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Short- and long-term effects of COVID-19 on bicycle sharing usage

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ABSTRACT

Using panel regression methods, this paper investigates how the COVID-19 pandemic impacted bicycle sharing system (BSS) ridership in Budapest. In particular, the paper aims to separate the effects of mobility and government restrictions on BSS ridership and analyse whether long-term positive effects are observable in this city. Results indicate that both mobility and government stringency measures significantly and positively affected BSS usage, particularly in residential areas and close to public parks. However, after the first wave of the pandemic passed and government measures were partially lifted, BSS ridership declined in line with the elimination of the restrictions. New users often churned after their first trial, and usage frequency dropped to lower levels than before the pandemic. This indicates that BSS was a valuable transportation mode during a pandemic, but a permanent increase in usage was not observed in Budapest despite a considerable price decrease in bicycle fares. The unsatisfactory experiences with this BSS, primarily due to heavy bike frames and solid rubber tires may be the cause of this. Our results prove the benefits of BSS in mitigating a pandemic but call the attention to the need to improve particular system characteristics that may undermine long-term ridership. These characteristics can be different for every BSS; hence, local market research is required. This limits the generalizability of the results.

Introduction

A new coronavirus disease, COVID-19, began to spread across Europe and the whole world in 2020. The World Health Organization (WHO) declared it a global pandemic on March 11, 2020 (Cucinotta and Vanelli, 2020). Governments responded quickly to the fast spread of the disease, and several restrictions on social contact were put in place. Social distancing, quarantine, and lockdown impacted modal choice in travelling and commuting as well as the utilization of different transportation systems. Some of these changes may have long-term impacts.

Since COVID-19 can easily spread via social contact, citizens became afraid of public transportation and preferred individual modes of travel. Several cities introduced measures to promote cycling and improve cycling infrastructure (Nikitas et al., 2021). These measures can be favourable for bicycle sharing systems (BSS), which are easy and inexpensive alternatives for public transport in cities. Park et al. (2020) found that BSS usage increased substantially during social distancing in South Korea. Similarly, Song et al. (2022) found that BSS usage doubled in Singapore during the first wave of the pandemic. On the other hand, Padmanabhan et al. (2021) showed that bicycle usage declined in New York, Boston, and Chicago over the same period. Zhang and Fricker (2021) found that bicycle activities declined in large and dense US cities but increased in lower density cities. Li et al. (2021a) and Heydari et al. (2021) concluded that the introduction of lockdown measures led to a significant drop in BSS usage in the short term in London but observed an increasing trend afterwards. Similar findings were also reported from other cities (e.g., Li et al., 2021b; Lei and Ozbay, 2021; Wang and Noland, 2021).

The decline in cycling can be attributed to the fact that lockdown measures significantly reduced the number of commuters with the rapid penetration of working from home and the mandatory closure of all but essential services (Molloy et al., 2021; Padmanabhan et al., 2021). However, the modal share of cycling increased substantially during the COVID-19 pandemic (Bucsky, 2020; Molloy et al., 2021; Scorrano and Danielis, 2021; Bergantino et al., 2021), which placed upwards pressure on total usage. The net effect can vary across cities. Furthermore, BSS usage may exhibit different trends than general bicycle ridership, as the former can be more easily used within cities, do not require substantial investment, and can be combined with other transportation modes. This paper investigates the connection between government measures in relation to the COVID-19 pandemic and BSS usage and their long-term effects on BSS ridership. The data originated from Budapest, Hungary, a capital city in Europe.

Hungary was not an exception to the effects of COVID-19. The first case was confirmed on March 4, 2020, and very strict measures were initiated just a couple of days later. Universities transitioned to online

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teaching as of March 12 and primary and secondary schools followed suit as of March 16. At the same time, the fare for the local BSS was significantly reduced to only €0.30 for a monthly pass as of March 16.

This paper contains four novel elements compared to prior research in this domain. First, COVID-19-related measures were quantified using a sophisticated policy-related index instead of a dummy variable or by the number of confirmed cases. This enables us to estimate the effects of changing these measures on BSS ridership. Furthermore, since this index reflects government measures, it can provide direct policy implications on how the introduction of additional restrictions affects BSS usage. Second, we separated the *ceteris paribus* effect of the restrictions (measured by the stringency index) from the *ceteris paribus* effects of changing mobility. Since the spread of COVID-19 has caused large variations in commuting, overall demand for all transportation modes needs to be taken into consideration when estimating BSS usage. Third, the dataset covers the full peak period of 2019 and 2020, allowing us to analyse the evolution of the churn rate and usage frequency during the pandemic. These can provide a more detailed understanding of BSS usage during a pandemic and its long-term impact on ridership. Fourth, the paper also investigates how land use impacted the changes in BSS trip generation during the COVID-19 pandemic. This can shed light on how mobility and trip generation patterns were modified during this time.

The remainder of this paper is structured as follows. Section 2 provides a short introduction of the BSS in Budapest. Section 3 introduces the data and the methodology. Section 4 presents the results, Section 5 discusses the analyses, and Section 6 summarizes the policy implications of the results. The paper is concluded with Section 7.

The BSS in Budapest

The paper considers the BSS of Budapest. The city had 1.75 million inhabitants at the beginning of 2020 (53% female and 47% male). 66% of the residents were between 15- and 64-year-old. In terms of income, the city is showing more favourable figures than the rest of the country. Average annual per capita net income was around €6,400 in Budapest in 2020, while the same number was around €5,000 considering the whole country.

The BSS of Budapest, called MOL Bubi, was opened in September 2014 with 76 stations and 1,100 bicycles. The number of stations and bicycles increased gradually, reaching 160 and 2,071 in 2020, respectively, and covers the inner part of the city. The system is owned and operated by the local government.

To use the bicycles, customers can purchase tickets or passes that range from €1.60 for a 24-hour ticket to €60 for an annual pass. In response to COVID-19, the price of the monthly pass was reduced to €0.30. Since then, users have not purchased any other types of tickets or passes. Other than that, no changes were made, the scale and level of service of the BSS remained the same as they were during 2019. This is also true for public transportation, capacity and frequency of public transport services were not reduced in Budapest despite the sizeable reduction in the number of travellers.

Data and methodology

BSS usage data were obtained from the system operator, the BKK Centre for Budapest Transport. The data include the records of all individual trips made in 2019 and 2020 (start station, final station, start time, end time, country of origin of the user based on phone number, ticket type, user ID). The raw dataset contained a total of 771,459 items but required cleaning to eliminate invalid entries. Trips that did not last longer than one minute or for which the start or final stations were missing were eliminated from the database, reducing the dataset to 753,356 trips. The number of trips and their average duration were calculated by day and generating station. Since BSS usage patterns are different on workdays and weekends (Faghih-Imani and Eluru, 2015; El-Assi et al., 2017; Bakó et al., 2020), these two types of trips were analysed separately. Workday usage is mainly connected to commuting to work, while weekend usage is more about leisure trips. This is also reinforced by the daily trip distribution. During workdays, a morning and an afternoon peak is observable, while during weekends, the majority of the trips were made between 10am and 7pm with a rather uniform distribution. 77% and 74% of the trips were made during workdays in 2019 and 2020, respectively.

One-time users and pass holders were not separated as one-time users completely disappeared in 2020 (they accounted for 0.9% of all trips made in that year). This can be traced back to two reasons. First, around 10% of the BSS users were international tourists (not Hungarian citizens) in 2019 and almost all of them (97%) were one-time users. Due to COVID-19, international tourists disappeared from Budapest (only 0.6% of the users were international tourists in 2020), hence, decreasing the number of one-time users. Second, after reducing the price of the monthly pass (from March 16, 2020 onwards), other types of tickets and passes were not purchased at all.

Government measures in relation to COVID-19 were quantified using the Oxford COVID-19 Government Response Tracker dataset. The Government Stringency Index, which is measured on a scale from zero to one hundred, was selected because it reflects all the official restrictions and shows substantial variability over time. These restrictions impacted the lives, daily routines, and behaviours of all citizens.

On the other hand, mobility can be influenced by other factors not limited to government restrictions (e.g., fear of the pandemic, percentage of employees working from home). This is affecting demand for transportation modes. Daily data for city traffic in Budapest were used to proxy overall mobility. Traffic was measured by vehicle counting cameras installed next to or over some roads. The cameras are constantly detecting the same area of the road that is not changing over time. The system is operated, and data were provided by the BKK Centre for Budapest Transport. Since only a limited number of cameras exists, the traffic numbers in itself are not relevant, but the changes can well reflect the changes in mobility. This is an appropriate proxy variable for the number of citizens travelling and commuting in the city.

Regarding the control variables, one of the most important determinants of BSS usage are weather conditions (Saneinejad et al., 2012; Gebhart and Noland, 2014; Liu et al., 2015; El-Assi et al., 2017; de Chardon et al., 2017; Chang et al., 2019; Bakó et al., 2020). Daily average temperature, daily total precipitation, and daily average wind speed data for Budapest were collected from the NASA Power Data Access Database. Since the effect of temperature on BSS usage is not linear, 5 °C intervals were applied similarly to Gebhart and Noland (2014) and Bakó et al. (2020).

Furthermore, the utilization of the docking stations substantially depends on their surroundings. Land use and built environment can significantly influence BSS trip generation (Mateo-Babiano et al., 2016; El-Assi et al., 2017; Guo and He, 2020). This is, however, rather stable in a short period of time, therefore, it can be treated as a time-invariant effect if the analysis considers a limited time horizon. This is particularly true in this case as the Budapest BSS covers the inner part of the city that is already built in; development projects mainly impact the outer districts of the city. Therefore, all the 160 stations were classified into one land use category and this was assumed to remain unchanged during the analysed time horizon. Seven land use categories were identified based on the classification proposed by Mateo-Babiano et al. (2016). The categories were adjusted to take the local circumstances into account. The seven land use types are the followings:

- Residential (46 stations): the neighbourhood of the station is primarily a residential area;
- Commercial (36 stations): the neighbourhood of the station is primarily a business or government area;
- Education (19 stations): the station is located next to a university campus;

- Parkland (24 stations): the neighbourhood of the station is primarily a recreation area with public park;
- Transport (17 stations): the station is located in a transport hub;
- Hospital (4 stations): the station is located next to a hospital;
- Entertainment (14 stations): the station is located near to entertainment facilities (e.g., museum, theatre, concert hall, party place, beach).

The prices of tickets and passes have important impacts on usage (Goodman and Cheshire, 2014; Fishman, 2016; Lin et al., 2017); however, only one price decrease occurred during the period considered (as indicated above). Since this price drop took place right at the beginning of the pandemic (as a part of the rapid response to the situation), it is not possible to separate its effect on BSS usage. However, different time horizons were applied in this study, and the price reduction occurred right at the beginning of the period considered, therefore, it does not invalidate the results. Descriptive statistics of the variables used are presented in Table 1.

To identify a causal relationship between government restrictions and BSS usage, the observed trip generation patterns should be compared to a counterfactual one without any restrictions. The difference of the actual and the counterfactual data will show the effect of the restrictions. Unfortunately, this counterfactual is not available at hand and needs to be constructed. It was done by using the same period of the year before the pandemic, i.e., 2019 data were used as a counterfactual for 2020 without any COVID-19-related restrictions. However, for a proper counterfactual, the differences across the two years need to be controlled for. These can be separated into two parts. First, several variables determining trip generation can change over time (temperature, precipitation, wind speed, traffic) and took different values in 2019 and 2020. Second, usage trends of the individual stations might be different due to differences in land use, built environment, transportation network development. This has to be considered as well in the model. Similar logic was applied by Bakó et al. (2020).

To operationalize the model, the differences of the 2019 and 2020 data were explained by the time variant factors and the station-level differences:

$$\Delta y_{it} = \beta_0 + \beta_1 \Delta Stringency_t + \beta_2 \Delta \log(Traffic_t) + \Gamma \Delta X_t + c_i + u_{it}, \quad (1)$$

Table 1
Descriptive statistics.

Variable	Obs.	Mean	Standard deviation	Min	Max
Number of BSS trips generated per station on workdays	68,833	8.00	8.21	0	89
Number of BSS trips generated per station on weekends	30,915	6.55	8.77	0	134
Average BSS trip duration by generating station on workdays (min.)	63,876	14.48	13.82	1	1,205
Average BSS trip duration by generating station on weekends (min.)	25,683	17.69	26.26	1.03	1,982
Government Stringency Index	699	22.08	29.00	0	76.85
Daily city traffic (# of cars)	699	151,027	27,601	46,267	212,044
Daily average temperature (°C)	699	11.84	8.61	−6.57	27.84
Daily total precipitation (mm)	699	1.92	4.03	0	42.28
Daily average wind speed (m/s)	699	3.40	1.40	0.88	9.12

where y_{it} is the number of BSS trips or the average duration of the BSS trips generated by station i on day t, $Stringency_t$ is the value of the Oxford COVID-19 Government Stringency Index on day t for Hungary, $Traffic_t$ reflects traffic data of Budapest on day t, X_t contains the weather related control variables outlined above, c_i is the station-level change from one year to another (station-level trend), while u_{it} is the idiosyncratic error term. The Δ refers to the difference between 2019 and 2020. This was calculated by subtracting the 364 days (exactly 52 weeks) earlier data from the 2020 data. Since there were no government restrictions in place in 2019, $\Delta Stringency_t = Stringency_t$ in this case. The model was estimated using fixed effect panel regression methodology.

The benefit of this regression is the ability to estimate *ceteris paribus* effects for government stringency measures, mobility, and weather conditions. Data indicate that government restrictions and traffic are not highly correlated, the correlation coefficient is −0.50 if considering the first period of COVID-19, but only −0.25 if considering the full year of 2020. This means that restrictions are not directly and immediately impacting traffic, the correlation is not very high in absolute terms, hence, it does not cause multicollinearity problems. The reason behind this can be that for e.g., a ban on social gathering might mean that people meet with their closest relatives only, but still travel to make this happen. If this restriction is lifted, people might commute the same amount, but do different activities and use different transportation modes.

On the other hand, it is not possible to estimate time-invariant variables using the fixed effect framework as these variables are captured by the fixed effect (c_i in Eq. (1)). Therefore, land use cannot be included in this model. To assess the effect of land use on BSS trip generation, the average station-level trends were calculated by the seven land use types introduced above. These averages show how the utilization of the stations with different land use types changed during the COVID-19 pandemic.

The regression analysis focused on the peak period of the BSS but was separated into two main parts: 1) the first wave of the pandemic, and 2) the period between the first and the second waves. The separation enabled us to verify whether any long-term impact is observable. If BSS ridership increased during the first wave as a response to the stringency measures but returned to its pre-pandemic level after the pandemic situation improved, then no long-term impact was observable. However, if commuters tried the BSS during the first wave and became long-term users, then lifting the measures would most likely not significantly or to a lesser magnitude impact BSS usage (after controlling for mobility), which would remain high. This should be particularly true for workday usage that is strongly connected to commuting to work. If the daily commuting habit of the citizens were altered during the first wave, they will also use BSS after the restrictions are not in force anymore and that will have a lasting positive effect on BSS ridership. This is the long-term effect this paper aims to estimate. A similar logic might apply to weekend usage and other usage purposes than commuting, but the effect might be less direct and lower in magnitude.

Results

This paper investigates how the COVID-19 pandemic impacted BSS ridership during the first wave and after the majority of the restrictions were lifted. The results are separated into three subsections. First, a descriptive analysis is presented in Section 4.1, which is followed by the results of the regression models in Section 4.2. Finally, we examine the effects of the measures on new users and churn rate in Section 4.3.

Descriptive results

BSS usage in 2019 and 2020 show similar seasonal patterns; however, 2020 proved to be more volatile. At the same time, data clearly show that usage increased significantly in 2020 (Fig. 1), when the number of BSS trips increased by approximately 30% compared to the

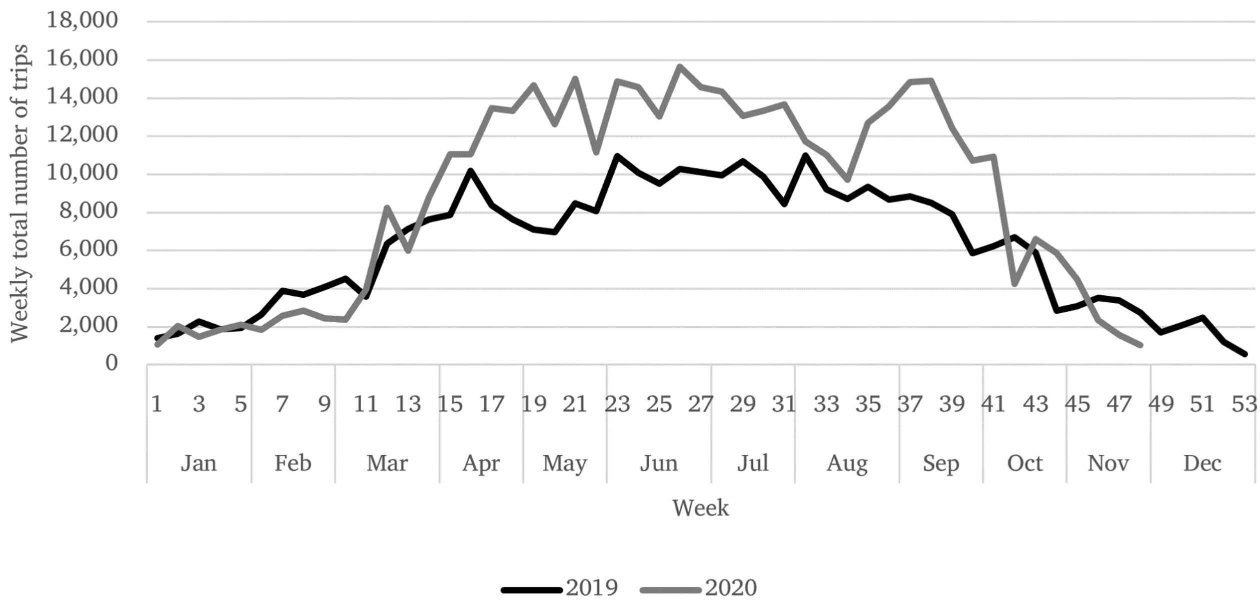

Fig. 1. Weekly BSS usage in 2019 and 2020.

previous year. This increase mainly occurred in the peak period and is likely connected to the government measures and the price decrease in response to the pandemic. As it is suggested by Fig. 2, in March 2020, several restrictions were imposed in a very short time frame. Schools and universities turned to online teaching in the middle of March, public events were cancelled, and public gatherings were restricted from March 29 in line with a stay-at-home order and restrictions on internal movements. International travel controls were in place since March 17. Furthermore, extensive public information campaigns with celebrities were aired on television, digital platforms, and social media to inform and engage the public. The restrictions were gradually lifted starting from May 2020, but some restrictions on social gatherings remained in force throughout 2020.

The number of citizens travelling or commuting in the city is an important determinant of BSS demand (El-Assi et al., 2017; Morton et al., 2021). Under normal circumstances, demand does not change dramatically across weeks, but the very fast spread of working from home (while 5.4% of the employees worked from home in Budapest in 2019, it was 21.3% in 2020 according to the Hungarian Central Statistical Office), the restrictive government measures, and the fear of the pandemic caused sizeable differences in this regard. The more volatile usage of the BSS in 2020 can likely be traced back to these reasons.

While the BSS generally experienced an increase in usage after the COVID-19 outbreak in Hungary, traffic in Budapest declined markedly after mid-March (Fig. 3). A slow catch-up in traffic is observable from May, which also saw an increase in BSS usage. This indicates that commuters also used the BSS after they returned to the city. When traffic reached its initial level around June and July 2020, BSS ridership was above its level one year prior; however, a slow decline was observable from the absolute height of May and June (Fig. 1 and Fig. 2).

Another increase in BSS usage was detected in September, which marked both the start of school and a jump in COVID-19 cases (Fig. 1 and Fig. 3). Traffic declined again, albeit much less compared to the spring period. However, at the end of September, when the peak period of the BSS normally ends due to colder weather (Bakó et al., 2020), usage declined substantially. Government restrictions were reintroduced only

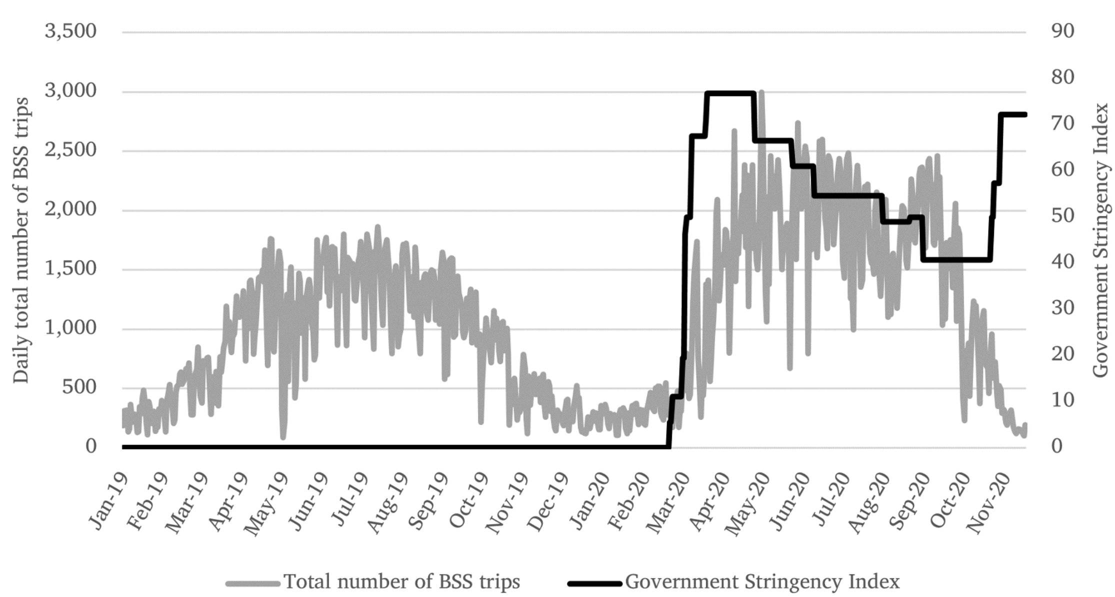

Fig. 2. Daily BSS usage and the Government Stringency Index, 2019–2020.

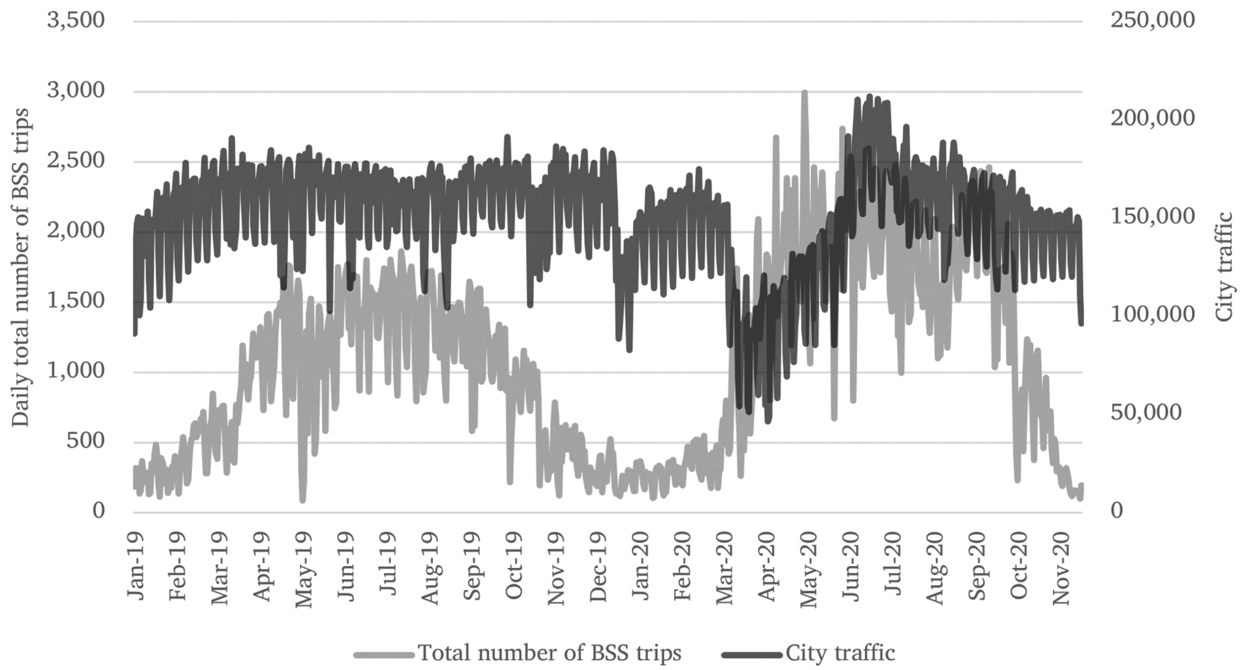

Fig. 3. Daily BSS usage and traffic in Budapest, 2019–2020. *Notes:* Traffic was measured at ten dedicated points in the city, therefore, the absolute value of the variable is less relevant, the changes in traffic should be considered.

at the beginning of November. BSS utilization was already very low at that time due to unfavourable weather conditions (Fig. 1). Even with extremely low fares for the BSS, the pandemic did not create sufficient incentives to overturn this trend.

Regression results

The previous subsection indicated that both government measures and overall mobility likely impacted BSS usage. Table 2 and Table 5 confirm these conclusions using panel regression estimates of Eq. (1). Since workday and weekend usage patterns of BSS are very different (Faghih-Imani and Eluru, 2015; El-Assi et al., 2017; Bakó et al., 2020); they will be analysed separately.

In the first wave of the pandemic, government measures had a high impact on BSS usage on workdays. Taking into consideration that the highest level of government stringency was 76.85 in Hungary (Table 1), the maximum *ceteris paribus* increase in usage was approximately 3.9 trips/station/day (compared to a case without any government restrictions). It is around half of the average utilization of the stations. At the same time, this massive increase was not associated with a change in

Table 2
Estimation results for daily BSS trip generation by stations on workdays.

Variable	Whole peak period in 2020 Mar 1 – Aug 31, 2020	First wave of COVID-19 Mar 1 – Jun 21, 2020	Between 1st and 2nd waves of COVID-19 Jun 22 – Aug 31, 2020
Government Stringency Index	0.060***	0.051***	0.268***
	(0.005)	(0.005)	(0.037)
Percentage change in city traffic	0.057***	0.057***	0.058***
	(0.003)	(0.005)	(0.007)
Temperature: –5–0 °C	−7.081***	−6.997***	–
	(0.689)	(0.687)	
Temperature: 0–5 °C	−4.886***	−4.852***	–
	(0.260)	(0.263)	
Temperature: 5–10 °C	−3.334***	−3.301***	–
	(0.223)	(0.219)	
Temperature: 10–15 °C	−1.783***	−1.843***	–
	(0.160)	(0.159)	
Temperature: 20–25 °C	−0.800***	−1.031***	−0.021
	(0.141)	(0.292)	(0.201)
Temperature: > 25 °C	−1.172***	−3.616***	−0.501**
	(0.188)	(0.488)	(0.218)
Precipitation	−0.347***	−0.388***	−0.296***
	(0.012)	(0.015)	(0.019)
Wind speed	−0.238***	−0.223***	−0.047
	(0.035)	(0.040)	(0.073)
N	16,728	9,808	6,920
R-square	0.237	0.292	0.254

Notes: The reference category for temperature is 15–20 °C. Standard errors are in parenthesis. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 3
Estimation results for average BSS trip duration by generating stations on workdays.

Variable	Whole peak period in 2020 Mar 1 – Aug 31, 2020	First wave of COVID-19 Mar 1 – Jun 21, 2020	Between 1st and 2nd waves of COVID-19 Jun 22 – Aug 31, 2020
Government Stringency Index	−0.003	−0.018	0.091
	(0.014)	(0.016)	(0.106)
Percentage change in city traffic	−0.037***	−0.035**	−0.009
	(0.008)	(0.015)	(0.021)
Temperature: –5–0 °C	−4.243**	−4.383**	–
	(1.960)	(2.039)	
Temperature: 0–5 °C	−3.683***	−3.775***	–
	(0.738)	(0.782)	
Temperature: 5–10 °C	−2.681***	−2.710***	–
	(0.633)	(0.650)	
Temperature: 10–15 °C	−1.020**	−1.170**	–
	(0.455)	(0.472)	
Temperature: 20–25 °C	−0.871**	−1.850**	0.412
	(0.402)	(0.868)	(0.572)
Temperature: > 25 °C	−1.128**	−0.578	−0.285
	(0.535)	(1.448)	(0.620)
Precipitation	−0.160***	−0.217***	−0.099*
	(0.034)	(0.045)	(0.053)
Wind speed	−0.116	−0.086	0.040
	(0.100)	(0.118)	(0.209)
N	16,728	9,808	6,920
R-square	0.027	0.032	0.045

Notes: The reference category for temperature is 15–20 °C. Standard errors are in parenthesis. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

average BSS trip duration (Table 3).

Mobility also significantly affected BSS usage. One percent decrease in city traffic led to a 0.06 trip/station/day decrease in BSS ridership. In the early period of the first wave, traffic was just half as the year before; hence, this shows a massive effect, a reduction of closely 3 trips/station/day (equivalent to roughly 40% reduction compared to the average utilization of the stations). During the first wave, mobility and stringency had opposite effects; the total change in BSS usage captures the net effect of these two.

Considering the period between the two waves shows similar results but indicates a different picture. The coefficient of the stringency index increased very substantially. Since restrictions were lifted in this period, BSS usage started to decline in line with the elimination of the restrictions. On the other hand, the data show a similar positive effect of mobility on BSS usage as during the first wave. These results indicate that the BSS was not able to maintain its new users. As the government restrictions were less severe, commuters switched away from the BSS. Therefore, long-term positive effects in ridership are not observable. This is further reinforced by the fact that neither stringency measures nor mobility impacted BSS trip duration in this period.

Results of the whole peak period indicate similar conclusions, namely that both stringency and mobility had a positive impact on BSS ridership. Furthermore, once mobility increases, BSS trip duration is expected to decrease. Lower traffic is, therefore, connected to more lengthy BSS trips, albeit the difference is only a couple of minutes.

The effect of land use is investigated by analysing the station-level changes (Table 4). It is important to note that these can contain other factors, too, not only land use. However, it can be concluded that during the first wave of the pandemic trip generation in residential areas and parklands increased while it decreased in commercial areas, next to universities, entertainment facilities and in transport hubs. Interestingly, BSS usage also decreased in stations close to hospitals. It can be explained by the fact that a visiting ban was in effect in hospitals during the pandemic as well as several elective operations were postponed as hospitals focused on COVID-19-related cases. Between the two waves of the pandemic, BSS trip generation was higher in stations located in transport hubs and lower in parklands. This is another sign that life started to normalize, and commuters combined BSS with other transportation modes again.

Weekend usage is mainly connected to leisure and free-time activities and therefore shows different patterns than workday usage (Faghih-Imani and Eluru, 2015; El-Assi et al., 2017; Bakó et al., 2020). While the BSS in Budapest is generally less frequently utilized during weekends (compared to workdays), a higher increase was observable in response to government stringency measures during the first wave of the pandemic (Table 5). The effect of mobility is also slightly higher in magnitude compared to workdays.

Table 4
Average station-level changes in trip generation from 2019 to 2020 by land use types (on workdays).

Land use type	Number of stations	Average station-level changes from the same period of 2019		
		Whole peak period in 2020	First wave of COVID-19	Between 1st and 2nd waves of COVID-19
Residential	46	1.46	1.46	1.55
Commercial	36	−0.47	−0.59	−0.44
Education	19	−1.80	−1.60	−1.34
Parkland	24	0.66	1.42	−0.49
Transport	17	−0.59	−1.63	0.85
Hospital	4	−1.16	−0.45	−2.15
Entertainment	14	−1.01	−0.54	−1.78

Notes: Negative numbers indicate a relative decline, while positive numbers indicate a relative increase in trip generation compared to the system-level change.

Table 5
Estimation results for daily BSS trip generation by stations on weekends.

Variable	Whole peak period in 2020 Mar 1 – Aug 31, 2020	First wave of COVID-19 Mar 1 – Jun 21, 2020	Between 1st and 2nd waves of COVID-19 Jun 22 – Aug 31, 2020
Government Stringency Index	0.147***	0.153***	0.281***
	(0.009)	(0.010)	(0.063)
Percentage change in city traffic	0.035***	0.067***	0.062***
	(0.003)	(0.005)	(0.012)
Temperature: 0–5 °C	−5.013***	−6.512***	–
	(0.554)	(0.615)	
Temperature: 5–10 °C	−2.916***	−3.295***	–
	(0.479)	(0.541)	
Temperature: 10–15 °C	−1.310***	−2.225***	–
	(0.364)	(0.407)	
Temperature: 20–25 °C	0.740***	3.851***	0.853*
	(0.268)	(0.443)	(0.512)
Temperature: > 25 °C	0.218	6.929***	0.795
	(0.465)	(0.892)	(0.623)
Precipitation	−0.313***	−0.391***	−0.072
	(0.021)	(0.030)	(0.047)
Wind speed	−0.058	−0.235**	−0.117
	(0.075)	(0.099)	(0.139)
N	7,681	4,774	2,907
R-square	0.237	0.292	0.254

Notes: The reference category for temperature is 15–20 °C. Standard errors are in parenthesis. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Analysing the period between the two waves shows similar results as in workdays, albeit the magnitude is somewhat larger. Similar to workdays, the BSS was not able to increase its long-term ridership.

Considering the whole peak period leads to analogous conclusions. Furthermore, average BSS trip duration was not impacted by the restrictions on weekends either, but increased mobility had a negative effect, similarly to workdays (Table 6).

The effect of land use is somewhat different during weekends (Table 7) than it was on workdays. Trip generation on residential areas and parklands increased substantially, while a sizeable decrease is observable on stations located close to entertainment facilities, commercial areas, and transport hubs. However, stations close to higher

Table 6
Estimation results for average BSS trip duration by generating stations on weekends.

Variable	Whole peak period in 2020 Mar 1 – Aug 31, 2020	First wave of COVID-19 Mar 1 – Jun 21, 2020	Between 1st and 2nd waves of COVID-19 Jun 22 – Aug 31, 2020
Government Stringency Index	−0.021	−0.014	0.526
	(0.033)	(0.029)	(0.383)
Percentage change in city traffic	−0.040***	−0.022	−0.170**
	(0.012)	(0.015)	(0.075)
Temperature: 0–5 °C	−5.008**	−5.614***	–
	(2.066)	(1.725)	
Temperature: 5–10 °C	−7.116***	−6.562***	–
	(1.785)	(1.516)	
Temperature: 10–15 °C	−3.694***	−4.057***	–
	(1.357)	(1.141)	
Temperature: 20–25 °C	0.503	2.531**	4.643
	(1.001)	(1.244)	(3.125)
Temperature: > 25 °C	0.460	3.330	6.409*
	(1.733)	(2.503)	(3.802)
Precipitation	−0.371***	−0.526***	0.246
	(0.079)	(0.084)	(0.287)
Wind speed	0.354	0.072	0.522
	(0.281)	(0.278)	(0.846)
N	7,681	4,774	2,907
R-square	0.039	0.062	0.056

Notes: The reference category for temperature is 15–20 °C. Standard errors are in parenthesis. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 7
Average station-level changes in trip generation from 2019 to 2020 by land use types (on weekends).

Land use type	Number of stations	Average station-level changes from the same period of 2019		
		Whole peak period in 2020	First wave of COVID-19	Between 1st and 2nd waves of COVID-19
Residential	46	0.78	0.82	0.88
Commercial	36	−0.50	−0.43	−0.70
Education	19	0.00	0.43	0.06
Parkland	24	0.23	0.30	0.04
Transport	17	−0.20	−0.38	0.14
Hospital	4	0.07	0.14	0.12
Entertainment	14	−1.45	−1.57	−1.25

Notes: Negative numbers indicate a relative decline, while positive numbers indicate a relative increase in trip generation compared to the system-level change.

education institutions and hospitals showed an increase in trip generation during the pandemic that is exactly the opposite of what was observed on workdays. Universities are normally closed on weekends therefore trip generation on these stations were likely not connected to higher education, but for other purposes. In case of hospitals, only a very few numbers of stations are considered and other factors might drive the changes.

New users, churn rate, and usage frequency

Both descriptive and regression results imply that BSS usage increased during the pandemic in Budapest. In this subsection, we take a closer look at the new users, their usage frequency, and the churn rate to investigate the attractiveness of the BSS.

A new user is defined as someone who did not rent a bike in the preceding four weeks of the trip considered. Unsurprisingly, the percentage of trips made by new users is higher in the early period of the year, as BSS usage is lower during cold weather. While new BSS users accounted for approximately 6% of the trips in February and March 2019, it gradually decreased to 2% in October and November 2019.

According to Fig. 4, a completely different picture is shown in 2020. The year began similarly to 2019, but there was a peak in the percentage of trips made by new users after the lockdown measures were introduced (the second part of week 11 and week 12). Roughly-one out of every-four trip was made by a new user. Later, new ridership decreased gradually but remained higher throughout 2020 than in 2019. The pandemic (and the price decrease) encouraged several citizens to try out the local BSS for the first time.

The dataset enables us to separate those users who did not use the BSS in 2019 at all. Fig. 4 also shows these 'true new users' and their trial rate. This implies that the majority of the new users after the COVID-19 outbreak did not use the BSS in the previous year.

A substantial portion of these new users may not have had satisfactory experience, as 22.3% of them did not use the BSS again in the subsequent four weeks. One year earlier, this ratio was 16.8%. Therefore, the churn rate (the percentage of trips after which the user did not use the BSS in the subsequent four weeks) also increased substantially in the first weeks of the pandemic and remained much higher throughout 2020 (Fig. 5). Considering the 'true new users' (i.e., those who did not use the BSS in 2019), we can state that they constitute the majority of the churning users.

Riders who used the BSS both in 2019 and 2020 decreased their average usage in 2020. While they rented a bike 7 times a month on average in 2019, they only rented a bike 4 times in 2020. This reduction might be due to the lockdown and the reduced overall mobility in 2020.

Therefore, the increased usage in 2020 is the result of a substantially larger trial rate than before. However, this positive effect is reduced by two main factors. First, only a fraction of these new users became long-term users. Second, even those who used the BSS frequently had a lower usage frequency compared to the previous year. The net effect of these two led to an overall 30% increase in BSS ridership.

Discussion

BSS is a clean, affordable, and healthy way of transportation within cities (Nocera and Attard, 2021). Encouraging commuters to use BSS can contribute to improved public health and reduced environmental pollution. The COVID-19 pandemic substantially increased interest in BSS (Nikitas et al., 2021) since this is a safe travel option as commuters minimize contacts with others. On the other hand, it is cheap and accessible for a much broader audience than a private car. Furthermore, in the case of Budapest, the fares of the BSS were reduced substantially, eliminating significant barriers to usage.

Our results show that BSS usage indeed increased substantially

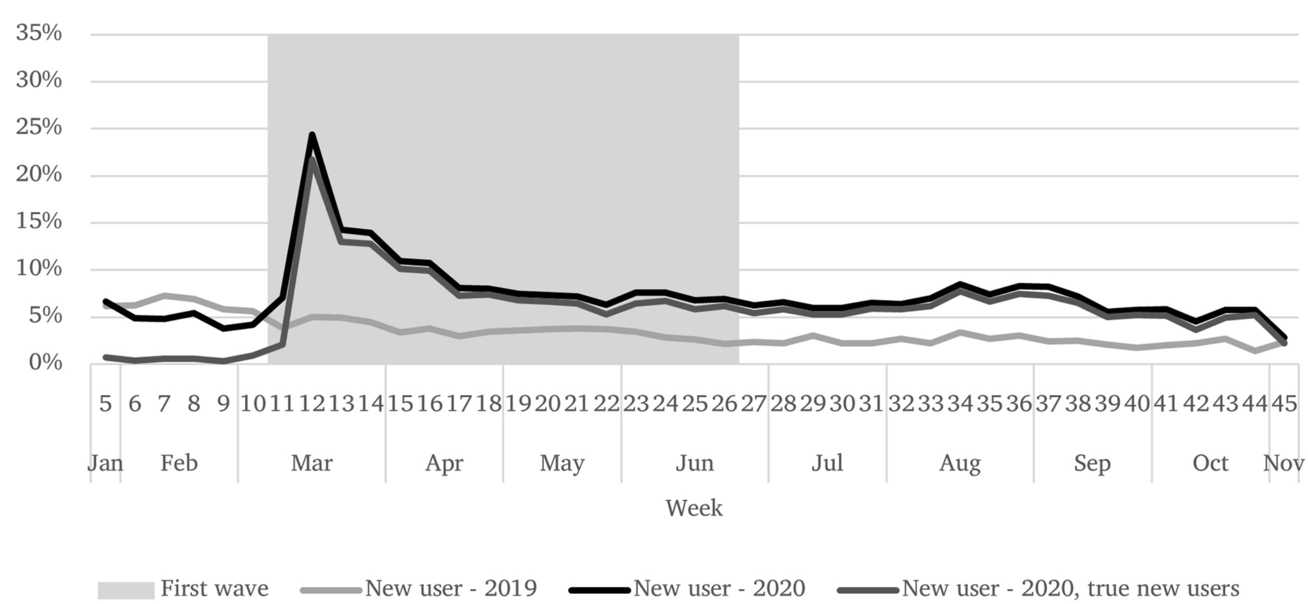

Fig. 4. Percentage of trips made by new BSS users, 2019–2020. *Notes:* Only pass holders are considered. A new user is defined as someone who did not use the BSS in the preceding four weeks. 'True new users' refers to those users who did not rent any bicycle in 2019.

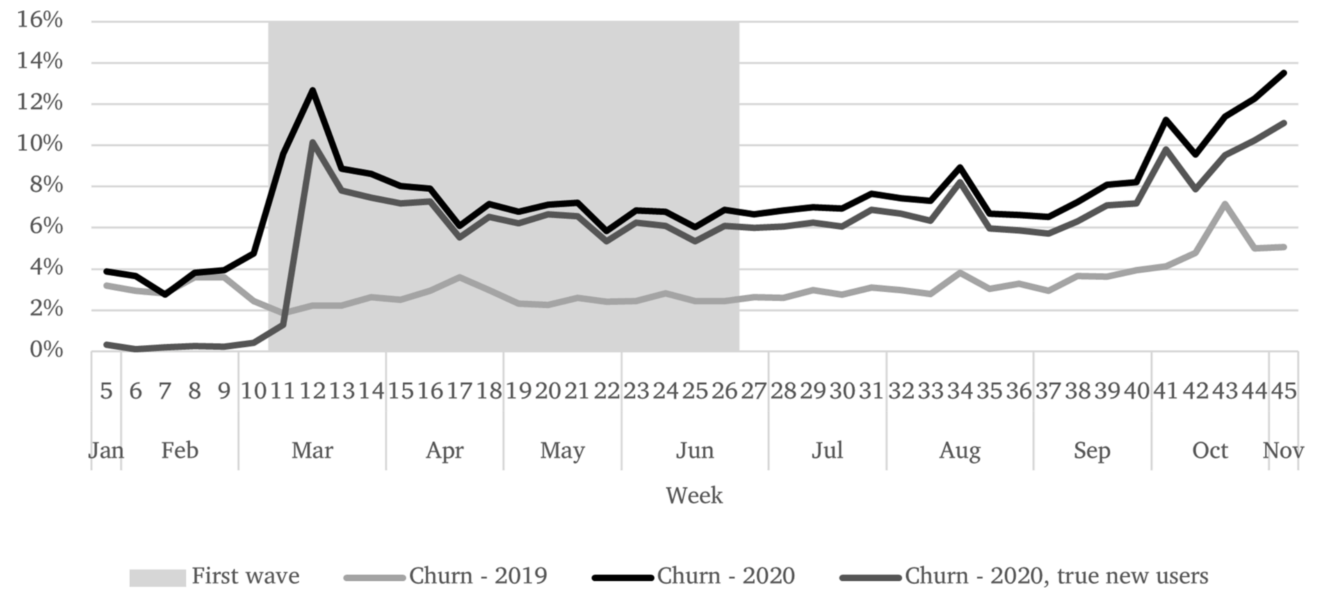

Fig. 5. Percentage of trips made by BSS users churned after the trip, 2019–2020. *Notes:* Only pass holders are considered. A churned user is defined as someone who did not use the BSS in the subsequent four weeks. 'True new users' refers to those users who did not rent any bicycle in 2019.

during the first wave of the pandemic. Song et al. (2022) found similar, but even larger effects in Singapore. Interestingly, evidence from London (Li et al., 2021a; Heydari et al., 2021), New York (Wang and Noland, 2021; Xin et al., 2022), Manhattan (Lei and Ozbay, 2021), and Zurich (Li et al., 2021b) showed a decline in BSS usage after lockdown measures were introduced. The differing trends can be attributed to the fact that two opposing forces are present: government restrictions increased while reduced overall mobility decreased BSS usage. The net effect of these two can cause BSS usage to increase in some cities but decline in others. This implies that local characteristics and preferences and the design of the given BSS can influence how its utilization changed during the pandemic. Furthermore, the impact might differ as the pandemic develops. Xin et al. (2022) pointed out that there was a constant change on how the pandemic impacted the BSS network in New York, hence, it is important to separately analyse the different periods of the pandemic.

Mobility on workdays is mainly associated with commuting to work. As found by Zhang et al. (2021), there is a shift, especially in Europe, in which some citizens replaced commuting previously made by public transport to bicycles due to fear of the pandemic. Based on our results, this can also be the case in Budapest as BSS usage increased significantly, while overall mobility declined.

Furthermore, a shift was observable within the BSS. Stations located in residential areas or close to parks gained users while stations close to universities, hospitals, entertainment facilities, and commercial areas lost users. This is a result of the restrictions and the spread of working from home, but also indicates that BSS was used for leisure purposes during workdays, too.

Between the first and second waves of the pandemic, workday usage slowly returned to its 2019 level, albeit it was still higher than a year ago. The system was able to attract more new users than in 2019, but the churn rate was also higher. Traffic climbed back to its pre-pandemic level during this period, and increased traffic was associated with increased BSS usage. However, lifting government restrictions led to a decrease in BSS usage. The results indicate that once life started to normalize, BSS usage tended toward its pre-pandemic level, although fares were not raised and were substantially below the prices in 2019. All these findings reveal that, unfortunately, BSS was not able to attract many long-term users.

The second wave of the pandemic started at the beginning of autumn. Infection cases soared, which led to a decline in mobility and increased BSS usage again. However, BSS usage is very seasonal, and as the peak period ends and colder weather starts, the number of BSS trips declines. In the off-peak period, even greater government stringency did not lead to an increase in BSS usage.

Weekend usage showed similar but more substantial effects. In general, weekend usage is connected to leisure and free-time activities (O'Brien et al., 2014; Maas et al., 2021). Due to the fast penetration of working from home during the first wave of the pandemic, citizens spent more time at home and may have desired to go out for a trip or to do some sports on weekends using the BSS. Considering that other free-time and sport activities were very limited due to the lockdown measures, the BSS became an attractive option for outdoor activities. Once mobility increased (i.e., citizens were less afraid of leaving their homes), BSS usage rose, further corroborating this idea. The increased BSS usage in residential areas and parks reinforces that it was used as a free-time activity. The large usage decrease in stations close to entertainment facilities indicate that before the pandemic BSS was frequently used in these places, but due to their mandatory closures, citizens did not visit these places anymore.

After the first wave was over, weekend usage started to decline, similar to workday usage. One cause could be that once more free-time opportunities (e.g., gyms, cinemas, theatres, hotels) became available again, citizens returned to these activities and did not use the BSS that often (or not at all) for leisure and sport purposes. Moreover, stations close to entertainment facilities and commercial areas were still not utilized that much as some of these places were still not open.

Interestingly, the average duration of BSS trips was not significantly altered by the government restrictions that is contrary to what Wang and Noland (2021) and Xin et al. (2022) found in New York, who observed an increase. Similar results were found by Heydari et al. (2021) for London.

The pandemic can be viewed as a natural experiment that led to a substantial increase in BSS usage. Several commuters tried out the BSS at least once. Regrettably, a sizeable portion of these new users were not converted into long-term users, and the overall usage frequency did not increase either. Furthermore, the elimination of the restrictions negatively affected BSS usage which means that commuters switched back from BSS to other transportation modes. This reveals a more general problem that BSS did not become part of people's everyday lives and travel routines. In the long term, this challenges the viability of these systems and reduces the positive health and environmental benefits that a BSS can deliver.

Policy implications

The results shed light on four important policy implications. First, BSS can be a valuable travel option during a pandemic that several citizens will likely use under severe government restrictions. This is primarily true in the peak period of the system. As similar pandemics may be more common in the future (Dodds, 2019; Ukuhor, 2021), improving BSS infrastructure can be a favourable mitigation tool. Since pandemics might lead to a temporal growth in demand, system operators should focus on increasing the flexibility of the BSS. This can be achieved, for example, by being able to set up pop-up stations or having an option to temporarily rent additional bikes. This policy recommendation is reinforced by the fact that contrary to motorized vehicles, BSS do not lead to additional greenhouse gas emissions; therefore, relying on BSS to reduce the spread of the pandemic is much more environmentally friendly than relying on private or shared cars.

Second, BSS stations located in residential areas and public parks were much more utilized than stations located in other areas of the city during the pandemic. The pop-up stations suggested above should be primarily placed in these locations. At the same time, stations located close to entertainment facilities, commercial areas, transport hubs, and universities experienced a relative decline. The BSS should be flexible enough to handle this in a relatively short amount of time. However, more research is needed to understand the connection of land use and BSS ridership during a pandemic.

Third, it is important to note that prices remained very low (€0.30/month) over the entire period; therefore, financial barriers likely did not play a substantial role in people's decision to use the BSS. This questions the view that prices play a major role in BSS usage (Goodman and Cheshire, 2014; Fishman, 2016; Lin et al., 2017). It must be recognized that prices that are too high can discourage ridership but reducing the price to near zero is not likely increase the number of long-term BSS users, especially not when the system is not providing a satisfactory experience. This can be a valuable insight in designing the pricing strategy of a BSS. However, a price reduction might make the BSS more affordable for low-income households. More research is needed for a deeper understanding of this topic.

Fourth, the pandemic or similar natural experiments can shed light on the weaknesses of such systems and can inform solutions. Understanding the determinants of BSS usage and satisfaction with the current system are essential to design a good performing system. Surveys are often implemented to collect the opinions of users (e.g., Castillo-Manzano and Sánchez-Braza, 2013; Molinillo et al., 2020), but it is difficult to understand the opinions of non-users. However, their involvement represents the potential growth of the system. A natural experiment, like the COVID-19 pandemic, can shed light on the preferences and motivations of a much broader set of potential users as several commuters tried out the system who would not have done otherwise. Their behaviour can provide valuable information regarding the growth potential of the system. In the case of the BSS in Budapest, the pandemic reinforced that the system has limited growth potential, as the majority of new users did not become long-term users and often churned after their first use. Interestingly, Heydari et al. (2021) found that BSS ridership returned to its pre-pandemic level in London, too, however, it was after a drop in usage, therefore, that can be viewed as a positive effect.

The system operator of the Budapest BSS was already aware of the problems (based on complaints received and surveys executed by itself) that are most likely the barriers to future development, namely, that the bicycles were difficult to ride because the bike frames were heavy and the tires were made from solid rubber. The pandemic made it clear that these problems need to be solved. As a consequence, the BSS was temporarily shut down in Budapest at the end of 2020, and a new system with new bikes was launched in April 2021. The renewed BSS can also encourage citizens to travel longer distances as less effort is needed to ride a bike. Other cities can follow this path and a better functioning BSS can be developed. This is essential for a cleaner and more bike-friendly future (Nikitas et al., 2021).

Conclusions

The COVID-19 outbreak and government lockdown measures impacted several, if not all, areas of life. BSS usage is not an exception. However, while stringency measures negatively affected the majority of the services, BSS is a counterexample. This paper investigates this phenomenon by separating the effects of changing mobility and the introduction of government restrictions.

The results indicate a sizeable increase in BSS ridership in line with more stringent government measures. A growth in BSS trip generation is observable both on workdays and weekends but for different reasons. Workday usage is primarily connected to commuting to work, while weekend usage is predominantly associated with leisure and sports. During the first wave of the pandemic, BSS usage was positively related to government measures and mobility, i.e., once more commuters entered the city, BSS became an inexpensive and available option to minimize social contact while travelling. Since BSS is more environmentally friendly than most other individual transportation modes, particularly private car or car sharing, this is also favourable from an environmental point of view.

On the other hand, after the first wave of the pandemic was over and government restrictions were partially lifted, BSS ridership declined. Generally, the results indicate that COVID-19 was not able to generate a permanent positive impact on BSS ridership, it only served as a contingency option during the most severe times of the pandemic.

The conclusions may differ across cities and BSS. The BSS in Budapest had several problems (e.g., heavy bike frames, solid rubber tires) that were known before the pandemic but were not seriously considered. More user-friendly bicycles, a dockless system, and installing electric bicycles may have been able to attract more long-term riders in a similar situation; however, the validation of this hypothesis requires future research.

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CRediT authorship contribution statement

Zombor Berezvai: Conceptualization, Funding acquisition, Data curation, Methodology, Formal analysis, Project administration, Software, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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