The link between bike sharing and subway use during the COVID-19 pandemic: The case-study of New York's Citi Bike

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ABSTRACT

The full societal impact COVID-19 pandemic is laid bare in urban mobility patterns. This research explored the recently published data on the operation of subway and bike share systems (BSS) during the COVID-19 outbreak in New York city, providing evidence on its impact over urban transport systems, but also on how its different components can work in conjunction. The BSS has proved to be more resilient than the subway system, with a less significant ridership drop (71% vs 90% ridership drop and 50% decrease on the ridership ratio) and an increase on its trips' average duration (from 13 min to 19 min per trip). Moreover, the study found evidence of a modal transfer from some subway users to the bike sharing system. The first effects of the free BSS programs aimed at essential service workers were also evaluated. BSS can improve the resilience of urban transport systems to disruptive events. Overall, this paper offers clues on how bike sharing, and cycling in general, can support the transition to a post-coronavirus society.

1. Introduction

The outbreak of COVID-19, for its severity and particularly for its global reach, has led to devastating impacts over the society, the economy and urban systems, creating scenarios never witnessed before. While to mitigate the immediate impacts, temporary, and often improvised, solutions are required, this situation can also provide the moment to rethink certain aspects of how cities operate, looking into a more sustainable operation as the threat of climate change prevails (Lenton et al., 2019). While high levels of public transport ridership are the pillar of an efficient transport system, alternative transport modes, such as the bicycle, are capable of working in conjunction (Villwock-Witte and van Grol, 2015). In a pandemic event, where the fear of overcrowding is exacerbated by the risk of contagion, the bicycle can serve as a lifeline to satisfy the mobility needs of urban residents. This paper focuses on the impact of COVID-19 on the transport system of New York City, a city chosen for its comprehensive subway and bike sharing systems, and where the impact of this pandemic was strongly felt.

The city of New York confirmed its first COVID-19 case on March 2nd (NYC Health, 2020). Just ten days after, on March 12th, the city declared a State of Emergency, implementing measures such as limiting occupation of spaces and allowing teleworking and flexible schedules among municipal workers (NYC Office of the Mayor, 2020). With the numbers of COVID-19 cases and fatalities mounting, the State of New York declared a Stay at Home Order on the 20th to curb the outbreak, ordering the closure of all non-essential businesses (New York State, 2020). Even with the Stay at Home Order in place, the number of COVID-19 cases continued to escalate throughout March, peaking over the first days of April with around 6,000 new daily cases (NYC Health, 2020). Due to the drastic curbs on the movement of New Yorkers and the need for social distancing, the impact on the necessities for transport was inevitable. Facing reduced demand, combined with a surge of COVID-19 among its workforce, New York's Metropolitan Transit Authority applied on March 25th an "Essential Service Plan" cutting capacity throughout the network, particularly on express lines and non-rush hour services (MTA, 2020). At the same day, a special program was unveiled featuring free trips on the city's bike sharing system (called Citi Bike) for 30 days for first responder, healthcare, and transit workforce (Citi Bike, 2020b). Entitled Citi Bike Critical Workforce Membership Program, this program was specially designed to provide healthcare workers with a safe mode of transport (Citi Bike, 2020b). This timeline of events (Fig. 1) reinforces the need to study the impacts of COVID-19 and inherent policy responses over the city's transport system, which this study proposes to accomplish.

After a brief revision of the existing studies on the impact of disease outbreaks on transport systems as well as the relationship between bike sharing systems (BSS) and public transport (PT), this paper presents the impacts of the coronavirus pandemic event on the use patterns of the subway and BSS of New York City, while attempting to establish a link between the systems through statistical analysis.

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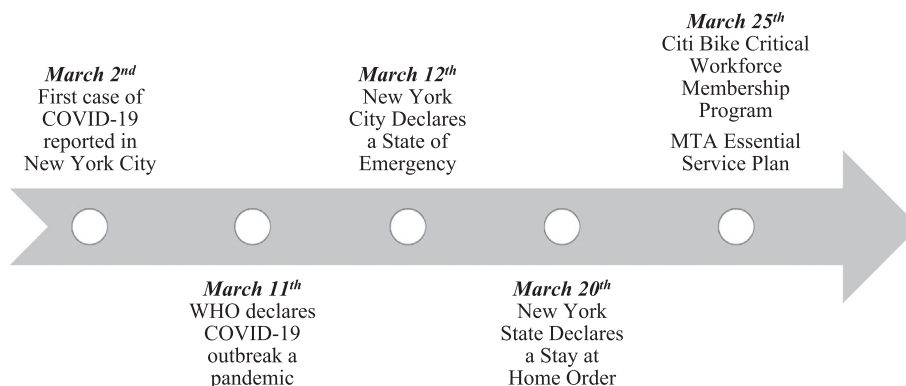
Fig. 1. Timeline of the policy responses to COVID-19 throughout March 2020.

2. Literature review

Infectious respiratory diseases such as coronaviruses and influenza type viruses are transmitted from person to person via three modes (droplet, aerosol and contact) either through direct skin-to-skin contact or indirectly through contaminated surfaces (Garner, 1996). As the main route of infection is via respiratory droplets of coughs and sneezes (Salgado et al., 2002; Weinstein et al., 2003; CDC, 2005), the physical proximity between non-infected and infected individuals poses the greatest risk.

While social distancing, either through quarantining or isolation is the most effective strategy in keeping such spread (Ferguson et al., 2006; Germann et al., 2006), for many the maintenance of an active role in the economy means keeping mobile.

Due to high occupation density and enclosed spaces, public transport (PT) provides prime conditions for person-to-person transmission, presumably much higher than other transport modes. This danger is exacerbated by the coronavirus' ability to remain active on surfaces like plastics and metals for a period of several hours (Taylor et al., 2020). Rail transport, for instance, took a key role in accelerating the spread of influenza to new areas in the 1918 A(H1N1) pandemic (Palmer et al., 2007). While studies have addressed air travel (Grais et al., 2004; Brownstein et al., 2006; Epstein et al., 2007), intercity bus (Piso et al., 2011) and rail (Cui et al., 2011; Zhang et al., 2011), few studies have incorporated the effect of proximity in urban public transport.

Ohkusa and Sugawara (2007) and Yasuda et al. (2008) presented different modelling approaches for a hypothetical spread of influenza which included the effect of mass transportation in the metropolitan area of Tokyo. Both studies concluded that public transport has a considerable impact in the geographic spread of the infection. Cooley et al. (2011), on the other hand, stated that transmission with New York's subway system would only account for a small percentage of the total number of infections, placing subway commuting at a level comparable to working. While being hypothetical models, these diverging opinions justify the need for a deeper study.

As it is unfeasible to detect pre-symptomatic or even asymptomatic passengers and prevent them from travelling, the longer the perception of the risk the slower the return of ridership to average values. While literature is scarce on the matter, an example from Taiwan during the 2003 SARS outbreak (Wang, 2014) demonstrated a quick and significant drop in ridership, which was only restored after a long and gradual increase in public confidence. This reinforces the emergency in increasing the attractiveness of other transport modes as suitable alternatives to satisfy the quintessential mobility needs of the population.

Cycling can be such an alternative mode of transport as it can be compatible with social distancing. Although literature exploring the role of cycling in previous epidemics is rare, it is recognized that one of the factors leading to the rise of e-bikes in China was the 2002–2004 SARS outbreak as people tried to avoid overcrowded PT services (Weinert et al., 2007; Simha, 2016).

One of the most popular policies currently promoting cycling is the implementation of bike sharing systems (BSS). Usually found in dense urban areas, BSS allow the short-term renting of bicycles either at stations (docked bike sharing) or within operational areas (*dockless* bike sharing), enabling low cost point-to-point trips (Demaio, 2009; Shaheen et al., 2010; Fishman, 2016; Si et al., 2019). These systems have witnessed a remarkable growth with nearly 2000 systems currently in operation (Nikitas, 2019) concentrated in China, Europe and North America (Shaheen et al., 2010; Fishman, 2016). BSS have the potential to improve urban transport systems by providing an additional mode of transport, therefore increasing accessibility by improving multi and inter modality opportunities (Ricci, 2015).

Among the most studied effects of BSS is their relationship with public transport, as bike sharing can either complement or compete with PT systems (Martin and Shaheen, 2014; Ricci, 2015). Bike sharing has been found to increase PT ridership by acting as a first and last mile connector (Martin and Shaheen, 2014; Ricci, 2015). For instance, Ma et al. (2015), by using Origin-Destination data of BSS trips, found that six of the seven BSS stations with higher usage rates were close to subway stations. Furthermore, through an OLS regression analysis, Ma et al. (2015) estimated that for each 10% increase on BSS trips, a 2.8% increase on subway ridership would occur. Likewise, Noland et al. (2016), by deploying a series of trip generation models, found that Citi Bike's (New York City's BSS) stations located near busy subway stations were among the stations with higher usage rates (Noland et al., 2016). However, BSS can also compete with PT as it can be a faster and cheaper alternative to often overcrowded PT services (Martin and Shaheen, 2014; Campbell and Brakewood, 2017). Evidence on this competition is corroborated by Campbell and Brakewood (2017) in New York City, using daily route-level bus and Citi Bike's ridership data, and comparing bus routes having Citi Bike's stations in their trajectories with bus routes without them. The study revealed decreases in bus ridership in routes with Citi Bike's stations in their vicinities. Specifically, for every thousand Citi Bike's docks along a bus route, a 2.42% decrease in daily unlinked bus trips was observed (Campbell and Brakewood, 2017).

BSS systems can also increase the resilience of the transport system, i.e., the ability to maintain its function of moving people and goods in response to external impacts, such as a major disruption (Mattsson and Jenelius, 2015). The most common transport modes rely on vast expanses of infrastructure, usually rigid in its physical configuration and requiring large monetary investments for retrofitting or upgrade. The bicycle, however, is highly versatile, as it can be accommodated on a small percentage of the existing road network, usually dominated by the car, on pedestrian streets and other leisure-purpose footways. Indeed, such versatility of the bicycle can be illustrated in the current examples of pop-up bike lanes and other tactical urbanism initiatives based on the open streets movement that have intensified as a response to the coronavirus (The Guardian, 2020b). Bike sharing systems can benefit greatly from this reallocation of street space (Marshall et al., 2016) especially as it solves one of the reasons often stated for not using bicycle, i.e. the lack of "safe" infrastructure (Fishman, 2016). Furthermore, the BSS themselves are highly flexible in

comparison with traditional modes of transport, as illustrated with the recent deployments of new BSS stations near hospitals to provide healthcare workers with a transport alternative (NYC DOT, 2020). This synergy can already be seen in previous studies analysing the impact of PT strikes on BSS such as the one from Saberi et al. (2018). The authors collected data from more than 1 million BSS trips to measure the impact of a subway strike on the mobility patterns of London's BSS in 2015 analysing the impacts before, during, and after the disruption. The results showed that the subway strike led to an 85% increase in the number of BSS trips and to an 88% increase on the trips' duration from an average of 23 to 43 min (Saberi et al., 2018).

Thus, with PT ridership plummeting as people try to avoid overcrowded spaces due to the coronavirus pandemic, bike sharing can position itself as a sustainable (Zheng et al., 2019), healthy (Otero et al., 2018) and competitive alternative (Faghih-Imani et al., 2017) both to PT and to car use.

3. Data and methods

3.1. Transport system

Citi Bike, New York City's BSS, was launched in May 2013 and has been continuously expanding every year. With more than 150,000 active annual members and an average of more than one million trips per month, Citi Bike is the largest bike sharing system in operation in the USA. Currently it has 14,500 bicycles available at 890 stations concentrated in Manhattan, Brooklyn, Queens and Jersey City (Citi Bike, 2020a, 2020c). Citi Bike has an open data policy, publishing disaggregated trip history for each station. The available data includes the start and end time of each trip and stations used (start and end). Furthermore, it also contains user information, including the type of user divided between annual members and casual users (24-hour or 3-day pass users), their gender and year of birth. Mostly located within New York city, this system was expanded to New Jersey in 2016, albeit with a limited number of docking stations (50 stations). Given this area's physical disconnection and absence of subway stations, the New Jersey portion of Citi Bike was excluded from this study.

The New York subway, operating since 1904, is one of the world's oldest public transport systems. Serving 472 stations and operating 24 h a day, this system boosts an average weekday ridership of 5.5 million trips, making it the most heavily used public transport system in the United States. Its relevance as the backbone of this bustling metropolis is particularly evident within the borough of Manhattan, where 35% of the trips made by its 1.6 million residents rely on this rail infrastructure (NYC, 2010). The subway database only provides information on the accumulated number of entrances and exits, per station, for each four-hour interval. As the focus was on the evaluation of the potential of BSS to replace subway usage during a pandemic event only daily entrances were evaluated. Fig. 2 presents the distribution of City Bike and subway stations in New York City.

3.2. Modelling approach

Ridership data for the subway and BSS was retrieved for the months of February and March in 2019 and 2020 using publicly available databases.[1] Data on the number of COVID-19 cases was downloaded from New York City's government online database (NYC Health, 2020). Outliers trips with inconsistent travel durations (<1 min and >6 h) were excluded from the assessment.

The impact of COVID-19 on the two transport systems was evaluated through a combination of statistical and GIS methods. Descriptive statistics as well as Mann-Whitney U tests and Ordinary Least Square (OLS) regressions were employed in this study. The Mann-Whitney U test looks for

differences between two independent groups by using ranks and is a non-parametric alternative to the independent t-test when the dependent variable is either ordinal or continuous but not normally distributed (Field, 2013a). Ordinary Least Square (OLS) regression is used to analyse the relationship between a dependent variable and one or more independent variables by minimizing the sum of squared residuals (difference between the observed and predicted values) of the dependent variable shaped as a straight line (linear relationship) (Field, 2013b). The motivation for the regression modelling was not so much to generate a predictive application, as numerous exogenous factors are at play, but rather to evaluate the significance and influence of COVID-19 on the behaviour of the two transport systems. The statistical analyses were conducted on IBM SPSS Statistics. Finally, a network subset was included featuring only the subway and City Bike stations located within 0.25 miles (402 m) catchment area of the former. This was calculated using ArcGIS's Network Analyst extension, as it provides a greater reliability when compared with the creation of simple buffers centred on each subway station. This includes 196 subway (42% of the total) and 532 BSS stations (60%). The generated catchment areas of the subway are represented in Fig. 2.

We began by employing a time series analysis to examine the two systems' daily ridership variation throughout the month of March 2020, and in the BSS case also the average daily trip duration. Based on the patterns emerging from that analysis, more in-depth analyses were conducted.

First, the COVID-19 impact on the average daily trip duration of Citi Bike's trips was evaluated by conducting a Mann-Whitney U test aimed at investigating possible differences between March 2020 and control months (February 2020 and March 2019) as well as through an OLS regression aimed at exploring its relationship with the number of COVID-19 cases.

Second, the competitiveness and possible modal transfers from the subway to Citi Bike were studied by developing a ridership ratio of the subway daily ridership and the Citi Bike daily ridership (Eq. (1)).

$$Daily\ ridership\ ratio = \frac{Subway\ daily\ ridership}{Citi\ Bike\ daily\ ridership} \tag{1}$$

The ridership ratio data was applied to two groups: inside and outside the subway catchment area (Fig. 2). A Mann-Whitney U test was then conducted to evaluate if the ridership ratio inside and outside the catchment areas of subway stations was statistically different in March 2020 and to compare such results with the control months of February 2020 and March 2019. We hypothesized that a modal transfer from the subway to the BSS would lead to a different behaviour of the ridership ratio between the two groups (inside and outside the subway catchment area). Hence, statistically significant differences would be perceptible between the two groups in March 2020 (impacted by the coronavirus) but not in the control months (reflecting the normal operation). Lastly, three OLS regressions were created to analyse the influence of COVID-19 on the ridership ratio of the two systems (entire system, inside, and outside catchment areas).

Finally, the impact of the Critical Workforce Membership Program was also evaluated. For each BSS station the ratio between average daily ridership and average trip duration for a period of five working days before (March 18th to 24th) and after (March 25th to 31st) the implementation of the program were compared with the distance to the nearest hospital. These distances were, once again, calculated with ArcGIS Network Analyst. This method would, therefore, analyse if the stations closer to these facilities would experience an increase in ridership or host longer trips.

4. Results

4.1. Variation of the subway and Citi Bike ridership

During the first week of March, the impact on daily lives of New Yorkers was practically inexistent, as the average subway ridership values demonstrate (Fig. 3 top graph). It was only by March 9th that the impact of COVID-19 started to become noticeable, with an immediate 12% decrease comparing with the average (Fig. 3 top graph), a trend that intensified

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[1] The Citi Bike system data, provided by its operator NYC Bike Share, LLC, Jersey City Bike Share and Motivate International, Inc., was downloaded from https://www.citibikenyc.com/system-data.
New York subway ridership data was provided by MTA and downloaded from http://web.mta.info/developers/turnstile.html.

Fig. 2. Location of City Bike and Subway stations within the city of New York.

gradually over the following days, as safety concerns started weighing on the collective conscience. At the end of March, the system had an average of 500,000 daily trips, which comparatively to the average of almost 5.5 million trips of the beginning of the month translates to a ridership reduction of 90%.

In comparison, Citi Bike's daily ridership actually increased on the day the subway ridership started to fall, with a 33% rise comparatively

to the previous week (Fig. 3 bottom graph). Between the 9th and the 11th of March, the system had the highest daily ridership of the month with more than 60,000 trips per day. However, the pandemic impact on Citi Bike started to be felt with the declaration of the State of Emergency on March 12th, with its ridership starting to significantly decrease. This tendency continued throughout March, reaching an average of 15,000 trips by the end of the month,
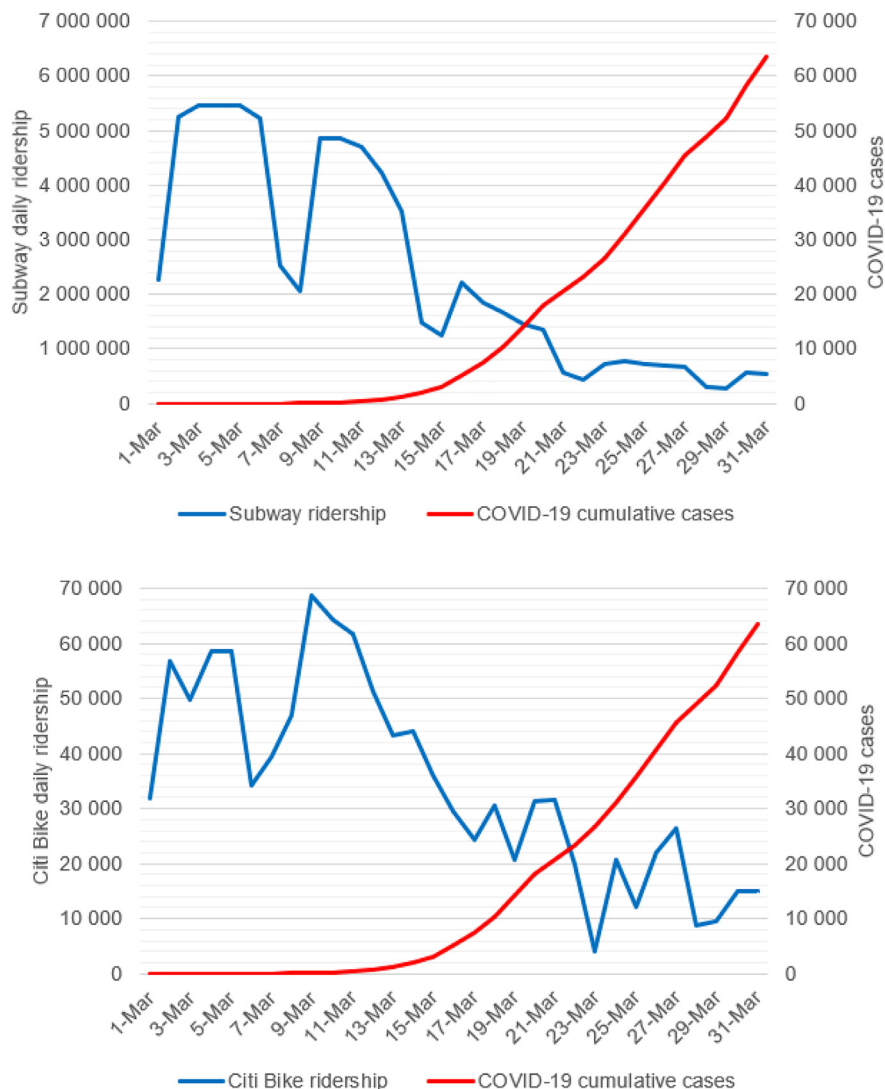
Fig. 3. Variation on subway (top) and Citi Bike (bottom) daily ridership versus the increase on the number of COVID-19 cases throughout March 2020.

translating into a 71% reduction comparatively to the levels observed early in the month.

A week by week comparison of the daily ridership on the workdays of the two systems provides additional insights on the COVID-19 impact (Table 1).

In the second week of March (9th to 13th), subway daily ridership fell by 18%, whereas Citi Bike increased by 12% comparatively to the first week of March (2nd to 6th). The State of Emergency declared on the 12th (a Thursday) while impacting the ridership in the second week is much more noticeable on the following week (16th to 20th). Hence, in the third week of the month the subway ridership fell by 68% comparatively to the month's first week and by 61% comparatively to the week before, whereas the BSS fell by 47% and 53%, respectively. As the Stay at Home order was

implemented on a Friday (20th), its impact was fully felt in the fourth week (23rd to 27th). During this week, the subway and BSS ridership dropped 58% and 38%, respectively, comparing to the third week, with a global decrease of 87% and 67% comparing with the beginning of the month. The ridership drop starts to stabilize towards the final days of March (30−31) with a 25% and 12% drop on the subway and BSS ridership, respectively, thus reaching an astonishing total ridership drop of 90% for the subway and 71% for the BSS in comparison with the beginning of the month.

4.2. Variation on Citi Bike's trips average duration

The duration Citi Bike's trips were aggregated by day to assess its variation throughout the month of March 2020. Fig. 4 represents this variation and compares with the reported number of daily new COVID-19 cases (top graph) and its daily ridership (bottom graph).

The data reveals a continued growth on the average trip duration, from a 13-minute daily average at the beginning of March to a 19-minute average by the end of the month, translating into a 44% increase. To determine if and how this increase on the trip's duration is related to the coronavirus pandemic, the daily trip duration of March of 2020 was compared with the ones on the months of February 2020 and March 2019. As BSS usage may differ between weekends and workdays (weekend usage associated to leisure activities while workdays to commuting), the analysis also

Table 1
Week by week comparison (workdays) of the ridership (percentage change) in the BSS and subway systems throughout March 2020.

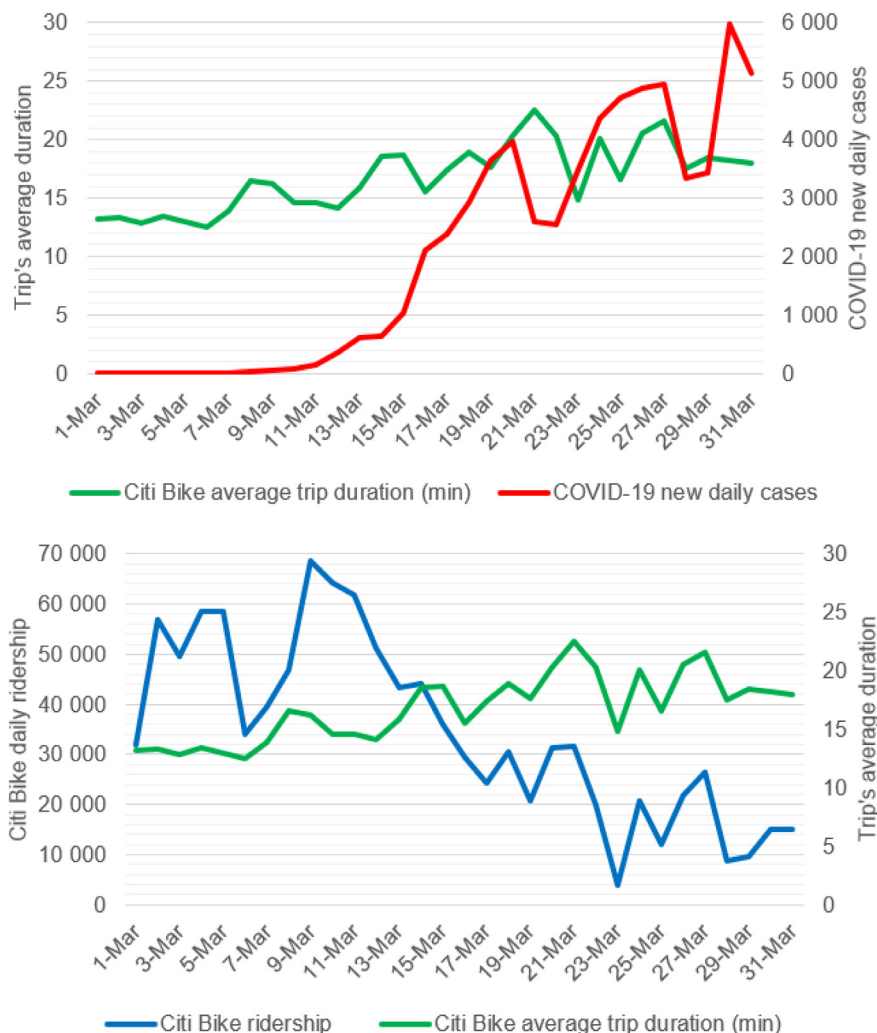| Weeks of March 2020	Change (%) vs 1st week		Change (%) vs previous week	
	Subway	BSS	Subway	BSS
2nd week (9th to 13th)	−18%	12%	−18%	12%
3rd week (16th to 20th)	−68%	−47%	−61%	−53%
4th week (23rd to 27th)	−87%	−67%	−58%	−38%
5th week (30th to 31st)	−90%	−71%	−25%	−12%

Fig. 4. Variation on Citi Bike average daily trip duration (minutes) versus the increase on the number of COVID-19 new daily cases (top graph) and its daily ridership throughout March 2020 (bottom graph).

compared the different months considering only workdays. The descriptive statistics of these months is represented in Table 2.

Trips in March 2020 had an average daily duration above 16 min, whereas the other two months the trip's duration was closer to 12 min. This increase was most noticeable on the maximum daily average. The monthly percentage change is presented in Table 3. While in the process of testing for possible statistical significance differences between the months, as the data did not follow a normal distribution,[2] the non-parametric Mann Whitney U test was applied. The rationality for such test was that if the COVID-19 was impacting the duration of Citi Bike's trips, the average daily trip duration in March 2020 would be statistical significantly different from the control months and there would not be a statistical difference when comparing between the two control months. The results of this statistical test and the associated statistical difference are also shown in Table 3.

The results uncover important differences between the month of March 2020 and the other two months. The average daily duration of Citi Bike's trips in March 2020 registered a 39% increase comparatively to February 2020 and a 34% increase comparing to March 2019 and is slightly more pronounced during the workdays. As expected, the differences between the control months (February 2020 and March 2019) were residual with a slightly decrease that can be explained by February having typically

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[2] The Shapiro-Wilk test was not significant for the months of March 2020 and 2019 but was significant for February 2020.

Table 2

Descriptive statistics of the average daily duration of Citi Bike's trips (minutes) in March 2020, February 2020 and March 2019.

Comparison between months		N	Daily Mean	Daily Median	Std. Deviation	Minimum daily Av.	Maximum daily Av.
March 2020	All days	31	16.8	16.5	2.8	12.5	22.5
	Workdays	22	16.4	16.1	2.8	12.5	21.6
February 2020	All days	29	12.0	11.7	1.1	10.8	15.6
	Workdays	19	11.5	11.4	0.6	10.8	13.1
March 2019	All days	31	12.5	12.2	1.6	10.2	17.6
	Workdays	21	11.9	12.0	0.8	10.2	13.6

Table 3

Variation in the monthly average daily duration of Citi Bike's trips as well as the results of the Mann-Whitney U test and associated significance.

Comparison between months		Change (%)	Mann-Whitney U test		Differences Significant at $p < .05$ (test)
			U	Z	
March 2020 vs February 2020	All days	39%	35	−6.132	Yes
	Workdays	42%	5	−5.333	Yes
March 2020 vs March 2019	All days	34%	74	−5.723	Yes
	Workdays	38%	10	−5.370	Yes
February 2020 vs March 2019	All days	−4%	356	−1.383	No
	Workdays	−3%	143	−1.530	No

Table 4

Regression model results with the average daily duration of Citi Bike's trips as the dependent variable and the daily number of new COVID-19 cases as the independent variable.

	Coef.	Std. Error	Significance	95% CI
Constant	2.519	0.045	*p* < .001	[2.426; 2.611]
Ln (COVID-19 cases)	0.049	0.007	*p* < .001	[0.035; 0.062]
Adj. R²	0.637		*Durbin-Watson*	1.900
N	30		*VIF*	1.000

worse weather conditions than March, with negative effects on cycling usage (Eren and Uz, 2020). These differences are reinforced by the Mann Whitney U test results which revealed statistically significant differences between March 2020 and February 2020 as well as March 2019, even when only considering workdays, but not between the control months (February 2020 versus March 2019).

The increase on the trips' daily duration of Citi Bike was further explored by conducting an Ordinary Least Square (OLS) regression, with the daily number of new COVID-19 cases used as an independent variable. By transforming the data using the natural logarithm the coefficients can be interpreted as percentage changes. Temperature fluctuations throughout March were also controlled, but that influence was not significant (presenting a R^2 of 0) and as such was not included in the final model. Table 4 presents the results of the regression, including the coefficients and standard error, their level of significance and confidence intervals (CI).

The model explains roughly 64% of the total variance within the available data. The number of daily new COVID-19 cases was found to be statistically significant at the 99% confidence level, positively influencing the average daily duration of Citi Bike's trips. As such, a 10% increase in the number of daily new COVID-19 cases is associated to a 0.49% (CI 0.35 to 0.62%) increase on the average daily duration of the Citi Bike's trips. It is important to stress that while seemingly low, this value is explained by the exponential nature of the evolution curve of COVID-19 cases.

4.3. Resilience of Citi Bike versus the subway

The daily variation of the ridership ratio between the subway and Citi bike (a proxy for assessing the relationship between the two systems) throughout March 2020 is represented in Fig. 5.

The graph reveals that the ridership ratio between the subway and Citi Bike suffers a 50% drop throughout the month of March.[3] Furthermore, the ridership ratio inside the subway's catchment areas tend to be smaller than outside, indicating a possible relationship between the two systems. Indeed, inside the subway's catchment areas there was a 60% decrease between the beginning and the end of March, whereas outside the catchment areas that percentage decreases to just 30%. This possible relationship between the subway system and Citi Bike is further examined by two distinct analyses.

Firstly, possible statistical differences between the ridership ratio within the subway catchment areas (Group 1) and the ridership ratio outside (Group 2) in March 2020 were assessed by conducting a Mann-Whitney *U* test.[4] These same groups were then tested for the control months of February 2020 and March 2019.[5] The results are presented in Table 5.

As hypothesized, the results reveal for the month of March 2020 a statistically significant difference in the ridership ratios between the two groups. This is further reinforced by the lack of statistical significance for the control months of February 2020 and March 2019. Thus, the evidence indicates that a different relationship between the two systems is occurring

during the month of March 2020, with the coronavirus pandemic being the most likely cause.

The influence of COVID-19 on the ridership of the two systems is further assessed through Ordinary Least Square (OLS) regressions. The number of daily new COVID-19 cases was considered as an independent variable, and the dependent variable results were transformed to the natural logarithm to ensure a normal distribution.[6] Three models were then developed:

- Model 1 considered the whole Citi Bike system versus the whole subway system with the objective of assessing the resilience of Citi Bike against the subway by analysing the variation of the ridership ratio;
- Model 2 focused on the ridership ratio inside the subway's catchment areas (Fig. 2);
- Model 3 focused on the ridership ratio outside the subway's catchment areas. The purpose of these two models was to assess possible differences on the significance and effect size on each model which could indicate possible modal transfers.

The evaluation focused on the statistical significance and direction of the estimated coefficients as well the total variance explained in each model to understand the effect of COVID-19 on the use patterns of the two transport systems. The results for the three models are presented in Table 6.

Firstly, the number of new daily COVID-19 cases is statistically significant in all three models and has a negative effect on the ridership ratio between the subway and Citi Bike. This indicates that as the number of new daily COVID-19 cases increases, the ridership difference between the subway and Citi Bike decreases. As such, the bike sharing system seems to be more resilient than the subway regarding the loss of ridership.

Secondly, the comparison between Model 2 (ridership ratio within the subway's catchment area) and Model 3 (outside the catchment area) indicates a stronger association within the subway's catchment areas illustrated in the total variance explained as well as on the statistical significance and value of the regression coefficient. Indeed, the effect of COVID-19 is most influential in Model 2, in which a 10% increase on the number of new daily COVID-19 cases is associated with a 1.47% (CI 0.79 to 2.15%) decrease on the ridership ratio at a 99% confidence level. Whereas in Model 3 the effect in much less significant with a 0.73% decrease (CI 0.08 to 1.38%) at a 95% confidence level. Thus, the results seem to suggest a possible modal transfer from some subway users to the bike sharing system.

4.4. Impact of the critical workforce membership program

This programme, launched at the same day as MTA's Essential Service, was destined to the city's critical workforce, particularly healthcare and transit workers, and featured free trips for a month and increased disinfection of the bicycles and stations. While some BSS stations near hospitals have indeed increased its ridership after this event, the analysis over the entire system points to these being mere isolated events. Statistical analyses performed to this dataset demonstrate that the distance of BSS stations to the closest hospital does not appear to have any noticeable effect on average daily ridership or trip duration (R^2 of 0). The analysis of geographic patterns reiterate this fact, as by considering a catchment area of 0.25 miles from each hospital, which includes the 61 stations most likely to be used by healthcare workers, the average ridership increases in only 21 of them (Fig. 6), while average trip duration increases in 38 stations. Hence, on its first week of implementation, this programme has not led to a noticeable adoption of Citi Bike by New York's healthcare workers.

5. Discussion

This analysis has shown the severe impact of the coronavirus pandemic on New York city with an unprecedented ridership drop (90%) in one of the most iconic subway systems in the world. Likewise, the city's bike sharing system also followed the same fate with a 71% ridership decrease

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[3] The spike on March 23rd may be a result of a malfunction of the reporting system of Citi Bike as no significant variations were identified in the subsequent days or in the subway data.

[4] Shapiro-Wilk test was significant thus rejecting the hypothesis of normal distribution.

[5] Even though Citi Bike in March 2019 had 121 less stations than in 2020, the proportion of stations inside and outside the subway's catchment area was the same (60%).

[6] With the log transformation the Shapiro-Wilk test revealed to be not significant.
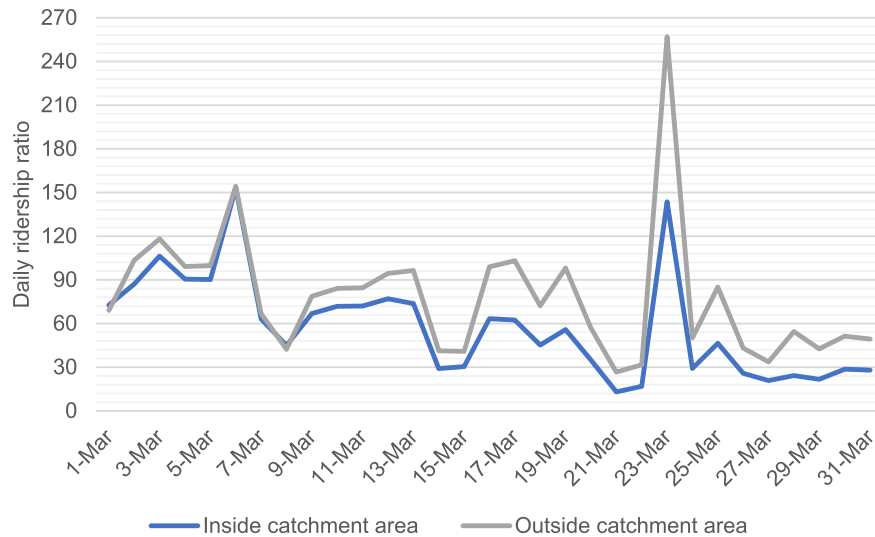
Fig. 5. Variation on the ridership ratio throughout March 2020 inside and outside the subway's catchment area.

comparing to the days prior to the coronavirus appearance. Still, this study provided evidence on the role that bike sharing systems, and cycling in general, can play in ameliorating the effects of this pandemic and, more importantly, in the post-coronavirus transition.

Firstly, the results clearly show the resilience of City Bike over the subway system. Despite the considerable drop in the city's BSS ridership, it was still smaller than the subway system (71% versus 90%). This is supported by the ridership ratio between the subway and Citi Bike decreasing by 50% between the beginning and the end of the month. Similarly, in a week-by-week analysis, Citi Bike's ridership reduction was always less significant than that of the subway system.

Secondly, the comparison between the ridership ratios inside and outside the subway's catchment areas in March 2020 was statistically different, suggesting a distinct behaviour of the two systems, as opposed to the control months of February 2020 and March 2019. Moreover, the regression results revealed a statistically significant negative effect of COVID-19 cases on the ridership ratios, which was significantly more pronounced inside the subway's catchment area, suggesting possible modal transfers from the subway to the bike sharing system. The literature has already shown that during disruptive events, such as transit workers' strikes, bike sharing systems can be a substitute to public transport, including subway systems (Saberi et al., 2018), and this also seems to be the case during the coronavirus pandemic.

This study also determined the existence of a statistically significant increase on the average duration of City Bike's trips, which was positively correlated with the number of daily new COVID-19 cases. Such increases were likewise observed during subway strikes (Saberi et al., 2018) and may, again, indicate a modal transfer especially as such increases were confirmed even when only considering workdays. Still, these assumptions must be taken lightly, as the enforcement of confinement measures has a dramatic impact on commuting needs, as opposed to a strike of limited duration where normal mobility needs must still be satisfied.

The adoption of temporary measures, such as the Critical Workforce Membership Program, while barely scratching the surface towards the intended modal shifts, as the results demonstrate, is still defended by the authors for its key social role. Further conclusions on the impact of such programs cannot be yet drawn as the current available data is still scarce. Additional data, either from a longer period, or from other cities implementing similar programs (TfL, 2020), could provide better insights on the impact of such policies.

6. Conclusion

This exploratory research studied the data that started to emerge from the impact of coronavirus in the world's urban transport systems and provided evidence on the importance of bike sharing systems during disruptive events.

While both systems saw their ridership plummeting, Citi Bike proved to be more resilient than the subway system, with a less significant ridership drop and an increase on its trips' average duration. Furthermore, the study found compelling evidence of a possible modal transfer from some subway users to the bike sharing system.

Table 5
Results of the Mann-Whitney U test and associated significance. Group 1: ridership ratio inside the subway's catchment area; Group 2: ridership ratio outside the subway's catchment area.

Month	Comparison	Mann-Whitney U test		Differences significant at $p < .05$ (test)
		U	Z	
March 2020 (N = 31)	Group 1 vs Group 2	295	−2.292	Yes
February 2020 (N = 29)	Group 1 vs Group 2	377	−0.676	No
March 2019 (N = 31)	Group 1 vs Group 2	420	−0.852	No

Table 6
Regression model results with the ridership ratio as the dependent variable and the daily number of new COVID-19 cases as the independent variable. Model 1: ridership ratio of the whole system; Model 2: ridership ratio inside the subway's catchment area; Model 3: ridership ratio outside the subway's catchment area.

|	Coef.	Std. Error	Significance	95% CI
Model 1				
Constant	4.706	0.212	$p < .001$	[4.271; 5.141]
Ln (COVID-19 cases)	−0.114	0.032	$p = .001$	[−0.179; −0.048]
Adj. R²	0.288		*Durbin-Watson*	1.954
N	30		*VIF*	1.000
Model 2				
Constant	4.753	0.220	$p < .001$	[4.301; 5.204]
Ln (COVID-19 cases)	−0.147	0.033	$p < .001$	[−0.215; −0.079]
Adj. R²	0.393		*Durbin-Watson*	1.867
N	30		*VIF*	1.000
Model 3				
Constant	4.678	0.211	$p < .001$	[4.246; 5.110]
Ln (COVID-19 cases)	−0.073	0.032	$p = .029$	[−0.138; −0.008]
Adj. R²	0.130		*Durbin-Watson*	2.005
N	30		*VIF*	1.000
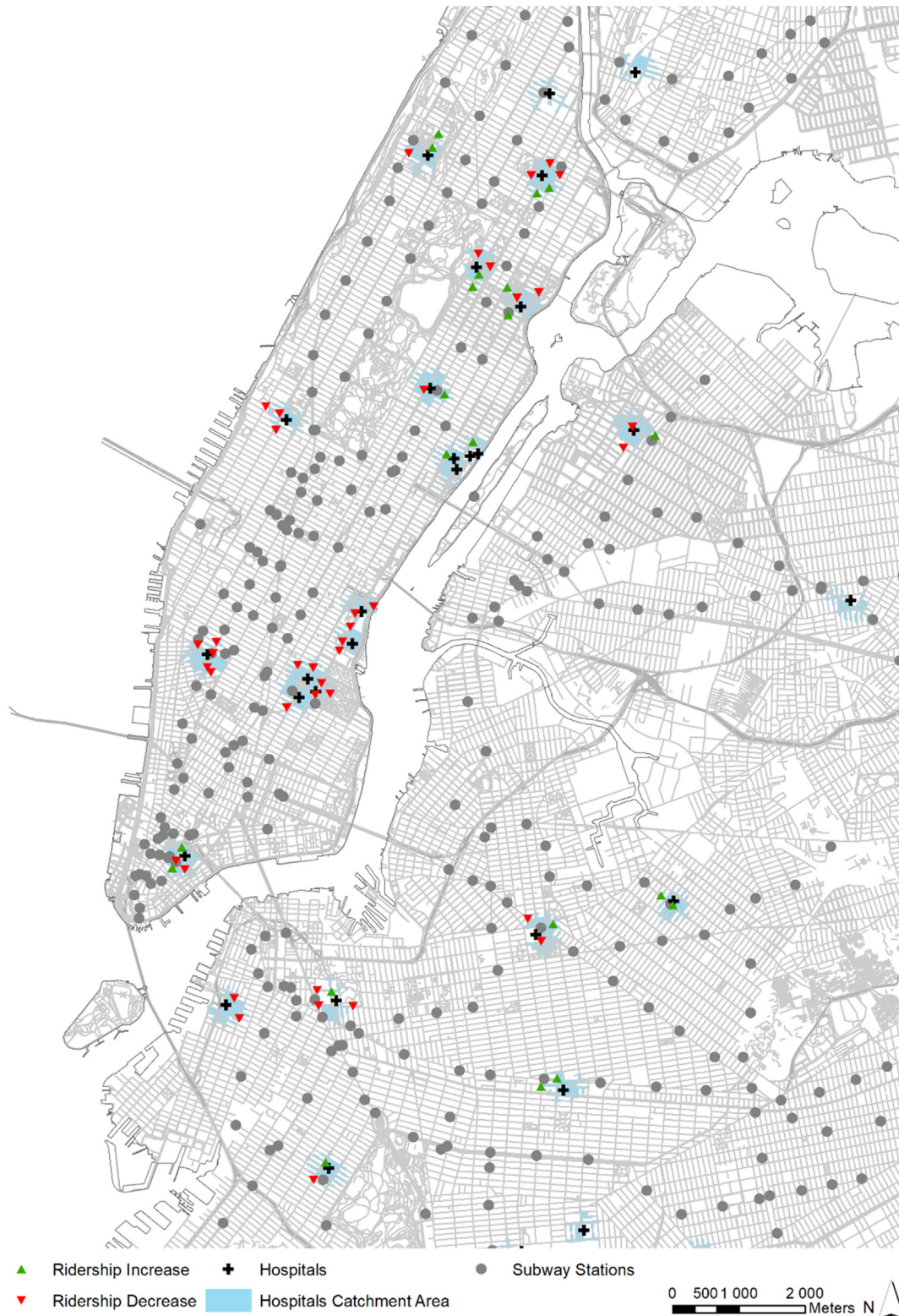
Fig. 6. BSS stations ridership variation in the last week of March 2020 and proximity to hospitals.

Importantly, this study presents evidence of the possible contribution of bike sharing systems to a more resilient transport system, as it can quickly provide alternative transport options to urban residents. As users are the ones who define the routes, bike sharing systems (*dockless* systems and docked mobile stations could be particularly useful) can quickly reinforce the transport offer to the areas with higher demand, at a fraction of the cost of new road or PT infrastructure. This can also provide a crucial lifeline

to lower income families who rely on PT for their commuting and that do not have access to a car (Reilly et al., 2020).

As data on the COVID-19 impact and the response of different transport systems is only starting to emerge, further research is required. For instance, additional analyses could focus on the relationship between bike sharing and other public transport modes, particularly bus systems as past research revealed the existence of competitiveness. Therefore, evaluating

if the coronavirus has reinforced or not this competitive relationship could also reveal important insights. As more data becomes available, particularly in other cities with identically comprehensive bike sharing systems, a clearer picture of the role of this transport mode in these emergency situations can be better evaluated.

With the natural reduction of new COVID-19 cases and a gradual ease of lockdown restrictions to reignite the economy, policymakers are considering how such transition can be accomplished without causing a new surge of the virus. Even though shared bicycles could still be a potential infection source as the coronavirus can survive on surfaces, they are still preferable to enclosed and often overcrowded PT systems. BSS, especially if complemented with enhanced cleaning protocols, can provide a mode of transport where social distancing can be maintained.

Still, it is expected that under normal circumstances most urban workers and residents will gradually return to pre-pandemic mobility habits. With PT ridership levels expected to remain lower due to contagion concerns, efforts should be made to avoid a modal shift from public transport to the car. Such steep increase in car use would have several negative repercussions, including on the current impact of the pandemic as increased air pollution has been associated with an possible increase on COVID-19 death rates (Wu et al., 2020). Indeed, some cities currently alleviating lockdown restrictions are taking into account such negative impacts of car use and are planning to reallocate large swaths of street space from the car to active modes (The Guardian, 2020a). We defend that such policies should be broadly adopted as the promotion of bike sharing and cycling in general, for its low-cost implementation and flexibility, could be the sustainable alternative to set a new paradigm for urban mobility.

CRediT authorship contribution statement

João Filipe Teixeira: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Miguel Lopes:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing.

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Declaration of competing interest

The authors have no conflicts of interest to declare.

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