation policies designed to promote bus transport use through connecting bus and subway services may be effective strategies.

Keywords: TOD; bus ridership; meso-scale urban form; spatial model

1. Introduction

Modern cities are faced with numerous problems, such as overcrowding, lack of housing, damage to the natural environment, and traffic congestion. Automobile-oriented urban planning approaches have been criticized as a major cause of these modern urban problems. In response, many urban planners and researchers have argued for the necessity of inhibiting the indiscrete outward spread of urban areas, and of developing public transportation to reduce the negative effects of automobile dependency [1]. The transit-oriented development (TOD) approach has consequently been taken to propose a city development method that is focused on the use of public transportation and high-density, mixed-use development patterns [2]. The concept of TOD differs slightly from country to country, but in general, the most important feature is the development of high-density, walking-friendly environments surrounding a public transportation node [3]. The TOD concept has been applied to numerous urban developments, and over 100 areas have been developed in the United States and Europe using this approach.

Most urban development projects that used early TOD theory have focused on railway stations; relatively few TOD projects have focused on bus stops [3], bus services, and bus terminals, which have all been proposed as potential areas for TOD expansion, especially those located near major railway stations [4]. However, with the recent speedy expansion of bus rapid transit (BRT), the development of TOD theory with a focus on bus stops has emerged as an important issue [5]. BRT has several advantages: it can be introduced in a short period, the costs of an express bus system are lower than those of railways, and the construction period is short. As of 2017, 5500 km in total of dedicated BRT routes have been set up in 205 cities, and approximately 4.8 million passengers use BRT every week around the world [6].

BRT was first introduced in Korea in 2004 under the Seoul bus system reform. Seoul's BRT system uses a dedicated bus lane and island-type bus stops. Continuous expansion of the route resulted in a total route length of 117.5 km across 12 routes as of 2014 [7]. Seoul thus has the sixth largest number of BRT routes in the world, following Jakarta, Rio de Janeiro, and Tehran in the short term [7]. Bus traffic in Seoul increased by 14%—from 771 to 883 million—between 2002 and 2017, and the modal share of bus transport increased from 26% in 2002 to 27% in 2014.

TOD research and projects remain somewhat biased toward railway station-based developments, although the term public transportation refers to both buses and subways. Considering that buses are a common means of transportation, it is necessary to investigate bus stop-based TOD theory in relation to urban environments and other public transportation systems. Therefore, the present study analyzes the impact of urban form and subway systems on bus ridership to shed light on effective pedestrian- and public- transportation-oriented development strategies. Specifically, this study explores how the urban form factors of Seoul influence bus ridership, as well as whether buses and subways, two major public transportation systems, have a competitive or complementary relationship. This study is expected to contribute to effective TOD approaches by highlighting the urban form elements that influence bus ridership.

2. Background

2.1. Concept of Transport-Oriented Development (TOD)

The TOD theory was first proposed by Peter Calthorpe, who argued in favor of city developments focusing on public transportation systems and moving away from automobile-dependent urban development [1]. TOD focuses on creating a high-density, mixed-use living zone in a 400–800 m area around public transportation nodes. Other areas are developed at a low density or are conserved. In this theory, high-density, complex land use is the major planning element around public transportation nodal points, with the further aim of creating walking- and bicycle-friendly environments [2]. In addition, minimizing traffic and promoting public and non-motorized traffic can contribute to sustainable development that reduces traffic congestion, energy consumption, and air pollution [8].

According to Ewing and Cervero [9], TOD is divided into "mixed use of land", "diversity in a range accessible from the center of the transit center", and "walking- and biking-urban design". In detail, land use density in the station area is one of the biggest factors determining the degree of public transportation use, and the magnitude of influence may vary according to the level and type of density developed.

2.2. Review of the Literature

Research on TOD can be divided into studies on the effect of TOD development on the surrounding landscape, and studies on methods to increase public transportation use in accordance with the TOD theory. Since this study is related to the latter subject, this review will focus on previous research on the relationship between urban environments and public transportation use. As mentioned, although studies on urban forms and railways have received attention since the late 1990s [10,11], few studies have investigated urban forms and bus services [12].

Many domestic studies have focused on railway station-based TOD research. Oh et al. [13] identified factors that influence transit users through examining land and transportation demand and supply variables. This study is significant because it adds operational variables, such as operating time and dispatch interval, and land use variables. However, a limitation of the study is that the urban design aspect is not considered.

Sohn and Kim [14] investigated the relationship between transit ridership and the urban characteristics of the Seoul Metropolitan area transit center. Although this research considered the walking environment, public transportation modes other than subway services were not considered. In addition, most railway station-based research does not take into account other public transport modes (e.g., [15,16]).

Lim et al. [17] analyzed the characteristics of actual public transport users by classifying the characteristics of subway users and transfer type (e.g., walking to subway or bus to subway) of subway station areas in Seoul. This study considered users who are transferring from subway to bus use. However, a limitation of this study is that it does not take into account users of only buses, as the study area is a railway station. Zhao et al. [18] analyzed the factors influencing the number of subway passengers in a subway radius of 800 m. Although bus-related factors were included as explanatory variables, there was insufficient consideration of bus users' characteristics or of urban design factors.

Sung et al. [19] analyzed the effect of city type on the number of railway station users and their transportation mode choice. Their study suggested that buses and subway transfer systems should be well established to encourage bus use, which can increase overall public transportation utilization. However, the analysis investigated transportation modes used by passengers entering and exiting the railway station according to the time of day, and the contents and interpretation of the research focused on the railway station.

Loo et al. [20] analyzed the factors affecting railway station use in New York and Hong Kong based on four major dimensions: land use, station characteristics, socioeconomic and demographic characteristics, and inter-modal competition. This study analyzed the relationship between railway and bus ridership while controlling for land use factors, station characteristics, and socioeconomic variables, and they found that buses have a positive effect on railway patronage in the combined Hong Kong and New York model. However, this study did not consider urban form factors.

Cascajo et al. [21] analyzed the effect of urban size, population density, and the supply of bus routes on the number of bus users. However, this study was a city-level analysis and was unable to investigate the meso- or micro-level design elements of the cities. Estupinan et al. [12] studied the relationship between city type and BRT ridership. Using factor analysis, they identified four factors correlated with the number of bus riders at the bus stop: walking supports, barriers to car use, low safety and insecurity, and connectivity. This study empirically explored factors affecting bus ridership in consideration of both socioeconomic factors and urban-type-related factors, but the reliability of the model is low due to the small size of the observations. Thompson [22] analyzed the correlation between socioeconomic factors, such as population density, furniture, income, work, parking fees, and public transportation demand. This study revealed a correlation between bus factors and the different socioeconomic factors from previous studies, but land use and urban design factors were not considered. Chakraborty [23] identified the correlation between the number of traffic users by accounting for not only land use factors, but also socioeconomic factors such as the number of vehicles and income level. However, the urban design elements were insufficiently included. Brown et al. [24] compared the characteristics of bus and subway users. The authors classified public transit users into five types according to their destinations. This study found that bus trips in Atlanta, Georgia, USA, originated from a larger number of zones with higher levels of transit-dependent characteristics compared to rail trips. Self-identified rail riders primarily access transit by automobile, and they value fast transport services within a convenient walking distance of their employment, such as in the central business district (CBD), and some but not all TODs. The results suggested that good transfer connections between buses and trains would increase bus ridership. Overall, these studies contribute by investigating the characteristics of bus and subway riders, as well as factors that influence both bus use and subway use. However, these studies tend not to consider land use and urban design factors that may also affect bus ridership.

In summary, most TOD studies have focused on railway-based developments, and studies focusing on buses generally lack consideration of urban design aspects. Therefore, the purpose of the present study is to examine the effects of urban form features, or urban design elements that are not being sufficiently studied, on bus utilization. In addition, this study aims to shed light on the relationship between the two major public transportation systems, bus and subway, because the relationship between the two systems is generally understudied, although they are usually developed together. Therefore, the questions of this study are as follows:

(1) Do meso-scale urban form elements such as density, land use mix, meso-scale urban design elements, and accessibility to transportation and destinations affect bus use?

The meso-scale urban form elements used in this study are based on TOD theory and literature reviews. TOD posits that high-density, mixed-use, and pedestrian-friendly environments (e.g., high intersection density, low hilliness, presence of a bike path) encourage public transit use. Therefore, bus ridership at bus stops located in dense, mixed, and pedestrian-oriented areas is expected to be greater than that in other areas.

(2) Is the relationship between the bus and subway modes of transportation competitive or complementary?

Subway and bus modes of transportation may compete with each other when the two systems serve the same origins and destinations. However, in many cases, buses can cover areas outside of a subway's service area. Thus, it is expected that bus stops near subway stations have a greater number of riders.

3. Method

3.1. Study Area

The spatial range of this study is Seoul city, which has the greatest number of public transportation users, such as subway and bus riders, in the Republic of Korea. As of December 2016, 7427 local buses were operating on 351 routes, and 6087 bus stops were located in Seoul [25]. Seoul's bus system includes BRT, which provides high-speed bus service through a limited number of stops, and a typical bus system, which provide slower bus service that fills the gap between the subway and BRT. As seen in Figure 1, the bus system covers most of Seoul, which is an already-developed, high-density city. In 2014, the modal share of bus transport in Seoul was 27%, the highest following the combined subway and railway share (39%) [26]. The modal share of bicycle transport was only 2% [27]. In addition, Seoul includes various urban forms, such as natural areas, grid areas, apartment areas, and high-density areas. Thus, Seoul is suitable for an analysis of the effect of the urban physical environment on the bus utilization rate.

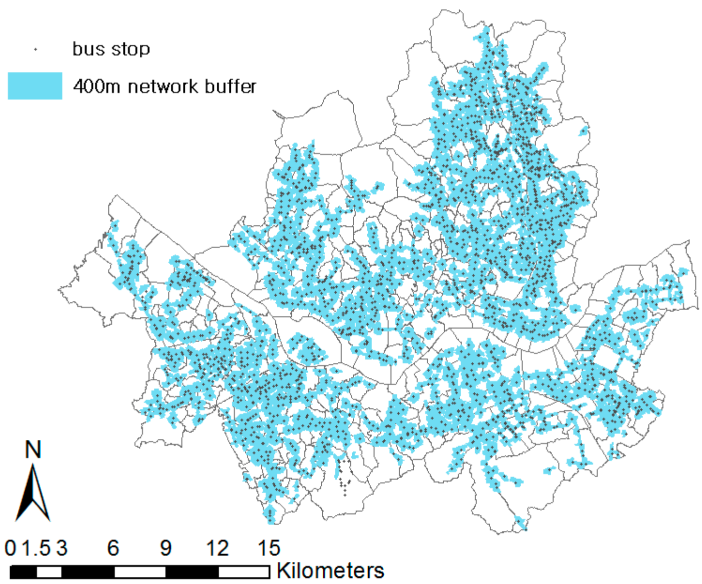

Figure 1. Bus stops and 400 m network buffers.

3.2. Data and Key Variables

This study empirically examines the TOD theory based on bus stops. Table 1 presents the definitions and descriptive statistics of the key variables. The dependent variable is the average number of people who boarded and alighted at each bus stop in Seoul. The bus rider data were collected from passengers who used a traffic card at each stop from January 2014 to October 2015. The average number of bus riders at the bus stop was calculated by determining the average number of people getting on and off at each stop on each day for 22 months. Due to the characteristics of the bus system, there are bus stops with the same name on both lanes. If these stops were treated as individual observation values, many network buffers would overlap due to the proximity of the stops. Thus, the average number of passengers using bus stops of the same name was calculated as a single observation value. In addition, the dependent variable was log-transformed for the analysis, because its distribution was positively skewed.

Table 1. Descriptive statistics (n = 2300).

Variable		Definitions	Mean	SD	Min	Max
Outcome Variable	Bus Ridership	Number of riders	842.15	1044.4	17.879	13,379.3
	ln (Bus Ridership)		6.222	1.045	2.885	9.501
Environmental Variables	Gravity Index		0.150	0.547	0.0001	9.530
	ln (Gravity Index)		−3.560	1.718	−8.758	2.254
	Land Use Mix		0.271	0.056	0.118	0.506
	Floor Area Ratio	%	108.90	70.507	0	493.32
	ln (Floor Area Ratio)		4.283	1.309	−4.605	6.201
	Intersection Density	unit/m	0.011	0.005	0	0.026
	Arterial Road	Dummy	0.758	-	0	1
	Collector Road	Dummy	0.088	-	0	1
	Hilliness	%	2.754	2.356	0	16.523
	ln (Hilliness)		0.639	0.980	−4.605	2.805
	Bike Road	Dummy	0.637	-	0	1
Socioeconomic Variables	Population	1000 persons	6.407	3.449	0.098	23.154
	ln (Population)		1.656	0.733	−2.326	3.142
	Firm	1000 firms	0.518	0.453	0.0029	5.068
	ln (Firm)		−0.986	0.886	−5.836	1.623
	Vehicle Ownership	1000 vehicles	6.834	3.489	0.747	19.222
	ln (Vehicle Ownership)		1.803	0.492	−0.292	2.956
	Parking Space	1000 parking spaces	2.319	1.333	0.047	11.479
	ln (Parking Space)		0.646	0.698	−3.064	2.440

The independent variables were selected based on the TOD theory: urban form factors related to walking were constructed, positing that pedestrian traffic is related to the number of bus users. The urban form factors were extracted using Geographic Information System (GIS) data provided by the Seoul Metropolitan Government Big Data Campus, with a 400-m network buffer zone for each bus stop as a basic unit [28]. Figure 2 is an example of network buffer zone from bus stop and shows shape of a basic unit. According to the TOD theory, the high development density near transit centers is an important aspect. The floor area ratio, which is the total floor area divided by the area of a network buffer, is an index that measures the development density around a bus stop.

The land use mix (LUM) index, which is an entropy type index, is used as an indicator of the degree to which the land mixed use, and is used in diverse urban studies [29]. However, previous studies identified shortcomings of this index e.g., [30–32]. For instance, LUM has the same value if the ratios are the same, regardless of the purpose of mixing, and thus the quality diversity of the mixed use is not confirmed. Another problem is that LUM is a measure of balance among uses rather than a functional mix: for example, adding a small amount of a new function will reduce the value of LUM index, because the new function distracts the existing balance. The land use mix (LUM) index measures the degree of mixed use of land, which is often used in urban studies [29]. The land use in Seoul was classified into commercial, dedicated residential, general residential (i.e., residential areas that allow small-scale, non-harmful commercial use), green, and semi-industrial, and the variables were created using the following equation:

$$\mathrm{LUM} = -\sum_{i\,=\,1}^{k} \frac{(p_i)\ \times\ \ln(p_i)}{\ln(k)},$$

where k refers to the number of represented land uses and p_i refers to the percent of land use i.

Figure 2. The 400-m network buffers from the bus stop.

The gravity index is generated by referring to the gravity model as a parameter to understand the relationship between bus and subway use. The gravity model is widely used for traffic volume forecasts in transportation [33] and for the law of retail gravitation in urban areas [34]. The gravity model assumes that the influence of the population on the two regions is inversely proportional to the distance between them. In this study, the gravity index is calculated by dividing the number of daily passengers at the nearest subway station at each bus stop by the square of the network distance from the bus stop to the nearest subway station, using the ArcGIS Network Analyst extension:

$$\mathrm{F} = \frac{n}{d},$$

where d is the distance to the nearest subway station, n is the average station patronages a day, and β is the distance-decay parameter.

A positive coefficient of the gravity index indicates that the bus and subway have a complementary relationship, and a negative coefficient implies a competitive relationship between the two modes. A challenge of using the gravity model is selecting a reasonable distance-decay parameter. Referring to previous studies (e.g., [35–37]), a sensitivity analysis is carried out by applying various distance-decay parameters, ranging from 1.0 to 2.2 with an increment of 0.2, to spatial regression models (see Table A1 in Appendix A). The sensitivity analysis result identified no remarkable changes in the results. The authors selected 2 as the value of β for computational clarity.

To control for the influence of road type and road density on bus users, we used the arterial road and the collector road, since the grade of roads approximate the capacity of bus service, and arterial roads tend to provide higher bus frequency and capacity. Intersection density variables were included, referring to previous studies (e.g., [38]). These variables approximate the block size: a higher intersection density indicates that city blocks are smaller. Smaller urban blocks are expected to improve pedestrian access and to therefore have a positive impact on bus use. In addition, the slope of the road is an important factor affecting walking activity [39]. The slope variable is computed from a digital elevation model of Seoul.

The continuity of the bicycle road is a pedestrian-friendly design element that potentially activates public transportation [38]. To examine the influence of the bicycle road, a bike path variable is constructed as a dummy variable by using location information on bicycle roads from the Open Data Plaza in Seoul.

The socioeconomic characteristics of the area around a bus stop, such as population, number of companies, number of parking spaces, and number of automobile registrations, are extracted from administrative area data. Because Seoul's administrative areas are larger than the buffer zone unit, the values of the socioeconomic variables within a network buffer are estimated by using the area ratio of an administrative area and a network buffer using ArcGIS. The population variable is taken from Seoul Metropolitan area data from 2015, provided by the National Statistical Office. The number of companies, which is intended to capture the intensity level of economic activity, is extracted from the 2014 national business survey of the National Statistical Office. The parking lot variable, which utilizes data on the number of parking places, was compiled from the parking plan of Seoul. It was created to confirm that parking service can hinder public transportation use by encouraging private automobile use, which competes with the public transportation service [40]. The number of automobile registrations was determined by utilizing a 2010 survey of household traffic [41]. Among the independent variables above, a natural logarithmic transformation is applied to the gravity models, slope, number of companies, number of registered cars, and number of parking lots, which have a high degree of asymmetry.

3.3. Method

Data that reflect spatial attributes are affected by spatial autocorrelation, which refers to the phenomenon that one observation is influenced by other observations that are close to each other [42]. Spatial autocorrelation implies that the more adjacent individual observations are in space, the more similar the characteristics obtained from them will be, and the higher the correlation. In this case, the reliability of an ordinary least squares (OLS) model may deteriorate due to its assumption of the mutual independence of the observations. Therefore, it is necessary to first verify the spatial autocorrelation of observations using Moran's I, and to then decide on the most appropriate model.

In some areas of Seoul, bus use is popular and, in other areas, few buses are observed. This suggests that the number of bus riders may have spatial autocorrelation. Therefore, Moran's I of the average number of bus riders, which is a dependent variable, was estimated (Figure 3): the Moran's I value of the natural log-transformed number of bus riders was 0.232, which was statistically significant ($p = 0.001$).

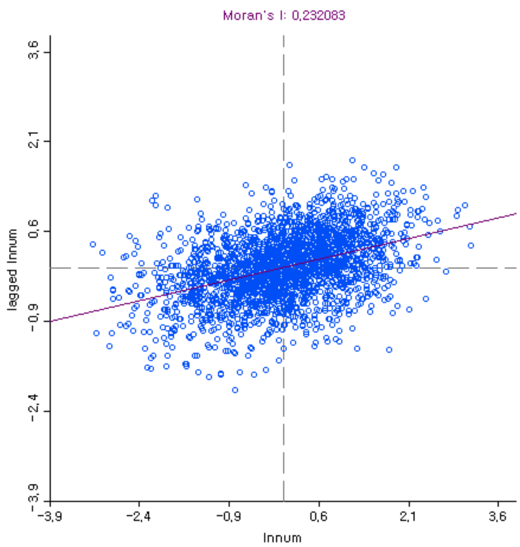

Figure 3. Moran's I of the residual of spatial error modeling (SEM).

Spatial lag modeling (SLM) and spatial error modeling (SEM) are designed to deal with the spatial dependency problem, if spatial autocorrelation is identified [43]. SLM assumes that the spatial autocorrelation occurs at individual dependent variable values. Thus, spatial autocorrelation is controlled by applying a space weight matrix (ρWy) to the surrounding observations that affect each observation value:

$$y = \rho Wy + x\beta + \varepsilon,$$

where y is a dependent variable vector, W is a spatial weight matrix, x is an independent variable matrix, ρ and β are coefficients, and ε is an independent and identically distributed residual vector.

On the other hand, SEM assumes that spatial autocorrelation is not observed in the values of individual dependence variables, and that it is consequently found in residuals. Thus, SEM controls for spatial autocorrelation by applying a space weight matrix ($\varepsilon = \lambda W + \mu$) to the residuals affecting the adjacent residual values.

$$y = x\beta + \epsilon, \epsilon = \lambda W + \mu,$$

where y is a dependent variable vector, W is a spatial weight matrix, x is an independent variable matrix, λ and β are coefficients, ε is a spatial-dependent residual vector, and μ is an independent and identically distributed residual vector.

To determine which models are suitable for controlling spatial autocorrelation, the authors used the robust Lagrange multiplier (LM) test after the regression analysis using the OLS method. Only the robust LM test of SEM was statistically significant at the 0.05 alpha level. Therefore, SEM was selected for the final model. Additionally, the variance inflation factor (VIF) was used to test for multicollinearity, and a few outliers were removed by examining the anomalies of the residuals.

This study employed GeoDa, a spatial analysis program, to conduct SEM, with the average number of bus riders as a dependent variable and environmental features and socioeconomic factors as explanatory variables. Based on the point data shapefile containing the bus stop location information, the Queen's contiguity spatial weight matrix was generated to control for the spatial autocorrelation.

4. Analysis Results

Table 2 shows the OLS and SEM results estimating the natural-log transformed average bus ridership. The R-squared value of SEM more than doubled over the OLS model; this result suggests that a notable portion of the average bus rider's variance is explained by spatial autocorrelation. In addition, the statistically significant spatial error coefficient (λ) indicates that SEM is more suitable than the OLS model. Comparing OLS and SEM results, some changes in the significance of a few variables' coefficients are identified. In the OLS model, the effect of land use mix is insignificant and the number of business establishments is significant. However, in SEM, the land use mix becomes significant, and the significant effect of the number of business establishments vanishes. Additionally, the VIF test result to diagnose the multicollinearity problem among the explanatory variables indicates that the variables used in this study do not have multicollinearity problems, because all of the VIF values were less than five [39].

The SEM results partially confirm the first hypothesis, which is that urban form elements, such as high-density, mixed-use, and pedestrian-friendly environments, encourage bus transport use. The positive and significant coefficient of the floor area ratio indicates that bus ridership tends to be greater at bus stops with a higher development density. The effect of land use diversity, which is an index showing the degree of mixture of land for various purposes, is also statistically significant. This result indicates that areas embracing diverse activities are likely to attract more activities, and thus more bus riders. Among the road type variables, the effect of arterial roads is significant, while the influence of collector roads is insignificant. This result indicates that the higher the road hierarchy, the greater the number of bus users attracted. This result is expected because arterial roads have more traffic than local roads, and bus stops in high traffic areas tend to have more users. However, SEM fails to detect the significant effects of intersection density and slope.

The significant and positive coefficient of gravity index supports the second hypothesis that buses and subways are complementary rather than competitive. Since the gravity index is calculated as the number of nearest subway station users divided by the square of the network distance from a bus stop to the nearest subway station, the positive gravity index implies that a bus stop tends to have more bus riders if there is a closer subway station, and if the nearest subway station has more subway riders.

Additionally, the negative effect of bicycle roads on bus users implies that some potential bus riders use bicycles if bike paths are provided. Thus, buses and bicycles may compete with each other. Lastly, no socioeconomic variables are statistically significant in the model.

Table 2. Ordinary least squares (OLS) and spatial error modeling (SEM) results for bus ridership.

Variable	Model 1: OLS		Model 2: SEM	
	Coef.	(S.E.)	Coef.	(S.E.)
Constant	5.881 ***	(0.474)	5.708 ***	(0.560)
ln (Gravity Index)	0.083 ***	(0.013)	0.116 ***	(0.016)
Land Use Mix	0.676 +	(0.392)	1.297 **	(0.441)
ln (Floor Area Ratio)	0.066 ***	(0.019)	0.062 **	(0.021)
Intersection Density	5.160	(5.638)	5.637	(6.930)
Arterial Road	0.235 ***	(0.059)	0.242 ***	(0.060)
Collector Road	−0.069	(0.089)	−0.062	(0.087)
ln (Hilliness)	0.065 **	(0.024)	0.037	(0.031)
Bike Road	−0.230 ***	(0.048)	−0.203 ***	(0.056)
ln (Population)	−0.009	(0.045)	0.002	(0.062)
ln (Firm)	0.138 **	(0.049)	0.059	(0.063)
ln (Vehicle Ownership)	0.027	(0.049)	0.029	(0.057)
ln (Parking Space)	−0.049	(0.063)	−0.031	(0.082)
Lambda (λ)	-	-	0.439 ***	0.028
R-Squared		0.085		0.198
N		2300		2300
Robust LM (Lag)	246.897			
Robust LM (Error)	266.838 ***			

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$; *** $p < 0.001$.

5. Conclusions

This study aimed to gain insight into a desirable public TOD method by deriving urban form features that can promote bus transport use. The authors focused empirically on bus transport, which has been relatively underexplored in conventional TOD-related research. SEM, dealing with the spatial autocorrelation problem of Seoul's bus stop ridership data, revealed that among the environmental factors, the effects of floor area ratio and land use mix are significantly related to bus ridership. This result supports the TOD theory that high-density and mixed-use environments encourage public transportation use. In addition, compared to local roads, the number of bus riders at bus stops located on the main roads tends to be greater. By investigating the relationship between bus transport and other transport use, it is shown that active nearby subway stations tend to have a positive influence on bus ridership, while bicycle roads seem to have a negative effect on the number of bus stop users. Based on the results of this study, conclusions and policy implications are presented as follows.

First, Seoul, which boasts a diverse urban environment, is an exemplar case for promoting bus transport through the reformation of the overall bus transit system and the introduction of BRT throughout the city. Thus, it is expected that the variables derived from this study can be used as basic data for evaluating land use public transport activation policy aimed at increasing the number of bus users. The result shows that bus stops in high-density compound areas and on roads with greater traffic tend to have more riders. Based on this result, it may be possible to evaluate bus stop locations and bus routes, and to present a direction for urban design and policy establishment toward the activation of public transportation use.

Second, this study aimed to clarify the relationship between buses and subways. It was confirmed that buses and subways have a complementary relationship with each other. The Seoul Metropolitan Government coordinates public transportation systems through the "T Money" service as a form of transportation card or as credit incorporated in users' credit cards. This service, which allows free transfer between bus and subway, is very widely used in Seoul. The analysis result implies that easy transfer between bus and subway routes may contribute to bus ridership, supporting the rationale that public transportation can be more effective when subway and bus systems, the two most popular public transportation modes in everyday life, are linked.

Lastly, unlike subway systems, bike paths seem to foster bicycle use, which may replace bus transport use. In Korea, bicycles are generally not allowed on buses and little bike parking is provided at bus stops, which may discourage transfer between bus and bicycle. Thus, bicycle riders may not consider the bus as an option to transfer to from their own bicycle. Instead, they may choose either their own bicycle or another transportation mode, including buses. More bicycle parking spaces at bus stops may change this relationship between bus and bicycle use in Seoul. In addition, considering that the number of bicycle users has been steadily increasing in recent years and that Seoul's public bicycle "Ttareungyi" [40] is being expanded all over the city, bicycles can be considered an alternative to bus transport where the provision of bus transport is insufficient.

Despite the findings, this study only analyzes the effects of meso-scale urban form features, defined as a 400-m network buffer, leaving the influence of micro-scale environmental factors unexplored. In particular, the present study did not reflect on the nature of the various types of bus stops, including the local bus stop, city bus stop, and town bus stop. To overcome these limitations, it is necessary in future studies to consider more detailed micro-scale factors, such as street-level design elements that may affect pedestrians, a diverse range of factors (e.g., cultural, social, economic, morphologic, etc.), and the characteristics of bus stops. In addition, the inclusion of characteristics of bus networks, such as bus frequency, may contribute to control of the potential autocorrelation of bus networks (i.e., parallel routes that offer different bus services may spatially influence each other).

Regarding road types, although we included the grade of roads to control for the impact of the overall capacity of bus services on bus ridership, details on the actual frequency and capacity of the bus system on each road are not available. The absence of the bus frequency and capacity data may lead to potential bias. Better data that include such information will improve the quality of future studies on bus ridership.

Lastly, this study was conducted in Seoul, which is the largest city in Korea, and it is supported by well-developed public transportation systems. Hence, the external validity of the analysis may be limited to similar large cities in East Asia, and the result may differ in studies on small and medium cities in different cultural, social, and economic contexts. Therefore, parallel studies that compare and analyze the indicators derived from this study in other types of cities are expected to improve the generalizability of the present research, as well as contribute to more applicable urban planning and policy approaches in accordance with the size and characteristics of each city.

Acknowledgments: This work was developed for Se Na Sun's master's thesis. This work was supported by a National Research Foundation of Korea grant, funded by the Korean government (MSIP) (NRF-2010-0028693). This work was also supported by the 2017 Hongik University Research Fund. Seoul Institute provided us with the data used in this paper for "The Fifth Research Paper Contest 2017 Seoul Utilizing Public Data".

Author Contributions: Se Na Sun and Jaeseok Her suggested the initial idea and conducted the data analysis. Sae-young Lee and Jae Seung Lee advised the theoretical framework and edited the manuscript. All authors have reviewed and approved the final manuscript.

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

Appendix A

Table A1. Sensitivity analysis result of the SEM of the distance-decay parameter (β) of the gravity index.

Variables	β : 1.0	β : 1.2	β : 1.4	β : 1.6	β : 1.8	β : 2.0	β : 2.2
	Coef. (S.E.)	**Coef. (S.E.)**	**Coef. (S.E.)**	**Coef. (S.E.)**	**Coef. (S.E.)**	**Coef. (S.E.)**	**Coef. (S.E.)**
Constant	4.664 *** (0.307)	4.975 *** (0.304)	5.232 *** (0.305)	5.440 *** (0.308)	5.607 *** (0.312)	5.743 *** (0.316)	5.853 *** (0.321)
ln (Gravity Index)	0.201 *** (0.025)	0.183 *** (0.023)	0.165 *** (0.020)	0.149 *** (0.018)	0.135 *** (0.017)	0.123 *** (0.015)	0.113 *** (0.014)
Land Use Diversity	1.209 ** (0.440)	1.231 ** (0.440)	1.250 ** (0.440)	1.266 ** (0.440)	1.279 ** (0.440)	1.290 ** (0.441)	1.300 ** (0.441)
ln (Floor Area Ratio)	0.063 ** (0.021)	0.062 ** (0.021)	0.061 ** (0.021)	0.060 ** (0.021)	0.060 ** (0.021)	0.060 ** (0.021)	0.059 ** (0.021)
Intersection Density	6.438 (6.892)	6.375 (6.900)	6.310 (6.906)	6.249 (6.913)	6.195 (6.919)	6.147 (6.924)	6.105 (6.929)
Arterial Road	0.248 *** (0.060)	0.245 *** (0.060)	0.244 *** (0.060)	0.242 *** (0.060)	0.241 *** (0.060)	0.241 *** (0.060)	0.240 *** (0.060)
Collector Road	−0.053 (0.087)	−0.054 (0.087)	−0.055 (0.087)	−0.056 (0.087)	−0.057 (0.087)	−0.057 (0.087)	−0.058 (0.087)
ln (Hilliness)	0.030 (0.031)	0.032 (0.031)	0.033 (0.031)	0.000 (0.002)	0.035 (0.031)	0.035 (0.031)	0.036 (0.032)
Bike Road	−0.186 *** (0.056)	−0.190 *** (0.056)	−0.194 *** (0.056)	−0.196 *** (0.056)	−0.198 *** (0.056)	−0.200 (0.056)	−0.201 (0.056)
ln (Population)	0.016 (0.061)	0.014 (0.061)	0.012 (0.061)	0.011 (0.062)	0.009 (0.062)	0.008 (0.062)	0.007 (0.062)
ln (Firm)	0.052 (0.063)	0.049 (0.063)	0.048 (0.063)	0.048 (0.063)	0.049 (0.063)	0.050 (0.063)	0.051 (0.063)
ln (Vehicles)	0.029 (0.057)	0.028 (0.057)	0.027 (0.057)	0.027 (0.057)	0.027 (0.057)	0.027 (0.057)	0.026 (0.057)
ln (Parking Space)	−0.029 (0.082)	−0.029 (0.082)	−0.029 (0.082)	−0.030 (0.082)	−0.031 (0.082)	−0.031 (0.082)	−0.032 (0.082)
Lambda (λ)	0.432 *** (0.028)	0.436 *** (0.028)	0.438 *** (0.020)	0.440 *** (0.027)	0.442 *** (0.027)	0.443 *** (0.027)	0.444 *** (0.027)
n	2300	2300	2300	2300	2300	2300	2300

Notes: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

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