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Causal impacts of the COVID-19 pandemic on daily ridership of public bicycle sharing in Seoul

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ABSTRACT

Public bicycle can be a disease-resilient travel mode during the *coronavirus disease 2019* (COVID-19) pandemic. Nonetheless, its evidence on public bicycle sharing is still inconclusive. This study used Bayesian structural time series models and causal impact inference for the data on the daily ridership of public bicycles in Seoul, South Korea, for 1826 days from January 1, 2017, to December 31, 2021. The study found that the usage of public bicycles was robust against the COVID-19 pandemic even in densely populated Seoul. Compared with the pre-pandemic period, public bicycles' usage was unaffected on days when weather conditions, such as snow, rain, and wind speed were not as severe, as well as on days with non-seasonal event factors, such as weekdays, public holidays, and traditional Korean holidays. In addition, its robustness against the pandemic became more pronounced as the number of bicycle racks increased and the intensity of social distancing increased. However, public bicycles were in demand primarily for leisure and exercise, not for travel, during the pandemic. Public bicycle sharing can be a disease-resilient travel mode. Continuous investment in infrastructure such as bicycle paths and public bicycle is required to become a more resilient travel mode against infectious diseases.

1. Introduction

Non-pharmaceutical measures to control the unexpected COVID-19 pandemic, such as lockdowns and social distancing, have disrupted human mobility. In response to the pandemic, sustainable transportation modes such as public transit and non-motorized transportation have had different consequences. In cities worldwide, the ridership of public transit decreased significantly during this period. On the contrary, non-motorized active transportation modes such as walking and cycling can be resistant, resilient, and sustainable in the face of the pandemic. According to several studies, the use of privately owned bicycles did not decrease or increase during the COVID-19 pandemic (Anke et al., 2021; Ehsani et al., 2021; Harrington & Hadjiconstantinou, 2022; Hensher et al., 2022; Bucsky, 2020; Monterde-i-Bort et al., 2022; Shaer & Haghshenas, 2021; Loa et al., 2021; Lee et al., 2021).

During this pandemic, in response to movement restrictions, as well as the transition to safer transport modes, people significantly increased their daily activities for leisure, exercise, and well-being rather than travel. According to a 2020 survey conducted in Chicago, USA, the travel mode with the highest risk of COVID-19 transmission was public transportation (78%), followed by taxis (61%), shared bicycles (48%), personal bicycles (16%), walking (8%), and private cars (6%). Similarly, in an online survey in Bangladesh, Zafri et al. (2022) identified that public transit is the most dangerous mode of transport for the spread of the COVID-19, followed by shared transportation modes and private cars. The difference in people's perceptions of transport modes contributing to the risk of infection comprised the avoidance of public transit and preference for cycling. During the pandemic, there has been a higher rate of use (Piras et al., 2022) and fewer confirmed cases of COVID-19 in cities where bicycles are more convenient (Wang et al., 2022). This proves that private bicycles are a robust and sustainable transportation mode during the pandemic (Chen et al., 2022; van der Drift et al., 2021).

However, the effect of the pandemic on public bicycle-sharing may be inconclusive. Sharing mobility modes, including public bicycle, are more acceptable to people and provides more increased sustainability to our society than private-owning ones (Gransterer et al., 2022; Shokouhyar, et al., 2021). In addition, the bicycle as a transportation mode is healthier one for people than vehicle ones by consuming more physical activity in travel (Jiang et al., 2017). People tend to perceive that their choice of travel using public bicycles poses a higher risk of infection than using private bicycles (Hua et al., 2021; Zafri et al., 2022). Therefore, in cities worldwide, the use of shared public bicycles, which can cause riders to become more vulnerable to infectious diseases (Hua et al.,

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2021), decreased in the early stages of COVID-19, despite recovering faster than that of public transit (Chai et al., 2021; Teixeira & Lopes, 2020; Wang & Noland, 2021). Additionally, the relationship between the use of shared bicycles and the pandemic may be related to the population density of cities. For example, Zhang and Fricker (2021) identified that during the COVID-19 lockdown period, the use of shared bicycles decreased as the population density increased in 11 US cities. According to Bouhouras et al. (2022) the use of shared bicycles in small- and medium-sized cities in Greece increased significantly during the COVID-19 lockdown period. This finding supports the assertion that the robustness of bicycle-sharing can decline and bicycle-sharing can become more vulnerable in densely populated cities. Meanwhile, it was confirmed that the ridership of shared bicycles in Singapore increased by 150% during the lockdown period when compared to that before the pandemic (Song et al., 2022). In addition, in Seoul, South Korea, which has a high population density, the use of shared-based public bicycles did not decrease or increase (Cho & Baik, 2021) during the pandemic period (Lee et al., 2021; Kim et al., 2021)). Notably, most of these claims are based on descriptive modeling-based evidence rather than descriptive evidence.

Few studies have demonstrated the effect of exogenous determinants, such as weather conditions, non-seasonal events, supply and demand, and COVID-19-related factors, on the change in ridership of shared-based public bicycles during the pandemic. Compared to other travel modes, bicycles are more sensitive to weather conditions such as temperature, wind speed, precipitation, and snowfall, as well as non-seasonal event factors such as public holidays and national holidays (Noland et al., 2016; Corcoran et al., 2014; Lee et al., 2016), bicycle supply and demand factors (Pucher & Buehler, 2006; Bachand-Marleau et al., 2012; Hampshire & Marla, 2012). In addition, ridership may vary depending on the daily number of confirmed COVID-19 cases during the pandemic (Hong et al., 2021).

This study not only examines whether daily ridership of public bicycles in Seoul, South Korea, with a high population density, can show robustness against the COVID-19 pandemic, but also identifies differences in the magnitudes of determinants such as weather environments, non-seasonal events, and demand and supply during the pandemic, compared to its previous period. This study uses data on public bicycle daily ridership in Seoul for 1826 days from January 1, 2017 to December 31, 2021. To prove whether its ridership was significantly robust against the COVID-19 pandemic, this study employs a customized causal impact inference model based on the Bayesian structural time series (BSTS) model, which allows us not only to forecast bicycle ridership under the assumption of no COVID-19 occurrence, but also to identify the daily pointwise differences in actual ridership. The other purpose of the study was to investigate how the determinants affecting bicycle use changed during the COVID-19 pandemic when compared to those of the pre-pandemic period. For this, the study applies the two BSTS models after dividing the daily ridership data into data before and during the pandemic, based on January 19, 2020, when confirmed cases of COVID-19 were reported. By empirically exploring the causal impacts on the daily ridership of public bicycle sharing during the pandemic, this study not only confirmed the robustness of shared public bicycles against infectious diseases but also identified the determinant factors increasing active bicycle use for daily activity during the unexpected COVID-19 pandemic.

2. Literature review

This study reviews the literature on travel behavior changes during the COVID-19 pandemic and the factors affecting the daily ridership of shared bicycles before and during the pandemic. First, it not only examines travel behavior changes during the pandemic but also explores previous studies on changes in the demand for bicycles as a shared personal mobility mode. Second, this study reviews the literature associated with the potential factors influencing behavior in the use of bicycles before and during the pandemic.

2.1. Travel behavior changes during the pandemic

Many studies have identified travel behavior changes, including shared personal mobility, due to the COVID-19 pandemic outbreak. For example, by identifying changing patterns in commuting choices in two metropolitan areas in Australia before and during COVID-19, Hensher et al. (2022) found that the choices of public transit, such as transit and bus, decreased, whereas those of personal transport modes, such as private cars, walking, and bicycles, increased. Surveying nearly 4,000 participants in Germany, Anke et al. (2021) found travel behavior changes, such as a shift from public transit to private transit, and increases in the mode of transport, such as driving, walking, and cycling. Scorrano and Danielis (2021) also found that the COVID-19 pandemic significantly impacted the mode choice of travel from public transit to motorized and non-motorized personal transit in Trieste, Italy. Lee et al. (2021) confirmed that during the COVID-19 pandemic, the ridership of public transit, such as subways and buses, decreased, whereas the use of shared public bicycles and personal cars increased. Surveying travel behavior changes for 453 older adults residing in Isfahan, Iran, Shaer and Haghshenas (2021) identified that the modal split of bicycles increased from 9% to 18% during the pandemic.

Many studies have also identified the robustness of shared public bicycles against pandemics. For example, through an online survey of U. S. adults, Ehsani et al. (2021) found no change in bicycle use during the pandemic, whereas significant decreases were observed in the use of other travel modes, such as public transit, walking, and even personal vehicles, compared with the pre-pandemic level. Chai et al. (2021) reported that the average demand for shared bicycles in Beijing, China, subsequently increased, although its overall use decreased significantly due to the COVID-19 pandemic. Investigating the impact of the COVID-19 pandemic on shared bicycle usage in three medium-sized Greek cities, Bouhouras et al. (2022) found that its usage significantly increased during the period compared with the pre-pandemic level. Cho et al. (2020) unveiled that the demand for roads and public transportation decreased, but that for shared cars and bicycles did not show a decreasing trend in Seoul, South Korea.

The bicycle can be a resilient and reliable mode of mobility due to the lower risk of COVID-19 infection. Van de Drift et al. (2021) explored the changing movement patterns in the Netherlands during the COVID-19 pandemic, showing that cycling is an alternative option for travelers. Similarly, Teixeira and Lopes (2020) proposed that shared public bicycles can be an alternative mode for public transit by responding more flexibly to the impact of COVID-19. Applying a Bayesian structural time series model, Zhang and Fricker (2021) demonstrated that the COVID-19 outbreak decreased the use of non-motorized travel activities in densely populated cities while identifying its increasing pattern in less densely populated cities in the United States. Surveying self-reported bicycling activity in Australia during the COVID-19 pandemic, Fuller et al. (2021) demonstrated that most of them increased their activity for exercise and well-being purposes but not for transport purposes.

2.2. Determinant factors in bicycle use before and during the pandemic

This study reviews the literature on the factors that determine bike use before and during the COVID-19 pandemic. First, weather conditions, such as temperature, precipitation, wind speed, and sunlight time, affect bicycle use (Corcoran et al., 2014; Dill and Carr, 2003; Gebhart and Noland, 2014; Lee et al., 2016; Nankervis, 1999; Noland & Ishaque, 2006; Thomas, Jaarsma, & Tutert, 2013; Zhang and Fricker, 2021). For example, analyzing the influence of weather conditions on bicycle use in the Netherlands during 1987–2003, Thomas, Jaarsma, and Tutert (2013) found that they accounted for 80% of the fluctuation in its usage, especially for leisure purposes. Identifying the factors affecting the use of shared public bicycles in Goyang, South Korea, Lee et al. (2016)

demonstrated that weather conditions significantly impacted its use when they were below or above a specific level rather than linear impacts. Investigating bicycle commuting ridership in major cities in the United States, Dill and Carr (2003) found that its use significantly decreased when the temperature dropped below freezing. Zhang and Fricker (2021) controlled covariates, such as precipitation and temperature, to estimate the causal impact of COVID-19 on the daily activities of non-motorized modes.

Second, periodic factors, such as the day of week and season, and non-periodic event factors, such as public holidays and Korean traditional holidays, tend to have different effects on bicycle use (Faghih-Imani et al., 2014; Lee et al., 2016; Noland et al., 2016). Faghih-Imani et al. (2014) uncovered that the use of the public bicycle system in Montreal, Canada, decreased more on weekends but increased on Friday and Saturday evenings. Lee et al. (2016) revealed that the use of shared public bicycles varied depending on the time of day, day of the week, and public holidays. Noland et al. (2016) also assumed that generators for trips of shared bicycles should be differentiated by day of the week and season. They found that subscribers of shared bicycles in New York City were more associated with their use on weekends than on weekdays.

Third, bicycle use is closely related to supply and demand factors (Buchand-Marleau et al., 2012; Nikitas et al., 2021; Pucher and Buehler, 2006; Wang and Akar, 2019). Analyzing the reasons why Canadian citizens use bicycles more than Americans, Pucher and Buehler (2006) found that the fewer bicycle lanes or dedicated lanes there are and the lower the fuel price, the lower the bicycle use rate. Analyzing factors affecting the use of shared public bicycles on the basis of the data surveyed in Montreal, Canada, Bachand-Marleau et al. (2012) found that those who subscribed to annual public bicycle members used it 15 times more in a year compared with non-members. Identifying the gender gap in shared bicycle ridership in New York, USA, Wang and Akar (2019) unveiled that the additional installation of bicycle racks was positively associated with their use by males and females. After reviewing policies implemented by cities in Europe and South America during the pandemic, Nikitas et al. (2021) found that bicycle use can be encouraged by providing bicycle infrastructure, such as expanding bicycle networks, pop-up bicycle lanes, and free bike-sharing services. Kim et al. (2021) also demonstrated that during the pandemic, the expansion of 500 new stations for shared public bicycles in Seoul, South Korea, in 2020 increased their usage for leisure but not for transport purposes.

Finally, the risk level resulting from the COVID-19 outbreak and social distancing measures to contain its proliferation may be closely associated with public bicycle use. By examining 72 cities in Massachusetts, USA, Wang et al. (2022) unveiled that the number of confirmed COVID-19 cases per 100,000 population was lower in cities with better bicycle accessibility. Similarly, Piras et al. (2022) confirmed that bicycle facilities positively impacted its use in Cagliari City, Italy, during COVID-19. Hong et al. (2021) found that confirmed cases of COVID-19 were positively associated with the use of shared public bicycles in Seoul City, South Korea. Investigating the impact of social distancing on the commuting behavior of 1,542 workers in India, Pawar et al. (2020) demonstrated that approximately 40% of them stopped commuting, whereas roughly 5% of them shifted from public to private travel mode. Lee et al. (2021) identified that social distancing measures positively impacted the use of shared bicycles and private cars but negatively impacted public transit, such as subways and buses, in Seoul, South Korea. Investigating changes in daily ridership of shared bicycles during the COVID-19 outbreak in Singapore, Song et al. (2022) identified that lockdown measures derived a 150% increase in its use compared with the pre-pandemic level. Using the data from shared bike trips in Nanjing, China, Hua et al. (2021) demonstrated that mobility restriction measures significantly decreased their usage, especially for commuting, during the pandemic. Heydari et al. (2021) and Li et al. (2021) found that the usage of shared public bicycles in London immediately decreased during the lockdown period in the UK but increased beyond the level of the pre-pandemic during its first ease period.

3. Material and method

3.1. Data and measurement

Table 1 lists summary statistics of variables measured to examine the robustness of the impact response effect on daily bicycle ridership during COVID-19, as well as the differences in the causal effects compared to those of the pre-pandemic period. The entire study period was from January 1, 2017 to December 31, 2021. The date, January 19, 2020, the one on which the first confirmed case of COVID-19 was reported in South Korea. The indicators measured in the study include daily bicycle ridership and weather conditions, seasonal and non-seasonal events, demand and supply of bicycle use, and exogenous factors related to COVID-19 that are expected to affect it.

This study focuses on the public bicycle system operating in Seoul, South Korea. This system, which was first launched in October 2015, had 37,500 bicycles in operation and 2,500 rental shops as of September 2021, with a total cumulative number of 83,807,669 (Seo & Cho, 2021)). The data were manipulated using the raw rental history information provided by the Seoul Open Data Plaza (https://data.seoul.go.kr/). As shown in Table 1, the average daily ridership over the previous five years was 48,112; during the pandemic period following January 19, 2020, when the first confirmed COVID-19 case was reported in South Korea, the daily average ridership was 75,203, which was 2.44 times higher than the period prior to COVID-19 (January 1, 2017, to January 18, 2020). Fig. 1 shows the time series trend of daily ridership and its seven-day moving average for public bicycles. The trend and variance have gradually increased since January 1, 2017, even after the first confirmed case of COVID-19. The study used log-transformed daily ridership to control the instability of the variance of the daily number of users.

A bicycle is a mode of transportation that is easily affected by weather conditions, seasonal and non-seasonal events, and the supply and demand of its use. Weather factors accounted for approximately 80% of the variation in bicycle use (Thomas, Jaarsma, & Tutert, 2013). Reviewing the literature on the relationship between weather conditions and the number of cyclists (Pucher et al., 2011; Gebhart & Noland, 2014; Kim, 2021; Thomas, Jaarsma, & Tutert, 2013; Zhang & Fricker, 2021), this study employed weather factors, such as sunlight time, temperature, average wind speed, and rainfall and snowfall. Among weather conditions, temperature is closely related to bicycle use (Pucher & Buehler, 2006), and Dill and Carr (2003) and Kim (2021) reported that bicycle use decreases, especially on cold or hot days. Therefore, the study coded cold days (below 0°C) and hot days (above 30°C) as 1 and coded days that did not correspond to these as 0 on the basis of the highest temperature on that day. These dummy variables allow us to estimate the effect of cold or hot days on public bicycle use compared with other days. The study also included the measures on fine particulate matter (PM. 2.5). Hong et al. (2022) demonstrated that air pollution was not statistically significant in bicycle share usage during the COVID-19 pandemic, while negatively associated with it before it. For the PM-2.5 level (ultra particulate matter), the study coded the days exceeding 76 $\mu g/m^3$, which was a “very bad” level in Korea, as 1, and those below it as 0. This dummy variable allows us to estimate the difference in the use of public bicycles on the days when PM-2.5 exceeds 76 $\mu g/m^3$, compared with other days.

Seasonal and non-seasonal events also influence public bicycle ridership (Corcoran et al., 2014; Noland et al., 2016; Lee et al., 2016). The study only uses weekends as a dummy to identify the effect on the use of bicycles for leisure, not essential travel, such as commuting, because seasonal factors by quarter and day of the week are controlled by the BSTS component models. Faghih-Imani et al. (2014) and Lee et al. (2016) reported that the use of public bicycles in Montreal, Canada, and Seoul, South Korea, decreased on weekends compared to

Table 1
Summary statistics.

		Entire period (no. obs. = 1826) (Jan-01-2017 to Dec-31-2021)				Period during COVID-19 (no. obs. = 713) (Jan-19-2020 to Dec-31-2021)			
		Mean	Std. Dev.	Min.	Max.	Mean	Std. Dev.	Min.	Max.
Dep. Variable	Daily ridership (no. of persons)	48,112	36097	982	150,202	75,203	35522	2,491	150,202
	Log-transformed daily ridership	10.41	0.966	6.89	11.92	11.07	0.653	7.82	11.92
Weather environment factors	Sunshine time (hr.)	6.71	3.982	0	13.70	6.10	3.958	0	13.50
	Temperature (below 0°C= 1, 0°C to 30°C = 0)	0.13	0.339	0	1	0.10	0.296	0	1
	Temperature (above 30°C = 1, 0°C to 30°C = 0)	0.02	0.153	0	1	0.01	0.118	0	1
	Average wind speed (m/s)	2.11	0.689	1	6.00	2.35	0.67	1.20	5.00
	Rainfall (mm)	3.42	12.395	0	144.50	3.90	12.849	0	103.10
	Snowfall (cm)	0.10	0.58	0	8.80	0.11	0.589	0	5.50
	PM 2.5 (> = 76 $\mu g/m^3$ = 1, < 76 $\mu g/m^3$ = 0)	0.01	0.104	0	1	0.01	0.075	0	1
Seasonal and non-seasonal event factors	Weekend (Saturday, Sunday = 1, Monday to Saturday = 0)	0.29	0.452	0	1	0.29	0.452	0	1
	Holiday (=1, Non-holiday = 0)	0.03	0.169	0	1	0.03	0.165	0	1
	Korean traditional holidays (=1, None = 0)	0.02	0.139	0	1	0.02	0.144	0	1
	Sandwich day (=1, None = 0)	0.01	0.084	0	1	0.00	0.053	0	1
Demand and supply factors	Gasoline price per liter (KWR, Log)	7.37	0.065	7.20	7.54	7.35	0.086	7.20	7.54
	Unemployment rate	4.61	0.689	3.30	6.50	4.70	0.802	3.30	6.50
	Cumulative number of new bicycle racks (Log)	9.63	0.557	8.13	10.31	10.13	0.142	9.73	10.31
	Cumulative number of new members per capita (Log)	0.85	0.096	0.34	0.94	0.92	0.014	0.90	0.94
COVID-19 factors	Social distance index					147.84	33.092	0	200.00
	Reduction of late-night operation of public transit in Seoul(=1, None=0)					0.15	0.357	0	1
	Stringer social distancing in Seoul metropolitan area (=1, None = 0)					0.37	0.482	0	1
	No. of new COVID patients (7-day moving average)					308.22	507.49	0	2720.6
	Number of secondary vaccines per capita					13.20	25.795	0	83.50

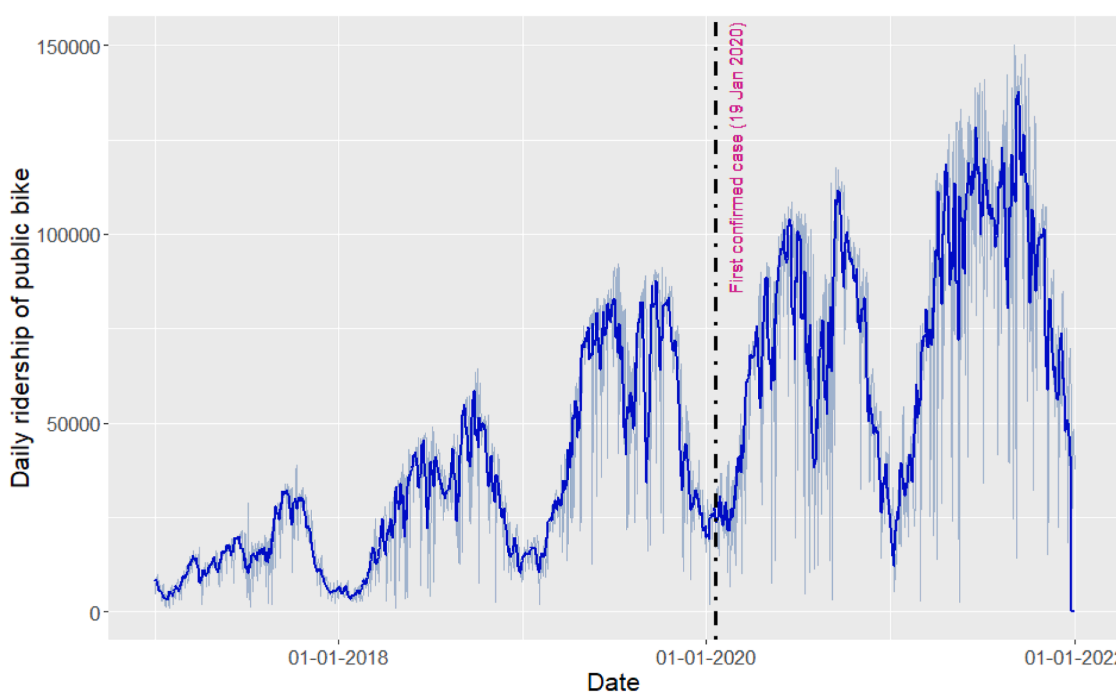

Fig. 1. Daily ridership of public bicycles in Seoul (2017-01-01 to 2021-12-31).

weekdays. The study coded weekends, which were either Saturdays or Sundays, as 1, and weekdays, which were from Monday to Friday, as 0. Non-seasonal events measured by dummy processing in this study are public holidays, traditional Korean holidays, such as lunar new year and thanksgiving. Given that traditional Korean holidays are legally required to last at least three days, most people tend to visit their hometowns or travel abroad, resulting in a reduction in intra-regional traffic volume while increasing inter-regional traffic volume (Lee et al., 2020). However, during the COVID-19 pandemic, the Korean government urged people to refrain from visiting their hometowns. Thus, the use of public bicycles for leisure purposes in Seoul might have changed during this period. The study also employs sandwich days, which are weekdays between public holidays and weekends, in the model as non-seasonal dummy variables. The study measured sandwich days because it had statistical significance on the effect of middle east respiratory syndromes (MERS), on transit ridership in Seoul, South Korea in 2015 (Sung, 2016). The study coded the days of these non-seasonal events, such as holidays and traditional Korean holidays, as 1 and the other days as 0. The dummy variables for seasonal and non-seasonal event days allow us to identify the differences in the ridership of public bicycles for their days compared with other days.

Bicycle use is affected by demand and supply factors. In this study, the demand-side factors include gasoline price per liter, unemployment rate, and the cumulative number of new members per day for public bicycles. Many studies have reported that bicycle use increases as fuel price increases (Pucher & Buehler, 2006), the unemployment rate reduces (Chibwe et al., 2021), and the annual membership increases (Bachand-Marleau et al., 2012). Additionally, the density and capacity of bicycle rental stations (Chibwe et al., 2021; Hampshire & Marla, 2012) and bicycle paths (Frank et al., 2021; Kim, 2021) have a positive effect on ridership. Several cities in European and Latin American countries supplying pop-up bicycle paths during the COVID-19 pandemic have experienced an increase in bicycle use (Büchel et al., 2022; Nikitas et al., 2021). Although Seoul did not take measures to supply pop-up bicycle paths during the COVID-19 pandemic, it installed 500 additional public bicycle rental stations in 2020 (Kim, 2021). The rental stations and racks for public bicycles were 1331 and 16738 before the COVID-19 period, respectively, while 2471 and 29918 during the pandemic, respectively. This was an already-planned supply and not a measure to respond to COVID-19. However, because of this, the density of public bicycle rental stations after the COVID-19 period increased by approximately 1.8 times. In this study, the cumulative number of racks for these public bicycles and per rental station were employed in the models. All supply and demand factors used in this study are log-transformed continuous variables, except for the unemployment rate.

In addition, public bicycle ridership during the COVID-19 pandemic might be influenced by corona-related factors. Hua et al. (2021) found that social distancing measures had a significant impact on usage of bicycle-sharing during the pandemic in Nanjing, China. This study measured the social distancing index, restriction measures on the late-night operation of public transit in Seoul, stronger social distancing measures in the Seoul metropolitan, the 7-day moving average of newly confirmed COVID-19 cases, and the number of secondary vaccine recipients per capita in Seoul. South Korea has implemented non-pharmaceutical intervention measures such as wearing a mask, school closure, workplace closure, canceling public events, restriction on gathering size, stay-at-home requirements, and restrictions on internal movement. Social distancing measures are highly correlated, because several measures are mixed and implemented simultaneously (Snoeijer et al., 2021). The Oxford COVID-19 Government Response Tracker (OxCGRT) provides data on daily scores at the national level through a global panel database of policies during the COVID-19 pandemic (Hale et al., 2021). This study adopted the Oxford Index in the model. In addition, there was a 20% reduction in late-night public transportation in Seoul (July 1 to October 24, 2021) and stricter social distancing at the national level (August 16 to September 13, 2020, and November 24, 2020, to July 14, 2021). This study employs these periods as dummy variables by coding the days on which the measure was implemented as 1 and the other days as 0 in the model. Each of these dummy variables allowed us to identify the extent to which public bicycle use increased or decreased on the days when these measures were taken compared with the days when these measures were not taken. In addition, the number of newly confirmed COVID-19 cases per day and the vaccination ratio may also affect the use of public bicycles. Since the number of new confirmed cases per day has seasonality by the day of the week, the 7-day moving average is employed in the model. In addition, since the proportion of COVID-19 vaccinations, which started on April 21, 2021, in South Korea, has varied depending on the age group to be vaccinated, the study employs the number of secondary vaccine recipients per population in Seoul.

3.2. Methods

This study applies the Bayesian structural time series (BSTS) model and causal impact inference modeling based on it, not only to identify the statistical significance of the robustness of public bicycles against COVID-19 but also to investigate the differences in the causal impacts before and during the pandemic. These models have been employed to identify either forecasting or causal impacts on transit ridership (Hu & Chen, 2021), non-motorized transport demand (Zhang & Fricker, 2021), hospital finances and costs (Cai et al., 2021), and the number of confirmed COVID-19 cases (Feroze, 2020; Xie, 2021) during the pandemic. The BSTS model is a recent statistical technique used in feature selection, time-series prediction, nowcasting, causal inference, and other applications.

This model consists of three main components: Kalman filter, spike-and-slap, and Bayesian model averaging (Jinwen Qiu, 2018; Xie, 2021). The first is a component of the Kalman filter process, which is a time-series decomposition technique. At this stage, various state variables can be flexibly added, such as trends, seasonality, and regression. The second component is the spike and slab method, which involves selecting the most important regression predictors in this step. The third component is the Bayesian model averaging process, which combines the results and prediction calculations. Numerical calculations were performed using the Markov chain Monte Carlo (MCMC) method because the analytical calculation of the Bayesian posterior distribution is very difficult (Feroze, 2020).

The BSTS model is a generalized time-series model in which a researcher can flexibly compose the model components. The formula for the BSTS model was as follows:

$$y_t = u_t + \tau_{1t} + \tau_{2t} + \beta_t{}^T X_t + \varepsilon_t$$

where y_t represents the log-transformed daily bicycle ridership at time t, which is estimated using a one-trend model (u_t), two seasonal models ($\tau_{1t} + \tau_{2t}$). In addition, $\beta_t{}^T$ is a vector of variables with the transition equation term T, and X_t is a vector of parameters in the regression model at time t. ε_t represents the residual at time t, which is not explained by this model, assuming a distribution with a mean of 0 and a variance of σ^2, $N(0, \sigma^2)$. In Fig. 1, the slope of the trend may increase steadily; therefore, a semi-local linear trend model (u_t) is applied. Fig. 1 also indicates seasonal fluctuations by day of the week and quarter. Therefore, in this study, two seasonal component models with 7-day and 91-day cycles (τ_{1t}, τ_{2t}) are included in the BSTS model. The last component is the regression model (X_t) with weather conditions, seasonal and non-seasonal events, and exogenous variables of demand and supply factors, excluding COVID-19-related factors, for the pre-pandemic model and including all exogenous predictors for the post-pandemic period.

Causal impact inference modeling allows to estimate the pointwise difference between the predicted and actual values based on BSTS modeling. Alternative models of this model include the difference-in-difference (DID) and impulse-response function models, which identify the difference before and after a certain shock occurs. However, the ridership of public bicycles fluctuates depending on complex responses combined with various causes, rather than uniform level shifts, during the entire period before and after the outbreak of an infectious disease. In this respect, these two traditional approaches have limitations (Zhang & Fricker, 2021). Meanwhile, causal impact inference modeling based on the BSTS model allowed to estimate the pointwise daily difference between the actual and predicted ridership of public bicycles during the pandemic.

The analysis procedure of this study was performed in the following order: validation of the BSTS model for data from the pre-COVID-19 period, causal impact inference modeling based on the BSTS model, and comparison of the results of the two BSTS models before and during the COVID-19 pandemic. In the data for the pre-COVID-19 period, the training model used the training data from January 1, 2017, to July 22, 2019 (933 days), and the validation model used the test data from July 23, 2019, to January 18, 2020 (180 days). The mean absolute percentage error (MAPE) was used as the model validation measure. The MAPE of the BSTS model using the validation dataset was 5.97. The model was valid because it had a prediction error of 5.97% when using the BSTS model.

Augmented Dickey-Fuller and Box-Pierce tests were employed to evaluate the BSTS models for the periods before and during the COVID-19 pandemic. The Dickey-Fuller test statistic of the two models was -10.643 and -9.7889, and the p-value of both models was less than 0.01. Thus, the null hypothesis that a unit root exists was rejected. The Box-Pierce test statistics of the two models were 1.9836 and 1.373, and the p-values were 0.159 and 0.2413, respectively. This indicates that there was no time-series autocorrelation of the residuals. In conclusion, these two statistics prove that the residuals of these models fulfill satiability and have no autocorrelation.

4. Results

4.1. Causal impact inference

Table 2 summarizes the results of the customized causal impact inferences based on the BSTS model for the pre-COVID-19 period. The actual number of log-transformed ridership of public bicycles during the post-COVID-19 period was, on average, approximately 11.06. Without the intervention of COVID-19, the average number of users was expected to be 10.46. The total cumulative ridership during the COVID-19 period was 7889, while it would have been predicted to be 7455 if COVID-19 had not occurred. As a result, the average daily ridership of public bicycles increased by 0.61 owing to the outbreak of COVID-19, and its cumulative total number is expected to increase by 434.50. These results indicate that COVID-19 occurrence had an average positive effect of 5.8% on the ridership of public bicycles in Seoul. However, the increase in the difference resulting from the COVID-19 shock was within the 95% confidence interval. The probability of obtaining this effect by chance was 0.309, which is not statistically significant.

The original plot in Fig. 2 shows the distribution of daily observations (black) and daily predicted values (blue). The pointwise graph shows the daily pointwise difference between these values, and the light blue section shows the 95% confidence interval. This figure also shows that the increase in ridership owing to the COVID-19 interruption has no significant effect because it exists within the 95% confidence interval, although it may have had a significant effect for a short time within the period. The lower part in Fig. 2 indicates that the pattern of the fluctuation in the pointwise differences is not consistent and may fluctuate depending on the combination of exogenous factors.

4.2. BSTS modeling before and during COVID-19

Fig. 3 and Table 3 summarize the results of the BSTS model for the log-transformed bicycle ridership for the two periods, before COVID-19 (2017-01-01 to 2020-01-18) and after (2020-01-19 to 2021-12-31).

Table 2
Results on posterior inference by customized causal impacts based on BSTS model.

	Average	Cumulative
Actual	11	7889
Prediction (std. dev.)	10 (1.3)	7455 (898.9)
95% Confidence Interval	[8, 13]	[5699, 9322]
Absolute effect (std. dev.)	0.61 (1.3)	434.50 (898.9)
95% Confidence Interval	[-2, 3.1]	[-1,433, 2190.7]
Relative effect (std. dev.)	5.8% (12%)	5.8% (12%)
95% Confidence Interval	[-19%, 29%]	[-19%, 29%]
Posterior tail-area probability p = 0.309, Posterior prob. of a causal effect = 69%		

Fig. 3 indicates the probability of including the most important variables in the BSTS modeling. There are seven exogenous variables that have a probability of 0.9 or higher, affecting public bicycle ridership before COVID-19: below-zero temperature, sunshine hours, rainfall, average wind speed, snowfall, traditional Korean holidays, and public holidays. On the contrary, under the same standard, there are only five events during the COVID-19 period: below zero temperature, sunshine hours, precipitation, average wind speed, and snowfall. This indicates that the exogenous determinants affecting the ridership of public bicycles in Seoul were adjusted by COVID-19 interruption.

Table 3 summarizes the average coefficients of the exogenous variables on the log-transformed daily ridership of public bicycles in Seoul before (Model A) and during COVID-19 (Model B). The variable with the largest differences in the values of the coefficients between Models A and B is traditional Korean holidays (0.3529), followed by public holidays (0.2115), and below-zero temperatures (-0.1432). Given that most people visited their hometowns during traditional Korean holidays with at least three holidays, it had the greatest effect of reducing the use of public bicycles in Seoul before the pandemic. However, during the COVID-19 pandemic, public bicycle use increased during traditional Korean holidays compared with those before the pandemic. The Korean government urged people not to visit their hometowns so that they would have more time and opportunities to rent shared public bicycles for leisure and exercise. They demonstrated that daily bicycle ridership during the COVID-19 period increased by 35.29% and 21.15% on traditional Korean holidays and public holidays, respectively, while it decreased by 14.32% on days when the maximum temperature was below zero, compared to those before it.

Among the coefficients of exogenous variables in Models A and B, the direction of influence on bicycle ridership changed owing to COVID-19 interruption. These are the weekend, unemployment rate, and the cumulative number of new members per capita. Bicycle ridership on weekends increased during the pre-COVID-19 period compared to weekdays, while it decreased during the pandemic. This indicates that the use of public bicycles in Seoul has changed owing to COVID-19, with more people using them on weekdays than on weekends. This may be because opportunities for use of public bicycles on weekdays generally increased owing to restrictions on movement, such as stay-at-home, work-from-home, school closure, and gathering and internal restrictions during the COVID-19 period. The increase in the unemployment rate had a positive effect on the use of public bicycles before the COVID-19 outbreak, whereas it had a negative effect during the COVID-19 period. Table 1 shows that the unemployment rate increased from 4.61to 4.70%. The non-normal increase in the unemployment rate owing to the COVID-19 pandemic may have had a different effect on the use of public bicycles. The cumulative number of new members per capita had a positive effect on public bicycle use before the COVID-19 period, while showing the opposite trend during the period. This result can be interpreted as an increase in the irregular and temporary use of public bicycles rather than regular use during the COVID-19 period.

However, the magnitudes of the regression coefficients for the weather condition factors during COVID-19 were relatively large compared to those before the period. This indicates that fewer Seoul citizens used public bicycles because the colder, hotter, stronger the wind, the more rain or snow, and the worse the PM 2.5 in the period during the COVID-19 outbreak. The magnitude of the influence of exogenous variables, such as non-seasonal event factors, including public holidays, traditional Korean holidays, and sandwich days, decreased overall compared to those before the outbreak. This indicates that the use of public bicycles has increased compared to the previous period, while avoiding long-distance travel for leisure or family meetings owing to COVID-19. Similarly, bicycle ridership increased as the gasoline price per liter decreased, and the cumulative number of public bicycle racks increased.

Table 3 shows that COVID-19-related exogenous variables also

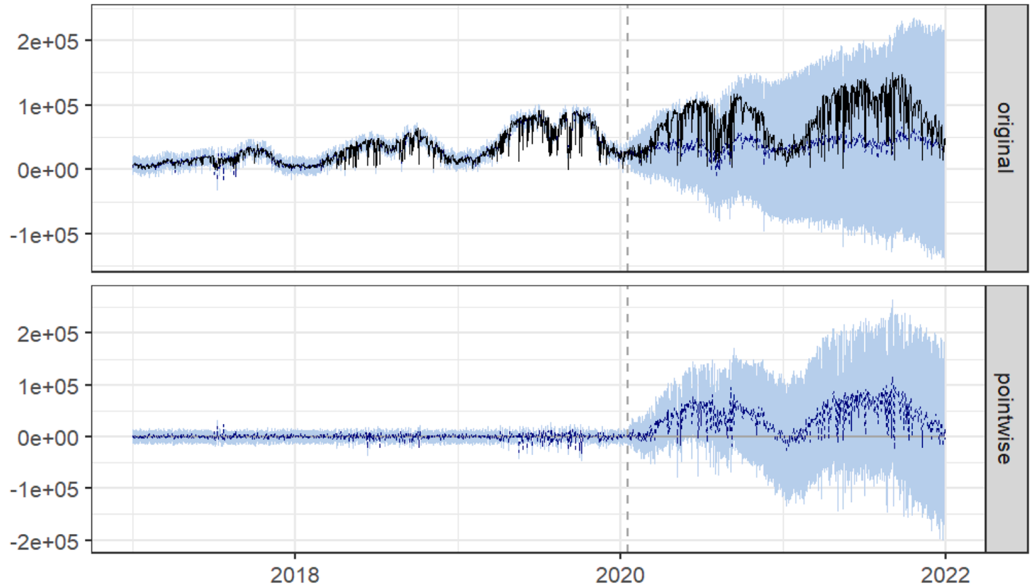

Fig. 2. Pointwise prediction and difference in daily ridership of public bicycle by causal impact inference modeling.

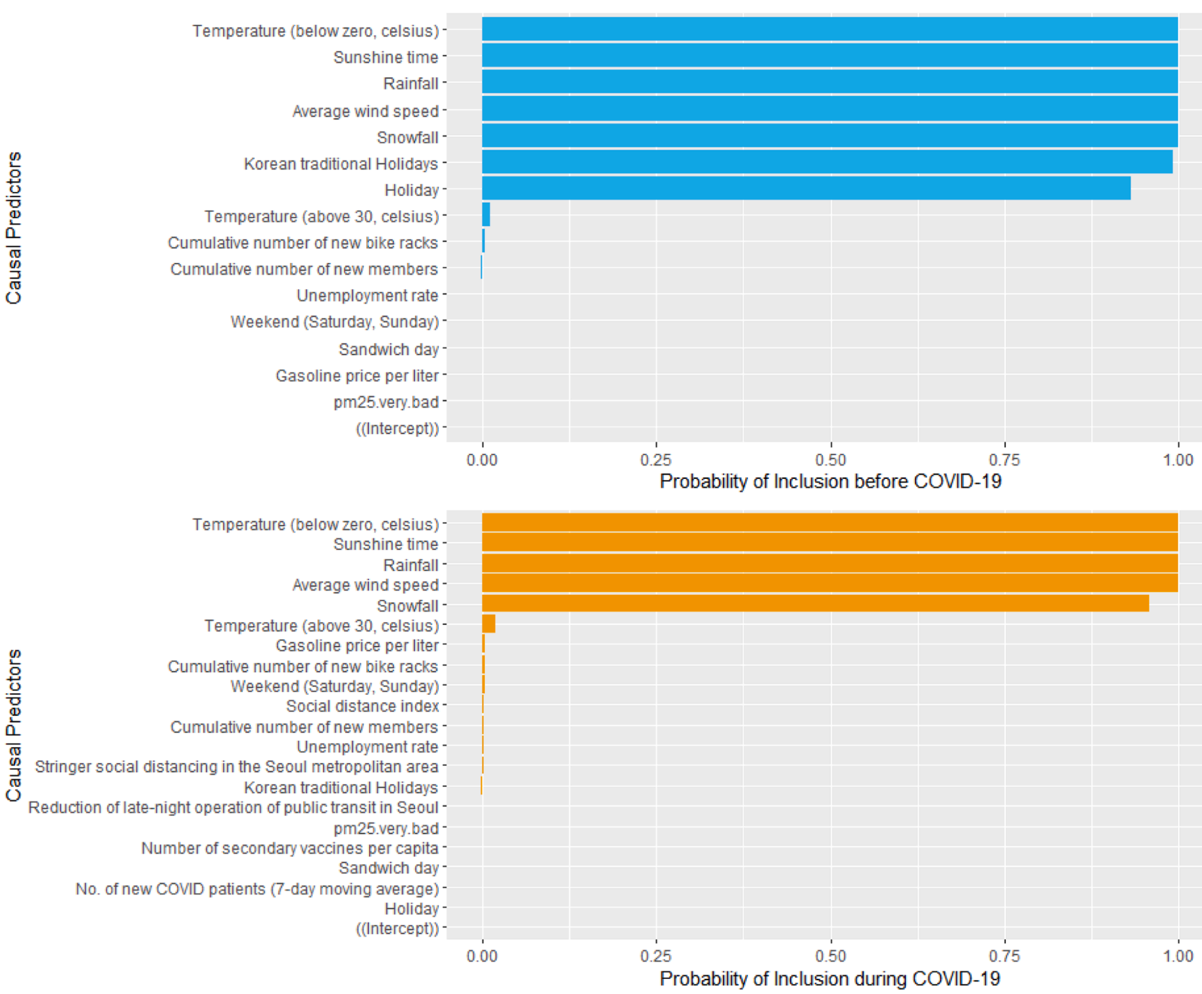

Fig. 3. Inclusion probability of exogenous regressors before and during COVID-19 pandemic.

influenced public bicycle ridership. As the intensity of social distancing increased, ridership also increased. The stronger the non-pharmaceutical measures owing to COVID-19, the more restricted the mobility of human activity; therefore, public bicycles may have been used for purposes, such as leisure while staying at home. On the contrary, measures of late-night reduction of public transit operations in

Table 3
Average coefficient of posterior Bayesian models before and during COVID-19.

		Model A Before COVID-19	Model B During COVID-19	Difference (=B-A)
Weather environment factor	Sunshine time (hr.)	0.0378	0.0358	-0.0021
	Temperature (below 0°C = 1, 0°C to 30°C = 0)	-0.2261	-0.3694	-0.1432
	Temperature (above 30°C = 1, 0°C to 30°C = 0)	-0.0023	-0.0073	-0.0050
	Average wind speed (m/s)	-0.0855	-0.0999	-0.0144
	Rainfall (mm)	-0.0178	-0.0191	-0.0013
	Snowfall (cm)	-0.0871	-0.1050	-0.0179
	PM 2.5 (> = 76 $\mu g/m^3$ = 1, < 76 $\mu g/m^3$ = 0)		-0.00005	-0.00005
Seasonal and non-seasonal event factor	Weekend (Saturday, Sunday = 1, Monday to Saturday = 0)	0.000003	-0.0004	-0.0004
	Holiday (=1, Non-holiday = 0)	-0.2115		0.2115
	Korean traditional holidays (=1, None = 0)	-0.3530	-0.0001	0.3529
	Sandwich day (=1, None = 0)	-0.00001		0.00001
Supply and demand factor	Gasoline price per liter (KWR, Log)	-0.000001	-0.00002	-0.00002
	Unemployment rate	0.00001	-0.00001	-0.00002
	Cumulative number of new bicycle racks (Log)	0.00002	0.00026	0.0002
	Cumulative number of new members per capita (Log)	0.0001	-0.0036	-0.0037
COVID-19 factor	Social distance index	na	0.0000020	
	Reduction of late-night operation of public transit in Seoul (=1, None = 0)	na	-0.0000337	
	Stringer social distancing in Seoul metropolitan area (=1, None = 0)	na	-0.0000370	
	No. of new COVID patients (7-day moving average)	na	-0.0001	
	Number of secondary vaccines per capita	na	-0.0000002	

Note: na is not available in the model

Seoul and stricter social distancing measures in the Seoul metropolitan area decreased public bicycle ridership. The results can be interpreted as a function of the trip chaining of public bicycles linked to public transit in Seoul, which has weakened owing to the COVID-19 pandemic. As the 7-day moving average number of new confirmed cases increased, the use of public bicycles decreased. This may have been because people refrained from using them to avoid the risk of COVID-19. As the number of secondary vaccinations per capita increased, the number of public bicycle users decreased.

5. Discussion

The results of this study on causal impact inference modeling demonstrated that the use of shared public bicycles in the densely populated city of Seoul was robust against the COVID-19 pandemic. Although the increase in public bicycle ridership for approximately two years after its first confirmation did not significantly increase, it did not decrease either. During the COVID-19 pandemic, the use of private bicycles increased (Anke et al., 2021; Ehsani et al., 2021; Harrington & Hadjiconstantinou, 2022; Hensher et al., 2022; Bucsky, 2020; Monterde-i-Bort et al., 2022; Shaer & Haghshenas, 2021; Loa et al., 2021; Lee et al., 2021). This proves that private ridership is more resistant to infectious disease pandemics (Chen et al., 2022; van der Drift et al., 2021). However, the evaluation of the sharing of public is mixed. This indicates that shared-based public bicycles have a higher risk of infection than privately owned bicycles (Hua et al., 2021; Shamshiripour et al., 2020; Zafri et al., 2022). In the early stages of COVID-19 in New York, the use of sharing decreased (Chai et al., 2021; Teixeira & Lopes, 2020; Wang & Noland, 2021). Zhang and Fricker (2021) also reported that among 11 US cities, the use of public bicycles increased in low-density cities, however it decreased in high-density cities during the COVID-19 lockdown. Bouhouras et al. (2022) also supported the results of Zhang and Fricker (2021), because the use of public bicycles increased significantly during the COVID-19 lockdown in small and medium-sized Greek cities. These results may indicate that the robustness of the shared public bicycle system is stronger in small-and medium-sized cities with low density than in high-density large cities. This study proves that public bicycles can be robust in response to COVID-19, even in Seoul, one of the most densely populated cities in the world. It was also confirmed that public bicycle ridership in Singapore increased by 150% during the lockdown (Song et al., 2022).

The robustness of public bicycle sharing in Seoul can be discussed from three perspectives: First, public bicycles were used more for leisure, exercise, and well-being than as a mode of travel during the COVID-19 pandemic. Because public bicycles in Seoul were mainly used for transit (Nam et al., 2021), the use of public bicycles was higher on weekdays than on weekends before the pandemic. However, its use increased on weekends, when public bicycles were mainly used for leisure and exercise during the COVID-19 pandemic when social distancing and movement restriction measures were considered to restrict human mobility. Kim et al. (2021) reported that the use of public bicycles in Seoul increased by 97.3% for leisure purposes such as weekends during the early period of the COVID-19 pandemic. In addition to the support from the cases of South Korea, Fuller et al. (2021) revealed that most bicycle activities increased for exercise and well-being purposes but not for transport purposes in Australia.

Second, the sharing of public bicycles may be further strengthened as an access mode for short-distance travel to major travel destinations during an infectious disease pandemic. Castillo-Manzano et al. (2016) indicated that the average journey distance by private bicycles was 700 to 800 m greater than that by public bicycles during normal times without the pandemic. Seo & Cho (2021) reported that the average distance of public bicycles traveled decreased from 0.83 km before COVID-19 to 0.58 km in the period thereafter. While analyzing the mileage, they confirmed that the average mileage of newly added routes after COVID-19 significantly decreased to less than 1,000 m.

Third, public bicycles may serve as an alternative to public transit during the rapid spread of infectious diseases. Many studies on other cities in the world have confirmed that bicycles were an alternative mode of mass transit during the COVID-19 pandemic (Campbell & Brakewood, 2017; Heydari et al., 2021; Lee et al., 2021; Schaefer et al., 2021; Scorrano & Danielis, 2021). Lee et al. (2021) revealed that public bicycles in Seoul had a significant substitution relationship during the period when the number of COVID-19 confirmed cases was amplified, although it had a weak correlation during the entire period of the pandemic. They observed that 2.28–4.33% of public transit users before the pandemic had changed to bicycles for travel during the pandemic in South Korea. In addition, lockdown and various movement restriction measures served as alternatives to fulfill mobility requirements in places where public transit services were limited (Song et al., 2022). However, the robustness of the use of shared bicycles against the coronavirus disease 2019 may vary depending on the density of the cities. Zhang and Fricker (2021) found that the COVID-19 outbreak decreased non-motorized travel activities in densely populated cities, whereas it decreased in less densely populated cities in the United States. The reason is that although shared public bicycles are a less dangerous mode of transportation during COVID-19, activities in high-density urban physical environments have an environment that is more susceptible to infectious diseases.

The public bicycle sharing system is one of the fastest-growing transport services worldwide (Wang & Akar, 2019). This public service should also work as a disease-resilient transport system (Song et al., 2022). Seoul has maintained a robust demand for the use of public bicycles during the COVID-19 pandemic by providing an unintentionally large supply of rental stations (Kim, 2021). This study confirmed that the usage behavior of public bicycles also changed during this pandemic. For example, the use of public bicycles increased on both weekdays and days when weather conditions were not bad. However, the robustness of this shared public bicycle service in response to the infectious disease pandemic in Seoul is not sufficient. Because the transport infrastructure for bicycle use in Seoul was relatively insufficient (Kim and Kim, 2020), it was difficult to gather evidence of the robustness of public bicycles as a travel mode against infectious disease pandemics. Other cities in Europe and South America have promoted the ease of use of bicycles resistant and resilient to infectious diseases as a travel mode, not only for leisure, exercise, or well-being, through active interventions, such as the provision of free use of public bicycles and the opening of pop-up bicycle paths during COVID-19 (Büchel et al., 2022; Nikitas et al., 2021). In this regard, the government must continuously intervene in the supply of bicycle infrastructure, particularly shared-based public bicycles, to function as a disease-resilient transport system during the epidemic period.

This study suggests a shared public bicycle system as an alternative robust travel mode against the COVID-19 pandemic. However, the study may have limitations in comparison with other shared travel modes in terms of the effects, competitive and complementary relationships with other travel modes, and only focusing on Seoul city in South Korea. First, further studies need to focus on identifying and comparing the causal effects of shared personal mobility during the current pandemic and new ones in the near future. Mouratidis (2022) identified that the use of shared mobility, such as bicycles, cars, and e-scooters, was associated with different demographic and socioeconomic factors as well as the residential physical environment of people. Wiseman (2021) also indicated that autonomous vehicles can be a better robust solution against the coronavirus pandemic, especially in isolated territories. Shared autonomous vehicles, a future transportation technology, need to be considered as a personal mobility mode to sustain daily activities during the coronavirus pandemic. Second, the study did not consider the competition and complementary relationships between the different modes of transportation resulting from the COVID-19 pandemic. Shamshiripour et al. (2020) identified that the perceived risk level of traveling with different modes during a pandemic differed. As a result, the robustness of shared public bicycles during the pandemic might result from an increase due to a decrease in the use of public transport, which was perceived as more dangerous. Therefore, in future studies, it will be necessary to empirically demonstrate how competition and complementarity between means due to this pandemic affected the use of shared public bicycles. Third, the study identified the causal effects on the daily ridership of shared public bicycles in Seoul, South Korea. Therefore, it is necessary to conduct a study comparing the results with those of other cities worldwide.

6. Conclusions

In conclusion, this study provides evidence on how to maintain daily life by activating the use of shared public bicycles during pandemics of infectious diseases that may recur in the future. This conclusion supports the idea that the public bicycle-sharing system can be robust against the COVID-19 pandemic, even in Seoul, which has a high-density population. However, because this robustness may be only a result of the strengthening of the use of public bicycles for leisure and exercise, and not mainly for the purpose of travel, sustaining infrastructure investments, such as bicycle roads, are required for public bicycles to play the role of a more robust, resilient, and sustainable transport mode against infectious disease pandemics.

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Declaration of Competing Interest

The author declares that (i) no support, financial or otherwise, has been received from any organization that may have an interest in the submitted work; and (ii) there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability

Data will be made available on request.

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