

Determining factors affecting public bike ridership and its spatial change before and after COVID-19

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ABSTRACT

COVID-19, which has spread since late 2019, has caused drastic changes in transportation use. A few studies have already addressed the relationships between COVID-19 and transportation mode choice. However, in most cases, the analysis has been based on transit ridership during the early phases of the COVID-19 pandemic. In addition, few studies have focused on public bike use before and after COVID-19. This study examines the effect of COVID-19 on the ridership of public bikes and various determining factors of public bike use. An origin–destination (OD) analysis and spatial regression models were used with public bike ridership data from Seoul, Korea. The findings of the analysis can be summarized as follows. First, this study confirms that public parks have significantly influenced the increase in public bike ridership since the COVID-19 outbreak. This finding indicates that outdoor spaces such as riverside parks have played important roles in public bike ridership during the pandemic period. Second, this study finds that accessibility to subway stations strongly impacts the increase in public bike ridership. This means that the demand for public bikes as a connected transportation mode has increased since COVID-19. Third, access to bike lanes has had a significant impact on the increase in public bike ridership. This finding indicates the importance of expanding the public bike infrastructure network. Finally, this study makes policy proposals to promote public bike ridership during the COVID-19 pandemic.

1. Introduction

1.1. Background of the study

COVID-19, which has spread since late 2019, has led to many infections and deaths worldwide and has had a tremendous impact on daily life. The first confirmed case in Korea occurred on January 20, 2020, and the World Health Organization (WHO) declared a pandemic on March 11, 2020. The number of confirmed cases in Korea was 103,088 on March 31, 2021. Because of COVID-19, an unusually infectious disease, the government has enforced contagious disease control and prevention acts and social distancing policies.

Due to the spread of COVID-19, movement between countries and individuals' travel behavior have changed significantly. For example, usage rates of modes of transit such as subways and buses are expected to decrease considerably due to the avoidance of transit used by unspecified persons. In addition, the spread of online education and telecommuting systems due to the reinforcement of social distancing is also expected to influence individual travel behavior greatly. For example, as

travel in countries and cities is restricted, the transit used by unspecified persons is expected to decrease significantly (Won, 2020; Lee, 2020). Many previous studies have shown that ridership of bikes, which are personal vehicles, has increased during COVID-19 (Shamshirpour et al., 2020; Teixeira & Lopes, 2020; Tan & Ma, 2020).

Significant changes in transit mode choice have occurred due to the spread of COVID-19. Therefore, it is necessary to examine changes in individual travel behavior under the spread of COVID-19. First of all, it is expected that the influence of COVID-19 on individual travel behavior will vary significantly by mode. Specifically, due to the transit used by unspecified persons in a small space, transit has a high potential of COVID-19 infection. This is why individual travel modes such as public bikes are preferred.

Additionally, due to COVID-19, there is a possibility of changes in travel behavior based on the purpose of travel; differences are expected between weekday travel, which includes essential travel such as commuting, and weekend travel, which includes leisure travel. Specifically, factors affecting weekday and weekend travel before and after COVID-19 will be different. Thus, it is necessary to subdivide and

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research the amount of transit ridership by the degree of spread of COVID-19 and the purpose of travel.

1.2. The purpose of the study

The purpose of this study is to compare and analyze the use of public bikes and its determining factors before and after COVID-19 in Seoul, Korea. Specifically, to compare and analyze the physical environmental factors that affect public bike ridership before and after COVID-19, this study separates weekday trips from weekend trips. Then, this study compares the changes in public bike ridership and its spatial characteristics before and after COVID-19. Finally, this study identifies determining factors of public bike use and suggests policies that could be implemented to promote public bike use.

2. Literature review

2.1. COVID-19 and mode choice

COVID-19, a pandemic disease, has lasted for more than a year as of 2021. Accordingly, various studies on changes in travel mode related to COVID-19 are being conducted. Orro et al. (2020) investigated the effects of city closures enforced by the government on bus ridership during COVID-19 in Coruña, Spain. Bus ridership was about half of automobile ridership during the city closure, and public bike ridership was zero. However, public bike ridership showed the fastest recovery at the end of the city closure, whereas buses showed a slow recovery. The fear of infection is the cause of this phenomenon. In the same vein, during COVID-19 in Sweden, transit ridership decreased drastically. The decrease in ridership was the largest in Stockholm (60 %). In this period, sales of short-period tickets dropped to almost zero (Jenelius & Cebe-cauer, 2020). Bhouiri et al. (2021) concluded that the 'stay-at-home' policy made confirmed cases decrease. Hu et al. (2021) determined that public bikes were more resilient than other modes such as transit, driving, and walking. Nikiforiadis et al. (2020) mentioned that public bikes provide a safe mode to contribute to the city's resilience and sustainability during COVID-19, providing evidence that public bike safety in terms of infection. Shang et al. (2021) found that during the COVID-19 pandemic, on Feb. 6, 2020, the energy consumption and emissions decreased to approximately 1/17th of those on an average day.

Studies have confirmed and predicted changes in the usage of modes of transportation during COVID-19 (Shamshiripour et al., 2020; Teixeira & Lopes, 2020; Tan & Ma, 2020). Teixeira & Lopes (2020) studied the effect of COVID-19 on subways and public bikes in New York. Both subways and public bikes showed decreases in ridership during COVID-19, but the reduction in public bike usage was relatively small, and the average usage time increased. Accordingly, public bikes were more resilient than subways, and mode transfer from subways to public bikes was expected. This result indicates that public bikes can be provided quickly as an alternative to transit and that use of automobiles should be reduced through policies to encourage the use of public bikes. Also, Pase et al. (2020) mentioned that encouraging commuters in New York to ride public bikes could reduce congestion related to automobile usage.

Shamshiripour et al. (2020) revealed that people living in Chicago perceive the risk of infection with COVID-19 as low in cars, bikes and walking, public transportation, and taxis. The study mentioned the potential of switching means from public transit used by an unspecified number of people to personal transit such as walking and cycling during COVID-19. Tan & Ma (2020) revealed that 97.0 % of commuters who did not choose rail transportation during the COVID-19 epidemic chose personal transportation (bike, car, and walking). Shang et al. (2021) revealed that the travel time has increased after COVID-19 in Beijing, China. Hong et al. (2021) also presented that the COVID-19 variable affected the demand for the public bike using the case study of Seoul, Korea. Similarly, Kim et al. (2021) confirmed that public bike ridership

rose during COVID-19. These studies imply that people who used to be traveled by public transits tend to ride a bike due to the COVID-19 pandemic. Nikitas et al. (2021) mentioned that the Asia countries kept transmission to low numbers of people, implementing some regulations to control the spread of infection, such as encouraging the transformation of mode choice from public transit to bicycle.

Schaefer et al. (2021) found that in Hanover, the bus is substituted by bike, car, and telecommuting. However, train ridership seems to be positively substituted by bike ridership and is not significantly replaced by a car. In the same vein, Scorrano & Danielis (2021) found high substitutability between the bike and the bus, but not the automobile.

The results of previous studies showed that the influence of COVID-19 on transportation was different for each means. Specifically, in the case of public transit, the decrease in usage was greater than that of personal vehicles such as passenger cars and bikes due to the high risk of infection. On the other hand, usage of personal vehicles such as passenger cars, walking, and bikes was not significantly reduced due to the low risk of infection. Studies have also mentioned the possibility of switching means from public transportation to personal transportation, suggesting that public bikes should be promoted over passenger cars. Therefore, this study suggests that COVID-19 provides an opportunity to compare and analyze the changes in factors that affect the usage of public bikes, and at the same time analyze changes in spatial patterns.

2.2. Determining factors affecting bike ridership

Studies have shown that COVID-19 has affected bike usage (Bergantino et al., 2021; Caulfield et al., 2021; Fuller et al., 2021; Li et al., 2021; Padmanabhan et al., 2021; Teixeira et al., 2021; Wang & Noland, 2021). Caulfield et al. (2021) conducted a survey and interview with faculty and students at Dublin University in Ireland on public transportation, walking, and bike use during the COVID-19 pandemic. They found that even after COVID-19, people are willing to use bikes and walking rather than transit. The desire to work from home is higher, which is expected to significantly reduce the utilization rate of public transportation when passing to work. Bergantino et al. (2021) studied public bikes in Italy before and after COVID-19. In particular, the amount of bike infrastructure plays a decisive role in bike usage, and it has been found that people are more willing to buy bikes after COVID-19. Teixeira et al. (2021) mentioned that COVID-19 had impacted public bike ridership. Specifically, COVID-19 and social distancing have made people avoid transit, which has affected the motivation to use public bikes. Fuller et al. (2021) investigated bike ridership during the 2020 COVID-19 pandemic in Australia, finding that 63 % of respondents increased cycling during COVID-19 restrictions. Bike ridership during leisure time has increased significantly, while commuting has decreased. Public bike ridership in New York returned to pre-pandemic levels, but subway ridership remained low and did not return to previous levels. This result implies that public bikes improve resilience in cities (Wang & Noland, 2021).

There are also studies showing that physical environmental factors affect the use of public bikes. Wang et al. (2016) measured the station activity of a bike-sharing system through various variables. It was concluded that the smaller the distance between bike stands, the higher the traffic volume. The restaurant industry was significantly related to bike usage in terms of economic activity variables. Faghih-Imani et al. (2017) stated that bike infrastructure attributes and land-use characteristics affect bike ridership. Sa & Lee (2018) studied the physical environmental factors affecting the rental and return of public bikes in Seoul. They found that physical environmental characteristics such as the total area of neighborhood facilities near rental centers, the total area of business facilities, and the distance to subway entrances affect the use of public bikes. Chibwe et al. (2021) examined the impact of several variables on the demand for London public bikes during 2012–2020 and found that the number of public bike stations affects ridership. Specifically, as the number of stations increases, the demand increases.

In addition, studies have shown that weather conditions and time affect the use of public bikes. Xu et al. (2018) figured out that people use public bikes a lot between 7:00–10:00, 11:00–13:00, and 17:00–18:00. Faghih-Imani et al. (2014) studied the factors affecting public bike usage in Montreal, Canada. As a result of examining the effects of weather characteristics, land use characteristics, time characteristics, and bike infrastructure on public bikes, they found that poor weather conditions negatively affect public bike usage, and the distance between CBD and public bike stations also affects public bike usage. In addition, it was found that bikes were used more during the weekdays than on weekends, and more in the afternoon than in the morning. Faghih-Imani et al. (2017) stated that the purpose of travel over time affects bike usage. Mattson & Godavarthy (2017) studied the factors affecting the usage of public bike stands on campus and the factors that enabled the public bike project to succeed. Specifically, the effects of weather and time variables on bike usage were revealed, and implications were derived from reducing the barriers to public bike use through the successful cases of public bike projects revealed in this study. Noland et al. (2019) studied bike traffic through CitiBike, a bike-sharing system in New York, and land use data. The analysis revealed the importance of access to subway stations in the morning and public bikes in the evening. Through this, the relationship between shared bikes and subways during peak hours was derived. In combination with land use, Noland et al. (2016) revealed the relationship between CitiBike ridership and subway use during peak hours when accessing subway stations through public bikes in the morning and evening.

The results of previous studies confirmed that the factors affecting the use of bikes vary, and the usage and travel patterns differ depending on the purpose of a bike trip. In addition, it was confirmed through previous studies that COVID-19 also has affected bike usage. Therefore, further studies should focus on the spatial changes in public bike use and determining factors affecting the use of public bikes based on the purpose of travel before and after COVID-19.

2.3. COVID-19 and government policy

Studies have shown that government policies related to COVID-19 affect travel behavior (Bucsky, 2020; De Vos, 2020; Hadjidemetriou et al., 2020; Hua et al., 2021; Kubafák et al., 2021; Nikitas et al., 2021; Park et al., 2020). De Vos (2020) predicted that social distancing policies could reduce traffic and cause a transition from transit to passenger cars. He also noted that isolation due to the distancing policy has a negative health impact, so safe and unthreatened of infections transit and bikes ridership should be promoted. However, the study is limited by a lack of empirical analysis. Results of a survey in the US showed that people who were unemployed due to COVID-19 increased public bike ridership by about 43 % (Jobe & Griffin, 2021). Nikitas et al. (2021) mentioned that temporary loosening of restrictive legislation like strict helmet laws also can raise public bike ridership.

Hadjidemetriou et al. (2020) found that the transit ridership decreased by the largest margin during the UK government's implementation of policies related to COVID-19. They concluded that the government's measures aimed at reducing each mode impacted the COVID-19-related mortality rate, suggesting the importance and necessity of the government's policy. Bucsky (2020) studied the government's movement restriction policy and changes in the amount of use by means in Budapest. As a result of the study, it was reported that public transportation showed the greatest decline, and bikes and public bikes showed the smallest decline.

Park et al. (2020) studied the relationship between government policies related to COVID-19 and public bike usage in Korea. As a result of the study, it was determined that commuting by bike and weekend usage increased due to social distancing. Accordingly, it was suggested that the government pay attention to public bike hygiene to prevent the spread of COVID-19 infection through public bikes. Moreover, Kwak et al. (2022) confirmed statistically significant associations between

social distancing policies and public bike ridership in Seoul, Korea.

In Nanjing, China, public bike ridership decreased by 72–82 % during COVID-19. Trips for commuting decreased, but health- and religion-related trips increased (Hua et al., 2021). In Slovakia, public bike ridership decreased during the COVID-19 pandemic due to travel restrictions such as lockdown. The largest decrease, about 62 %, was in October. However, demand increased slightly in November, when restrictions were relieved (Kubafák et al., 2021). The same phenomenon of decreasing bike ridership also was noted in Zurich, Switzerland during the COVID-19 lockdown period (Li et al., 2021).

Previous studies confirmed that the government's COVID-19-related policies affect the travel mode choice and the amount of bike ridership. Therefore, this study suggests that physical environmental factors and spatial patterns should be identified in consideration of the effect of COVID-19 on bike usage.

2.4. Limitation of previous research

After reviewing previous studies, the limitations of previous studies can be summarized as follows. First, as a result of a study on the relationship between COVID-19 and travel mode choice, it was reported that the use of personal modes of transportation such as automobiles and bikes increased due to COVID-19. However, most of these studies compare ridership before and after COVID-19 or predict ridership post-pandemic. In other words, existing studies did not sufficiently address the determining factors affecting bike ridership before and after COVID-19 pandemic.

Second, as a result of a study on COVID-19 and travel mode choices, it was confirmed that the recovery speed of public bike usage was faster than those of other modes of transportation after the COVID-19 lockdown period, and the potential of switching to public bikes was confirmed. However, studies that analyze the physical environmental factors affecting public bike ridership after COVID-19 by dividing trips by travel purpose are insufficient. Therefore, this study compares and analyzes the physical environmental factors affecting the use of public bikes before and after COVID-19 by subdividing the total amount of public bike ridership into weekday usage, which is dominated by essential travel, and weekend one, when leisure travel is more common.

Third, studies of the relationship between COVID-19 and bike usage in Western countries have noted significant decreases in bike usage during the implementation of COVID-19 related policies. Asian cities, including Seoul, had different characteristics of bike ridership with their government policies on COVID-19. For example, most of the global cities except Seoul have had very strict COVID-19 quarantine policies such as stay-at-home or lockdown. However, the city of Seoul has not had a stay-at-home or lockdown policy during the pandemic period and might have different spatial patterns and determining factors of public bike usage. Therefore, this study focused on the effect of COVID-19 on public bike ridership through a spatial analysis and compared determining factors before (2019) and after (2020) COVID-19 by the spatial regression model.

3. Research methodology

3.1. Case study area

The case study area is Seoul metropolitan city (see Fig. 1). The 'Ttareung-i' Seoul public bike program has been implemented in 25 administrative districts in Seoul and started service with 967 bikes on September 19, 2015. The number of bikes and rental stations continues to increase every year, and the Seoul Metropolitan Government has announced that the ridership increased by 24.6 % in 2020 compared to 2019 (Seoul open dataset, 2021; Seoul TOPIS data in 2020, 2021). The ridership data of public bikes in Seoul is a public database that is suitable to analyze public bike ridership and its change before and after the COVID-19 outbreak.

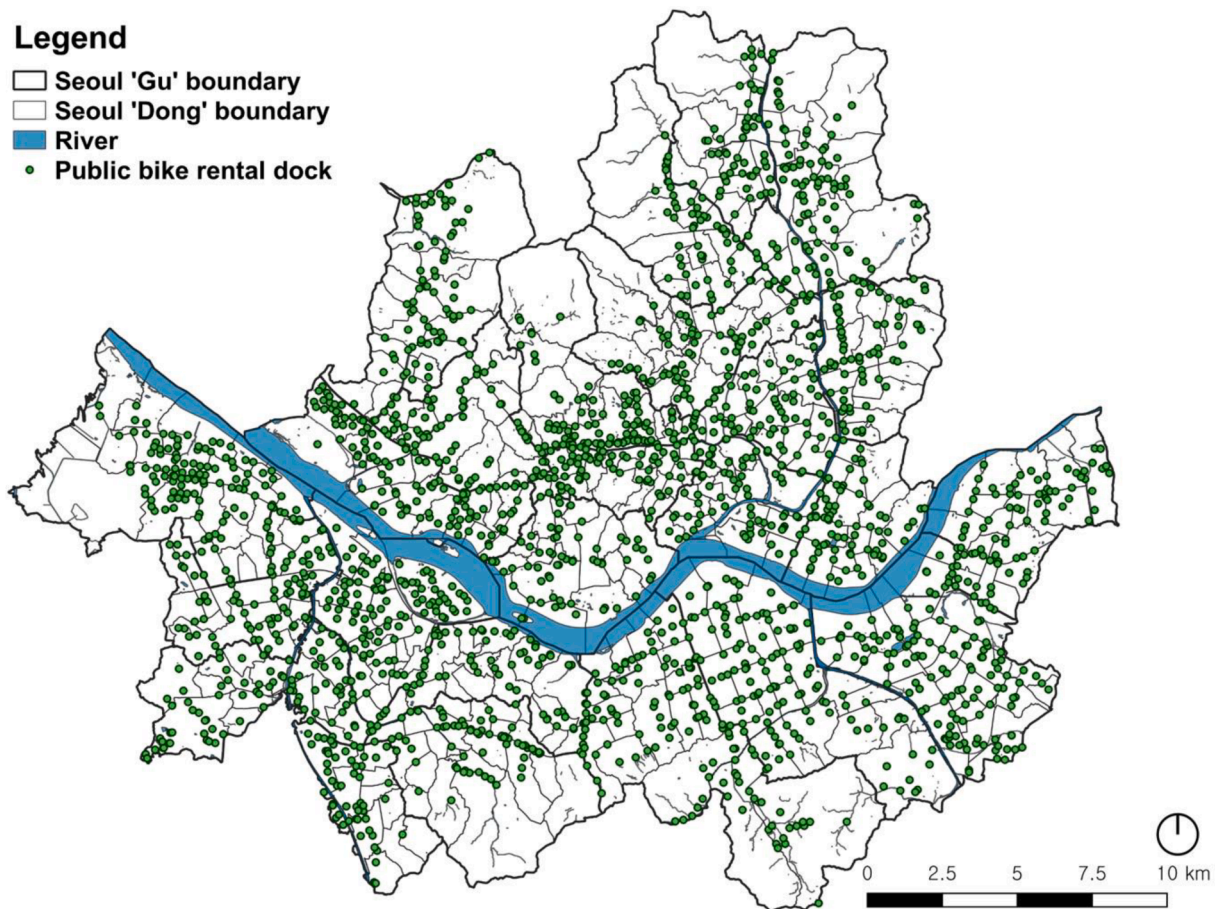


Fig. 1. The study area of Seoul and locations of public bike rental stations.

This study aims to analyze spatial patterns of public bike usage and identify determining factors of public bike ridership before and after COVID-19 in Seoul, South Korea. Specifically, this study intends to compare and analyze the factors and spatial flow patterns affecting the ridership into weekdays, when essential travel occurs, and weekends, which are dominated by leisure travel.

3.2. Data sources

The list of data used in this study is as follows (see Table 1). This study used public bike ridership data provided by the Seoul open dataset to confirm public bike ridership changes in Seoul due to COVID-19. In addition, this data provided the rental status of public bikes collected daily and hourly at 2,042 rental stations in Seoul (see Fig. 1).

To determine the change of spatial ridership, Seoul public bike rental data, including the rental and return information collected daily and hourly, were utilized. These data include information on public bike rentals and returns for each cradle. The daily population of Seoul, used as a population factor, was used as a control variable because the more people are present around the rental station, the more ridership occurs. The maintenance period of rental stations and the number of rental stations were considered, and Seoul public bike rental station information was used. In general, rental stations that were installed earlier had greater ridership than those that were installed later. Therefore, the rental station installation date was used as a control variable. The number of cradles per rental station also was used as a control variable because stations with many cradles are utilized more than those with fewer cradles.

The land-use factors, which have been linked to public bike ridership in previous studies, were used as independent variables (Faghih-Imani

et al., 2014; Noland et al., 2016). For each land use, previous studies calculated the total floor area density (commercial, office, and residential areas) and park area (riverside, forest, and neighborhood parks) within a 250 m radius of the rental station (Sa & Lee, 2018; Wang et al., 2016). The access to station factors, which are the shortest network distance from the rental station to each facility, were calculated and used as independent variables. For these variables, the average value of the access to station factors were used in each census tract of the 'administrative dong' unit.

3.3. Methodology

This study aims to analyze the influence of COVID-19 on the ridership of public bikes and its spatial change in Seoul. To this end, it was analyzed by 250 m buffer from rental station unit, and independent variables were constructed; the population factor in each 'administrative dong' which has rental stations, and the others were established by 250 m buffer from rental station. In addition, the rental stations that were analyzed existed in both 2019 and 2020. Based on this, the number of rental stations analyzed was 1,473 in 2019 and 2020.

This study excluded days that had irregular external conditions, such as severe weather conditions affecting the ridership of public bikes. Previous studies have stated that the weather conditions influence public bike ridership, specifically precipitation (over 10 mm), snowfall (over 5 cm), wind speed (over 7 m/s), and temperature (over 29 °C). In addition, variables related to national holidays such as New Year's Day and data with zero usage time judged to be a system error or not actual usage also were excluded based on previous studies (de Kruijf et al., 2021; Faghih-Imani et al., 2014; Lee et al., 2016; Mattson & Godavarthy, 2017; Wang & Noland, 2021; Scott & Ciuro, 2019). Specifically,

Table 1
Description of data sources.

Data		Time	Description	Data source
Public bike	Seoul, public bike rental data	Jan. – Dec., 2019, Jan. – Dec., 2020	bike information (number, rental, return)	Seoul open dataset
Population	Seoul, public bike rental station information Seoul, daily population	Jul. 13th, 2020 Jan. – Dec., 2019, Jan. – Dec., 2020	rental station information (number, name, location) population information (daily, hourly)	
Park	Service facility park	Mar. 27th, 2020	park information (name, location)	National Spatial Data Center (Korea) National Weather Service (Korea)
River	River	Apr. 6th, 2021	river information (name, location)	
Weather	Daily weather	Jan. – Dec., 2019, Jan. – Dec., 2020	weather information (rainfall, wind, snowfall)	
Landuse	E-map building layout	Dec. 2019, Dec. 2020	landuse information (type of building, area, floor)	Road name address
Bike lane	Seoul, bike lane	Jul, 26th, 2018	bike lane information (name, length, location)	Esri KR open data

Borowska-Stefańska et al. (2021) mentioned that weather conditions such as temperature and rainfall correlate with bike ridership. Based on these conditions, this study uses public bike ridership data for 300 days in 2019 (excluding 65 days of 365 days) and 286 days in 2020 (excluding 80 days of 366 days).

In addition, referring to previous studies that found that the change in public bike ridership is affected by travel purpose, the purpose of travel was divided into weekdays, including mandatory travel, and weekends, when leisure travel occurs (Faghih-Imani et al., 2017; Ministry of Land, Infrastructure and Transport, 2016).

By verifying the multicollinearity in the independent variable, variables with a high variance inflation factor (VIF) were excluded from the final model. It was confirmed that all VIF values of the last variable were three or less, indicating no multicollinearity issues (see Table 2). The analysis method used spatial regression analysis models. To identify the factors affecting the public bike ridership data, ridership data from 2019 (before COVID-19), and 2020 (after COVID-19) were analyzed separately, and differences in ridership between 2019 and 2020 were identified. The analysis was divided into weekdays and weekends in ‘administrative dong’ census tracts and by 250 m buffers from a rental station. The factors influencing public bike ridership before and after COVID-19 were confirmed by coefficient (coef.), and Akaike info criterion (AIC).

4. Analysis results

4.1. Descriptive analysis

Table 2 is the result of a descriptive statistical analysis of the variables used in this study. Average, standard deviation (S.D.), minimum value, maximum values, and VIF values of dependent variables, population characteristics, rental station characteristics, and accessibility of rental station characteristics are presented for a 250 m radius of the rental station, which is existed in 2019 and 2020 both year (Obs. = 1,473).

To make a dependent variable normal distribution, this study applied log transform on ridership. In the case of weekday public bike ridership for each rental station, which is a dependent variable, the average public bike ridership per station was 3.31 vehicles per day in 2019 and 3.41 vehicles in 2020. Compared to 2019, it can be seen that the public bike ridership per station on weekdays in 2020 was higher. On weekends, the average ridership (3.29 vehicles) in 2020 also was higher than in 2019 (3.13 vehicles).

The population variable consists of the average daily population per ‘administrative dong’, which has a public bike station. On weekdays and weekends in 2019, averages of 13,776 and 13,142 people were in the census tract, respectively, whereas on weekdays and weekends in 2020, averages of 13,433 and 12,924 people were in the census tract, respectively. The maintenance periods for rental stations that existed in both 2019 and 2020 ranged from 13 to 70 months.

Within the 250 m buffer from rental stations, there were averages of 12,722.14 m² of neighborhood parks, 1,878.35 m² of riverside parks, and 1,632.97 m² of forest parks. The neighborhood park area appears the largest within the 250 m buffer. In access to station variables, the largest deviation between the minimum and maximum value is the distance to riverside park and distance to forest park. Due to the characteristics of these parks, being in a specific area caused a large deviation between the minimum and maximum value. The existence of facilities within the 250 m buffer of each station also was determined.

4.2. Origin-destination analysis

4.2.1. Weekday trips

Public bike ridership on weekdays in Seoul increased 31.2 %, from 8,523,159 trips in 2019 (before COVID-19) to 11,180,549 trips in 2020 (after COVID-19). Fig. 2 shows the public bike origin–destination (OD) on weekdays before and after COVID-19. Trips under 1,000 were excluded from the map to highlight trips over 1,000 m. The analysis result shows significant changes before and after COVID-19 in Gangseo-gu (western part of Seoul), Seongdong-gu (around the riverside park and forest park), Gwangjin-gu (around the riverside park and forest park), and Gangnam-gu (CBD).

Public bike ridership increased in Gangseo-gu after COVID-19 due to new town development of Magok district that has greater accessibility to the Han River bike lane, which connects Magok new town to the Han River (Seoul metropolitan government, 2020). Seoul TOPIS data in 2020 (2021) indicates that the highest public bike ridership in 2020 appeared in Gangseo-gu, which has a well-established bike infrastructure. In contrast, public bike ridership after the COVID-19 outbreak decreased in Seongdong-gu and Gwangjin-gu except in some districts that are close to riverside parks or forest parks. The public ridership analysis of OD on weekdays confirmed that access to riverside parks or forest parks has a significant impact on the increase in public bike ridership after the COVID-19 outbreak.

4.2.2. Weekend trips

Weekend public bike ridership in Seoul increased 33.9 %, from 3,006,435 trips in 2019 (before COVID-19) to 4,026,902 trips in 2020 (after COVID-19). The weekend public bike OD analysis shows significant changes before and after COVID-19 in Gangseo-gu (western part), Yangcheon-gu (western part), Seongdong-gu (around the riverside park and forest park), and Gwangjin-gu (around the riverside park and forest park). In particular, public bike ridership increased in Gangseo-gu and Yangcheon-gu after the COVID-19 outbreak (Seoul metropolitan government, 2020; Yangcheon-gu office, 2020). However, public bike ridership decreased in most areas of Seongdong-gu and Gwangjin-gu after the COVID-19 outbreak, except in some areas that are close to riverside parks or forest parks (see Fig. 3).

The OD analysis on weekends confirmed that access to bike lanes, riverside parks, and forest parks influences the public bike ridership,

Table 2
Descriptive statistics analysis.

Variable			Obs.	Mean	S.D.	Min.	Max.	VIF				
								Weekdays		Weekends		
								2019	2020	2019	2020	
Dependent variable	Public bike ridership	Weekday average ridership in 2019 by station	1,473	3.31	0.75	0.39	5.10	–	–	–	–	
		Weekday average ridership in 2020 by station	1,473	3.41	0.77	0.08	5.12	–	–	–	–	
		Weekend average ridership in 2019 by station	1,473	3.13	0.77	0.35	5.04	–	–	–	–	
		Weekend average ridership in 2020 by station	1,473	3.29	0.80	0.01	5.12	–	–	–	–	
Independent variables	Population factors within administrative dong	Weekday average population in 2019	1,311	13,776.00	23,786.00	13.00	936,513.00	1.304	–	–	–	
		Weekday average population in 2020	1,311	13,142.00	18,339.00	22.00	645,553.00	–	1.209	–	–	
		Weekend average population in 2019	1,311	13,433.00	21,173.00	19.00	832,577.00	–	–	1.177	–	
		Weekend average population in 2020	1,311	12,924.00	16,017.00	17.00	671,017.00	–	–	–	1.147	
	Rental station factor	Station duration	1,473	45.46	11.00	13.00	70.00	1.132	1.127	1.121	1.120	
		Land use factors within 250 m buffer	Total floor area density of commercial facilities (250 m)	1,473	0.04	0.07	0.00	1.02	1.310	1.310	1.316	1.312
			Total floor area density of office facilities (250 m)	1,473	0.04	0.10	0.00	1.08	1.317	1.318	1.269	1.261
			Total floor area density of residential facilities (250 m)	1,473	0.17	10.17	0.00	1.29	1.196	1.186	1.185	1.169
	Area of neigh. park (250 m, m ²)		1,473	12,722.14	31,992.29	0.00	359,731.90	1.440	1.441	1.439	1.442	
	Area of riverside park (250 m, m ²)	1,473	1,878.35	10,324.11	0.00	115,076.00	2.007	2.008	2.004	2.005		
	Area of forest park (250 m, m ²)	1,473	1,632.97	14,423.10	0.00	192,990.58	1.216	1.216	1.231	1.226		
	Existence of primary destination factors within 250 m buffer (dummy variable)	Existence of subway	1,473	0.52	0.50	0	1	2.231	2.231	2.233	2.232	
		Existence of bike lane	1,473	0.67	0.47	0	1	2.063	2.064	2.063	2.066	
		Existence of river	1,473	0.46	0.50	0	1	2.410	2.409	2.410	2.408	
		Existence of university	1,473	0.12	0.32	0	1	1.187	1.187	1.186	1.186	
		Existence of neigh. park	1,473	0.37	0.48	0	1	2.086	2.086	2.086	2.086	
	Accessibility factors from rental station	Existence of riverside park	1,473	0.07	0.25	0	1	2.229	2.229	2.229	2.229	
		Existence of forest park	1,473	0.07	0.26	0	1	1.423	1.423	1.425	1.424	
		Distance to subway (m)	1,473	484.85	407.32	6.95	3,181.92	2.468	2.469	2.467	2.469	
		Distance to bike lane (m)	1,473	360.73	397.94	2.97	2,444.14	2.218	2.215	2.214	2.215	
		Distance to river (m)	1,473	500.05	354.34	8.00	1,868.86	2.332	2.331	2.329	2.329	
		Distance to university (m)	1,473	1,970.17	1,278.51	24.50	6,725.38	1.400	1.409	1.414	1.431	
		Distance to neighborhood park (m)	1,473	773.95	546.74	28.28	3,356.65	2.003	2.003	2.005	2.005	
		Distance to riverside park (m)	1,473	2,318.14	1,642.69	4.85	9,830.19	2.007	2.008	2.004	1.316	
		Distance to forest park (m)	1,473	2,502.70	1,622.17	12.99	9,176.90	1.401	1.401	1.401	1.401	

which can be maintained or increased after COVID-19. After the COVID-19 outbreak, access to riverside parks and forest parks greatly affected public bike ridership. Also, the extension and maintenance of bike infrastructure play important roles in increasing public bike ridership.

4.3. Spatial regression analysis

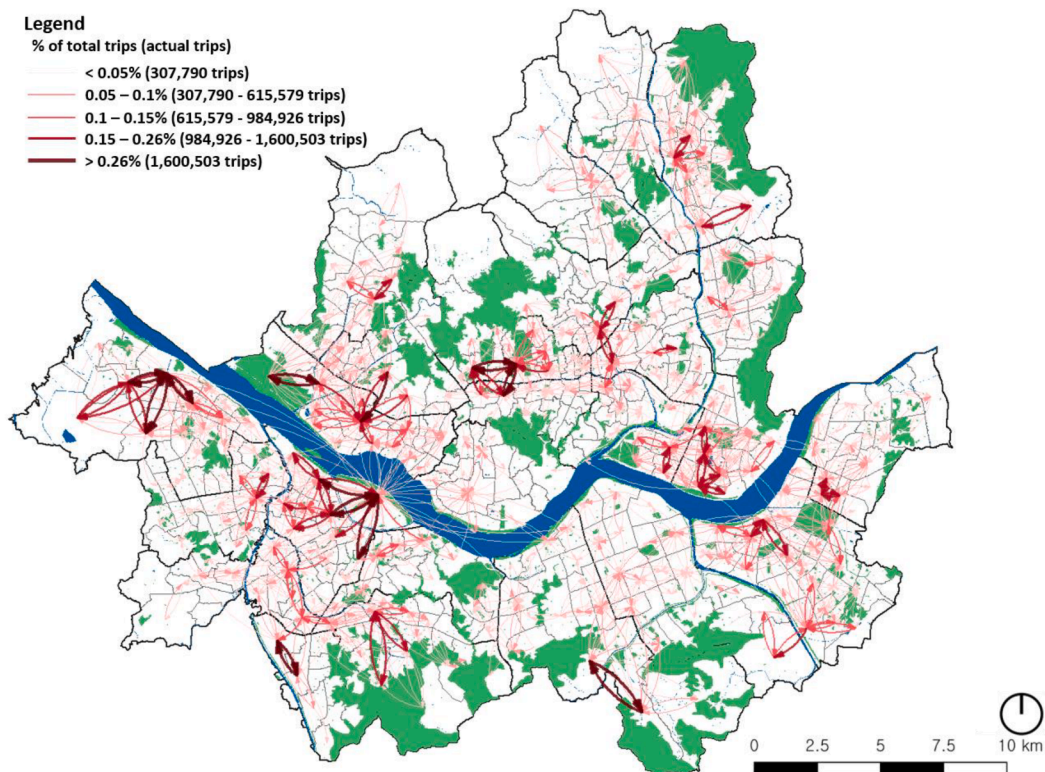
4.3.1. Weekday trips

This study analyzes the ridership of public bikes in Seoul before and after the COVID-19 outbreak using spatial regression analysis models to control spatial autocorrelation. This study compared three models such as Ordinary Least Squares(OLS), Spatial Lagged Model(SLM), and

Spatial Error Model(SEM). When variables have spatial information, the spatial autocorrelation should be controlled (Anselin, 1988; LeSage, 1997; Tobler, 1970). Furthermore, the spatial autocorrelation should be considered and controlled because Seoul public bike stations are placed close to each other, not randomly. This study tested the impacts of determining physical environmental factors on public bike ridership using 250 m buffers from a rental station. The final models indicate that the 250 m buffer model has higher explanatory power than the 100 m buffer model.

Table 3 shows the determining factors affecting the public bike ridership before and after COVID-19 within a 250 m buffer from a rental station during the weekdays. This study presents two models: 2019

(A) Weekday public bike trips in 2019



(B) Weekday public bike trips in 2020

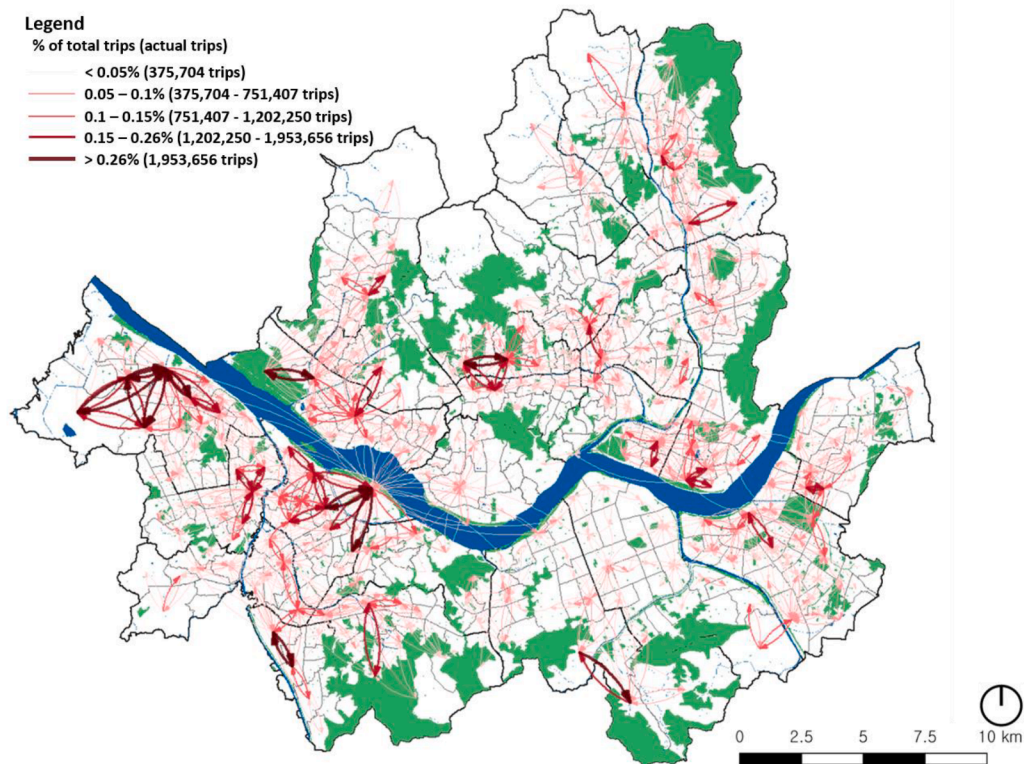


Fig. 2. Origin-destination analysis for weekday public bike trips (A: 2019, B: 2020, spatial unit: 'administrative dong').

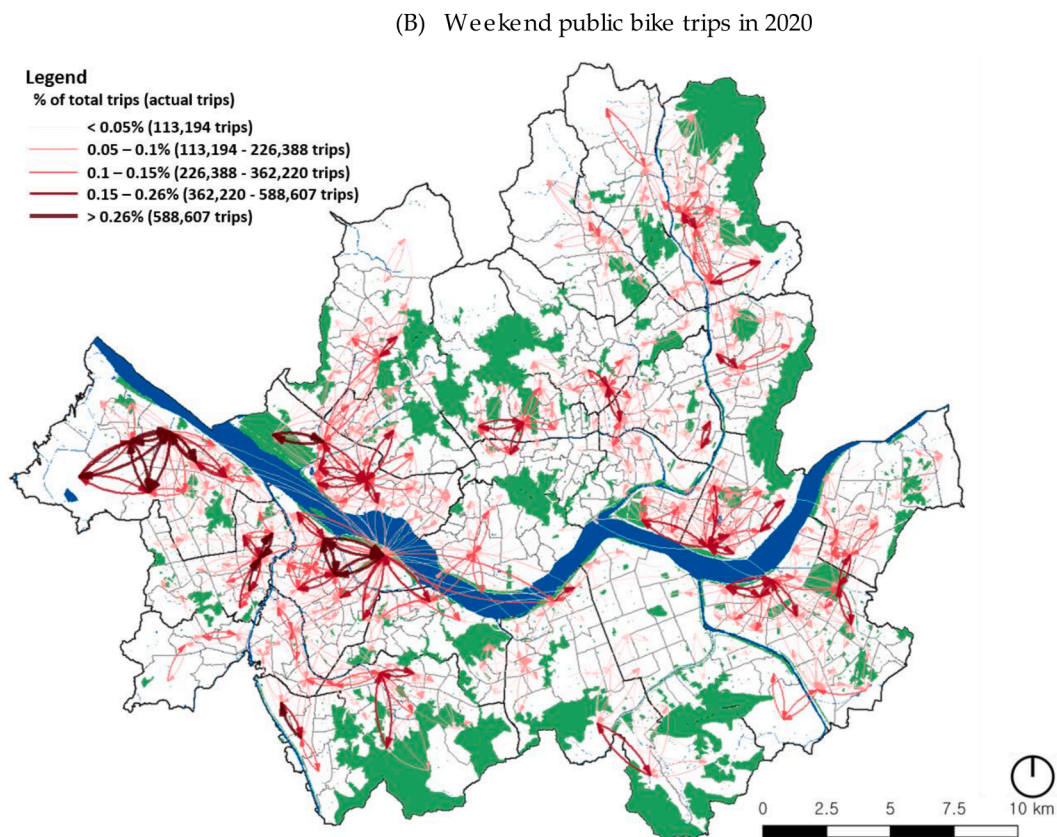
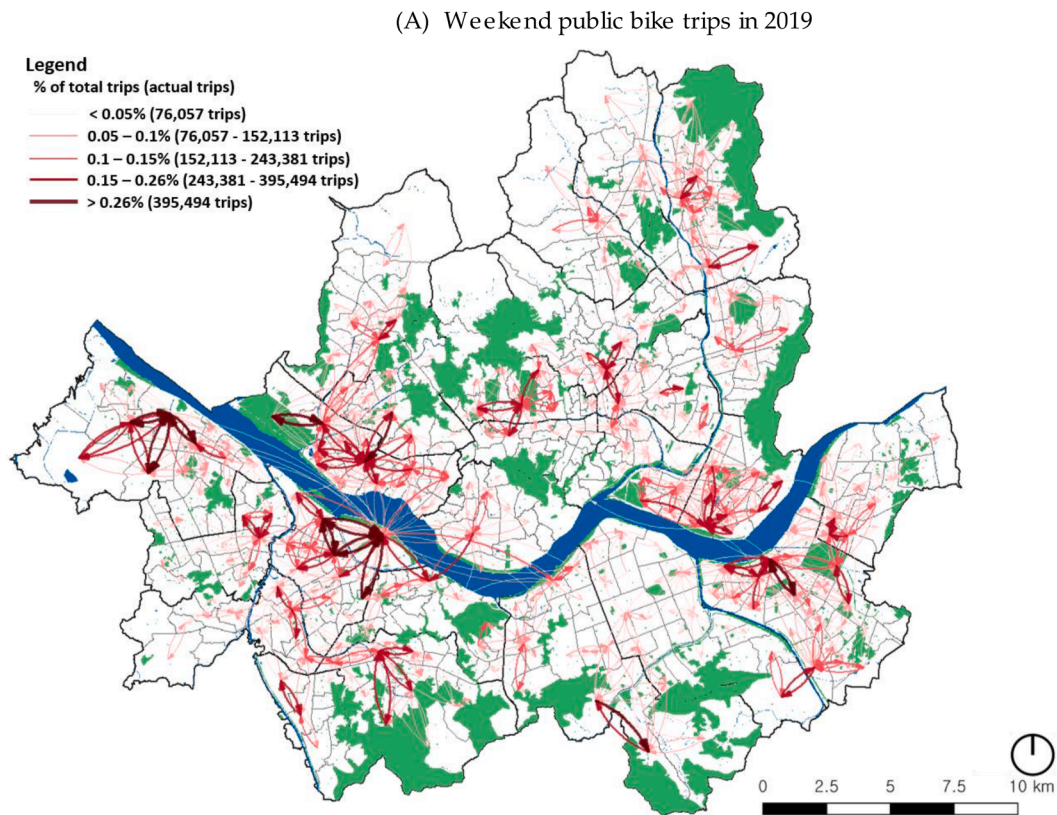


Fig. 3. Origin-destination analysis for public bike trips during the weekend(A: 2019, B: 2020, spatial unit: census tract of 'administrative dong').

Table 3

Analysis results of spatial regression model for weekdays (unit: 250 m buffer from rental station).

Variable		2019						2020					
		OLS		SLM		SEM		OLS		SLM		SEM	
Population factor	De facto. population	0.007	***	0.007	***	0.007	***	0.007	***	0.007	***	0.007	***
Rental station factor	Station duration	0.011	***	0.009	***	0.012	***	0.007	***	0.005	***	0.007	***
Landuse factors within 250 m buffer	Total floor area density of commercial facility	1.632	***	1.611	***	1.650	***	1.517	***	1.526	***	1.557	***
	Total floor area density of office facility	0.501	***	0.457	**	0.480	***	0.377	*	0.345	*	0.370	*
	Total floor area density of residential facility	0.102		0.119		0.156		0.106		0.119		0.148	
	Area of neigh. park (m ²)	−2.242	***	−2.236	***	−2.281	***	−2.650	***	−2.711	***	−2.693	***
	Area of riverside park (m ²)	7.772	***	7.250	***	6.975	***	8.567	***	8.528	***	8.500	***
	Area of forest park (m ²)	3.533	***	2.941	**	2.233	*	3.437	**	3.093	**	2.780	**
Existence of primary destination factors within 250 m buffer	Existence of subway	0.047		0.042		0.039		0.080		0.068		0.066	
	Existence of bike lane	0.060		0.076		0.090		0.043		0.052		0.051	
	Existence of river	0.047		0.047		0.040		0.067		0.066		0.060	
	Existence of university	0.128	**	0.132	**	0.128	**	0.038		0.050		0.057	
	Existence of neigh. park	0.111	**	0.113	**	0.117	**	0.091	*	0.084		0.087	*
	Existence of riverside park	0.367	***	0.337	***	0.329	***	0.238	**	0.224	**	0.217	**
	Existence of forest park	0.268	***	0.248	***	0.239	***	0.251	***	0.246	***	0.251	***
Accessibility factors from rental station	Distance to subway (m)	−0.285	***	−0.286	***	−0.312	***	−0.256	***	−0.265	***	−0.288	***
	Distance to bike lane (m)	−0.419	***	−0.424	***	−0.443	***	−0.434	***	−0.426	***	−0.428	***
	Distance to river (m)	−0.142	**	−0.145	**	−0.151	**	−0.197	**	−0.203	***	−0.204	***
	Distance to university (m)	−0.032	**	−0.032	**	−0.041	**	0.020		0.016		0.015	
	Distance to neigh. park (m)	−0.159	***	−0.150	***	−0.156	***	−0.145	***	−0.134	***	−0.145	***
	Distance to riverside park (m)	−0.039	***	−0.031	***	−0.038	***	−0.029	**	−0.022	*	−0.028	**
	Distance to forest park (m)	−0.051	***	−0.043	***	−0.040	***	−0.099	***	−0.087	***	−0.088	***
Constant		3.697	***	3.209	***	3.717	***	3.935	***	3.455	***	3.936	***
Rho		–		0.161		–		–		0.146		–	
Lambda		–		–		0.197	***	–		–		0.161	***
No. obs.						1,473							
R-squared		0.313		0.343		0.353		0.265		0.298		0.301	
Log likelihood		−1340.09		−1317.80		−1312.17		−1427.36		−1403.88		−1403.04	
AIC		2726.18		2683.60		2670.35		2900.72		2855.76		2852.08	
SC		2846.98		2809.65		2791.15		3021.50		2981.79		2972.87	
Residual Moran's I		0.196	***	0.027		−0.008		0.211	***	0.008		−0.010	

*p < 0.1, **p < 0.05, ***p < 0.01.

(before COVID-19), and 2020 (after COVID-19). The AIC values of each model, which the lower, the better the explanatory power are 2726.18 (OLS), 2683.60(SLM), and 2670.35(SEM) in 2019, respectively. In 2020, each model indicated 2900.72(OLS), 2855.76(SLM), and 2852.08(SEM), respectively. The best explanatory power models for each year on weekends are SEM, respectively.

In Table 3, SEM model in 2019 and 2020, the population factor and rental station factor, which are used as control variables in this analysis, are significant in all models. In land-use factors, commercial and office areas have significant and positive associations with public bike ridership during the weekdays in both models. However, the coef. and

significant values are lower than on weekdays in 2019. The work-from-home policy might be the reason that the office area does have lower coef. and significant values during the weekdays in 2020. The area of neighborhood parks shows significant negative associations in both models because of the large-size mountainous neighborhood parks, which do not allow the bike to enter or have limited bike infrastructure. These are the reason of negative association between the areas of neighborhood park and public bike ridership. In addition, the riverside park and forest park areas have significant and positive associations with public bike ridership in 2019 and 2020. Particularly, the riverside park area has a positive impact on the increase of public bike ridership

between 2019 and 2020. These findings suggest the importance of parks on public bike ridership during the pandemic period.

Next, the various rental station factors within a 250 m buffer from the rental station might have significant impacts on the public bike ridership. In particular, the existence of university has a significant and positive impact on public bike ridership during the weekdays in 2019, but not significant in 2020. Analysis results indicate that the university factor after COVID-19 is not as important as before COVID-19 due to campus closures. And the existence of neighborhood park, riverside park, and forest park have significant and positive impacts on public bike ridership in all models. These results pertaining to the positive association between the existence of parks and public bike ridership are consistent with previous studies (Duran-Rodas et al., 2019; Jiao et al., 2022; Roy et al., 2019; Tu et al., 2019). The presence of a neighborhood park, riverside park, or forest park shows a significant and positive association with public bike ridership in 2019 and 2020 models. In the case of the existence of a riverside park, Wang et al. (2016) indicated that the public bike ridership is more likely to increase with proximity to the river. This finding suggests the importance of linear riverside parks and infrastructure for public bike use.

Finally, accessibility factors of the shortest distance to key destinations show significant associations with public bike ridership. With the

increasing proximity of rental stations to subway stations, bike lanes, and river, public bike ridership increased in the 2019 and 2020 models. On the other hand, the distance to the university variable strongly negatively affects public bike ridership only in 2019. This finding indicates that accessibility to universities became a lower critical variable to the ridership during the COVID-19 pandemic period. In addition, accessibility variables of neighborhood parks, riverside parks, and forest parks show significant associations with public bike ridership. In particular, public bike ridership has increased from 2019 to 2020 at rental stations that have shorter distances to riverside and forest parks.

4.3.2. Weekend trips

Table 4 shows the determining factors affecting the public bike ridership before and after COVID-19 for a 250-m buffer from rental stations during the weekends. The AIC values of each model are 2857.81 (OLS), 2803.92(SLM), and 2796.98(SEM) in 2019, respectively. In 2020, each model indicated 3089.44(OLS), 3035.58(SLM), and 3028.98(SEM), respectively. The best explanatory power models for each year on weekends are SEM, respectively.

Analysis results indicate that the associations between public bike ridership and physical environmental factors during the weekends are slightly different from those of weekdays. Among land use factors,

Table 4
Analysis results of spatial regression model for weekends (unit: 250 m buffer from rental station).

Variable		2019			2020		
		OLS	SLM	SEM	OLS	SLM	SEM
Population factor	De facto. population	0.006 *	0.006 *	0.006 *	−0.001	−0.001	−0.002
	Station duration	0.010 ***	0.007 ***	0.010 ***	0.007 ***	0.005 ***	0.007 ***
Landuse factors	Total floor area density of commercial facility	1.678 ***	1.672 ***	1.727 ***	1.483 ***	1.498 ***	1.571 ***
	Total floor area of density office facility	−0.039	−0.045	−0.001	−0.153	−0.154	−0.131
	Total floor area of residential facility	0.366 ***	0.354 ***	0.385 ***	0.361 ***	0.356 ***	0.380 ***
	Area of neigh. (m ²)	−1.761 ***	−1.732 ***	−1.742 ***	−1.517 **	−1.555 **	−1.464 **
	Area of riverside park (m ²)	13.124 ***	12.759 ***	12.210 ***	14.175 ***	13.923 ***	13.383 ***
	Area of forest park (m ²)	6.825 ***	6.136 ***	5.580 ***	7.299 ***	6.876 ***	6.547 ***
Existence of rental station factors	Existence of subway	0.118 **	0.101 **	0.091 *	0.154 ***	0.135 **	0.134 **
	Existence of bike lane	0.037	0.057	0.071	0.021	0.004	0.005
	Existence of river	0.046	0.038	0.029	0.054	0.045	0.041
	Existence of university	0.110 *	0.112 *	0.106 *	0.040	0.049	0.054
	Existence of neigh. park	0.096 *	0.098 *	0.104 **	0.104 *	0.099 *	0.105 *
	Existence of riverside park	0.476 ***	0.446 ***	0.433 ***	0.331 ***	0.303 ***	0.277 **
	Existence of forest park	0.280 ***	0.257 ***	0.248 ***	0.267 ***	0.263 ***	0.261 ***
Accessibility factors	Distance to subway (m)	−0.264 ***	−0.269 ***	−0.297 ***	−0.208 ***	−0.218 ***	−0.242 ***
	Distance to bike lane (m)	−0.430 ***	−0.433 ***	−0.457 ***	−0.413 ***	−0.417 ***	−0.426 ***
	Distance to river (m)	−0.149 **	−0.145 **	−0.148 *	−0.232 ***	−0.227 ***	−0.243 ***
	Distance to university (m)	−0.017	−0.019	−0.025	0.051 ***	0.044 **	0.049 ***
	Distance to neigh. park (m)	−0.134 ***	−0.120 ***	−0.120 ***	−0.117 **	−0.110 **	−0.115 **
	Distance to riverside park (m)	−0.043 ***	−0.034 ***	−0.045 ***	−0.035 ***	−0.027 **	−0.036 **
	Distance to forest park (m)	−0.069 ***	−0.058 ***	−0.057 ***	−0.113 ***	−0.098 ***	−0.102 ***
Constant		3.504 ***	2.978 ***	3.528 ***	3.710 ***	3.201 ***	3.724 ***
Rho		−	0.180	−	−	0.161	−
Lambda		−	−	0.207 ***	−	−	0.181 ***
No. obs.					1,473		
R-squared		0.299	0.337	0.343	0.253	0.294	0.299
Log likelihood		−1405.91	−1377.96	−1375.49	−1521.72	−1493.79	−1491.49
AIC		2857.81	2803.92	2796.98	3089.44	3035.58	3028.98
SC		2978.58	2929.94	2917.74	3210.22	3161.61	3149.76
Residual Moran's I		0.204 ***	0.017	−0.007	0.232 ***	0.015	−0.009

*p < 0.1, **p < 0.05, ***p < 0.01.

commercial and residential land uses show significant positive associations with public bike ridership in the 2019 and 2020 models. The area of neighborhood parks indicates significant and negative associations in both models because mountainous neighborhood parks are not suitable for riding public bike because of the lack of bike infrastructure and the prohibited bike riding. However, the areas of riverside parks and forest parks show strong and positive associations with public bike ridership in all models. Moreover, both parks indicate higher coefficient values. This finding suggests that people are more likely to use public bikes during the weekends if there are larger areas of riverside parks or forest parks within the 250 m buffer from the rental stations. And it implies the importance of riverside and forest park during COVID-19 for people's leisure time. In addition, this tendency has been stronger during the COVID-19 pandemic period because indoor recreational activities have been prohibited.

The existence of key rental station factors such as a neighborhood park, riverside park, and forest park within the 250 m buffer from rental stations is statistically significant in all models. The existence of a forest park is significant in both 2019 and 2020 models. In particular, the impact of a riverside park on public bike ridership is very strong during the weekend. Furthermore, the existence of neighborhood or forest park shows a stronger association with public bike ridership in 2020 rather than 2019. This finding indicates that people prefer visiting outdoor facilities such as forest and riverside parks and open spaces during the COVID-19 pandemic period.

Accessibility factors show consistent results regarding public bike ridership. The shortest distances to the subway, bike lane, river, neighborhood park, riverside park, and forest park are statistically significant in all models. In addition, access to university is statistically positive significant which is the farther, the more ridership in the 2020 model. Therefore, it implies that the university factor after COVID-19 is not as important as before COVID-19.

In sum, these findings indicate that access to subway, bike lane, river, university, and public parks are determining factors in public bike ridership. Also, these factors are becoming more important to public bike ridership during the COVID-19 pandemic period.

5. Discussion and conclusions

This study compares and analyzes the determining factors of public bike ridership in 2019 (before the COVID-19 outbreak) and 2020 (after the COVID-19 outbreak) in Seoul. With spatial analysis of OD of public bike use and spatial regression models, this study identifies the determining factors that have statistically significant impacts on public bike ridership during the COVID-19 pandemic period. The key findings and conclusions are as follows.

First, most land use factors show statistically significant associations with public bike ridership in the 2019 and 2020 models. Analysis results show that densities of commercial and office land use have significant positive impacts on public bike ridership on weekdays. And commercial and residential land use densities show significant positive impacts on public bike ridership on weekends. In addition, public bike ridership is higher if the 250 m buffer areas from rental stations have larger areas of the riverside park and forest park on weekdays and weekends. Furthermore, the coef. values of weekend models indicate that both areas of riverside park and area of forest park have strong positive impacts on public bike ridership on weekends. In particular, this finding indicates that the riverside park area plays a significant role in increasing public bike ridership before and after the COVID-19.

Second, the presence of several types of rental station facilities shows significant associations with public bike ridership. The analysis results show that the existence of subway stations within the 250 m buffer from the rental station has a significant positive impact on public bike ridership in weekend models. In other words, on weekends, the public bike ridership of rental stations near subway stations has increased over the COVID-19 pandemic. This finding indicates that people shifted their

travel mode from transit to public bike (Hong et al., 2021; Kim et al., 2021; Kwak et al., 2022). In contrast, rental stations near the university factor after COVID-19 are not as important as before COVID-19 because many universities have closed their campuses during the pandemic. The existence of riverside park and forest park show significant and positive associations with public bike ridership. This finding suggests the strong impact of riverside parks on public bike ridership during the COVID-19 pandemic period.

Third, most accessibility factors show statistically significant associations with public bike ridership. Shorter distances to subway station, bike lane, river, and parks are significantly associated with higher public bike ridership on both weekdays and weekends. However, distance to university is significant and has a negative impact on weekdays' public bike ridership in the 2019 model and a positive impact on weekends' in the 2020 model. Therefore, the importance of the university variable decreases after COVID-19. During the weekends, in particular, shorter distances to bike lane, river, neighborhood park, and forest park have increased public bike ridership during the COVID-19 pandemic period. This finding indicates that accessibility to bike lanes, rivers, and parks plays an important role in public bike ridership and outdoor activities because indoor activities have been restricted during the COVID-19 pandemic period.

Overall, this study suggests a few policy implications of promoting public bike ridership during the COVID-19 pandemic era. First, previous studies found that during COVID-19, transit ridership decreased because of the fear of infection (Basu & Ferreira, 2021; Bucsky, 2020; Caulfield et al., 2021; Habib & Anik, 2021; Hu & Chen, 2021; Park, 2020; Shamshiripour et al., 2020; Teixeira & Lopes, 2020). The city of Seoul has also experienced a decrease in transit ridership during the COVID-19 pandemic period of 2020 (Kwak et al., 2022; Park et al., 2020). On that basis, this study found that the public bike ridership near subway stations increased after the outbreak of COVID-19. This finding indicates that public bike demand increased during the COVID-19 pandemic because people tend to avoid the risk of infection in public transit systems. Kalambay & Pulugurtha (2022) and Zhang & Fricker (2021) mentioned confirmed cases, and the density variable decreases bike ridership during COVID-19, but this study found that the more density, the more bike ridership appeared. The dissimilar policies for COVID-19 in each country make the difference between this study and previous studies.

Next, accessibility of bike lane, riverside park, and forest park are determining factors of public bike ridership. In particular, public bike ridership is very high near riverside parks that are connected to the broader network of citywide bike lanes. Those results are in line with Wang et al. (2016) also noted that the rivers are a crucial factor for bike ridership, and Jiao et al. (2022) mentioned green infrastructure such as parks is a positive impact on bike ridership. Therefore, bike lane infrastructure investments, expanding the broader network of citywide bike lanes, and maintaining green areas are crucial to promote public bike ridership. Also, this policy will be beneficial to potential public bike users who would like to avoid the risk of COVID-19 infection in the overcrowded environment of Seoul's public transit system. Caulfield et al. (2021) and Wang & Noland (2021) also noted the importance of the public bike as personal mobility during COVID-19. This study also suggests that bike infrastructure such as stations and bike lanes in and around various parks needs to be managed and installed better than before because people will ride public bikes more after COVID-19 than before.

Finally, this study has highlighted the determining factors of public bike ridership before and after the COVID-19 outbreak and suggests policies to promote public bike ridership. However, a few limitations as follows exist. First, the city of Seoul did not have lockdown policies during the COVID-19 pandemic period, although the city has enacted social distancing policies and encouraged work-from-home telecommuting. These COVID-19-related policies might have affected transportation mode choice and travel patterns. However, this study is

limited in its ability to consider the impacts of social distancing policy and telecommuting on public bike ridership. Second, this study provides different analysis models for weekdays and weekends, assuming that weekday trips are work-related and weekend trips are leisure-related. However, the public bike OD data does not provide user information such as age, travel route, and travel purpose due to privacy reasons. If detailed public bike OD data were available, more specific policy proposals could be suggested to promote public bike ridership. Third, non-physical environmental factors affecting bike ridership such as new bike models, discount vouchers, etc. were not considered due to the difficulties of quantification and the lack of available data.

Nevertheless, this study is crucial because it analyzed determining factors that have significant impacts on public bike ridership before and after COVID-19 in Seoul. Also, this study makes policy suggestions to promote public bike ridership during the COVID-19 pandemic period.

CRedit authorship contribution statement

Junman Kim: Conceptualization, Methodology, Data curation, Visualization, Writing – original draft. **Sugie Lee:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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