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Bikeshare and subway ridership changes during the COVID-19 pandemic in New York City

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ABSTRACT

The COVID-19 pandemic has been unprecedented in its scale and speed, impacting the entire world, and having an impact on metropolitan transportation systems. New York City (NYC) was especially hard hit in March and April 2020. A mandatory stay-at-home order was instituted, with all but essential businesses ordered closed. In this paper we examine the impact on the Citi Bike system and the NYC subway. Usage patterns during the lockdown are compared to corresponding days in 2019. Controlling for weather patterns we examine the effect of the lockdown and subsequent reopening of economic activity up through the end of September 2020. The results show that both subway ridership and bikeshare usage plummeted initially; bikeshare usage has nearly returned to normal while subway ridership remains substantially below pre-COVID levels. Implications for policy suggest that the bikeshare system provides resilience to the overall transportation system during disasters when public transit is considered dangerous or is disrupted.

1. Introduction

As of October 21, 2020, the COVID-19 pandemic has resulted in more than 40.6 million cumulative cases and 1.1 million deaths worldwide. In response to the COVID-19 pandemic, countries and US states have implemented policies to reduce community spread of the virus. These policies include stay-at-home orders, cancellation of public events, closure of facilities, limitations on indoor gatherings and business activity, and mask-wearing mandates. This has led to major changes in travel behavior in cities, mainly due to the shutdown of economic activity, but for subway systems, the fear of close contact has also diminished ridership.

In this research, we examine the impact of the COVID-19 pandemic on the usage patterns of bikeshare and the subway in New York City. How have bikeshare and subway use patterns changed during the COVID-19 pandemic? What factors (e.g. weather conditions and policy responses) contribute to bikeshare and subway ridership changes? And, critically, is there evidence that travelers who previously took the subway are now using bikeshare?

Reports show that cities in the United States and the world have seen significant mobility reductions as people have adapted to the virus (De Vos, 2020; Kamga et al., 2020; Warren and Skillman, 2020). Individuals have reduced trip frequencies and durations, avoided public transit, and shifted to non-motorized travel modes, especially biking. For instance, Fig. 1 shows changes in driving, transit and walking in New York City from February to October in 2020, based on Apple Mobility Data.[1] It is unknown whether these changes will be sustained post-COVID. However, the increase in cycling activity may be introducing people to a mode they had not previously considered and one which may offer comparable travel times for short distances, compared to the subway. We examine these changes during the COVID-19 pandemic and consider the potential resilience of cycling as a transport mode. This paper focuses on the impact of the pandemic on bikeshare and subway ridership in New York City, the first epicenter of cases in the US, and a city characterized by its comprehensive bikeshare and subway system.

Ten days after the identification of the first case of COVID-19 in New York State, on March 12th, a state of emergency was declared. On March 20, the State declared a stay-at-home order,[2] known as the “New York State on PAUSE” executive order, to contain the outbreak (details of all COVID related events are shown in Table 1). Accordingly, transportation agencies and companies took actions in response to reduced travel demand as the city shut down and employees shifted to working at home.

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[1] *Mobility Trends Reports*. Apple. https://www.apple.com/covid19/mobility. Accessed October 21, 2020.

[2] *New York State on PAUSE*. New York State Department of Health. https://coronavirus.health.ny.gov/new-york-state-pause. Accessed October 23, 2020.

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Table 1
Timeline of key events during the COVID-19 pandemic.[a].

Date	Event	Details
03/02	The first case of COVID-19 was reported in New York City (NYC)	
03/12	Governor Andrew Cuomo declared a state of emergency in New York State	
03/20	NYC implemented a Stay-at-home order	Close all non-essential businesses; only allow essential businesses to remain open (utility companies, delivery services, groceries, pharmacies, etc.); cancel or postpone non-essential gatherings of individuals; practice social distancing of at least six feet.
03/25	Citi Bike critical workforce membership program and MTA essential service plan launched	Free rides on Citi Bike for critical workforce; MTA service reductions to maintain essential service.
05/07	Governor Andrew Cuomo that there will be a four-phase reopening plan for businesses	
06/08	Phase one reopening	Construction, manufacturing, agriculture, forestry, fishing, and select retail that can offer curbside pickup.
06/22	Phase two reopening	Restaurants with outdoor dining, hair salons and barber shops, offices, real estate firms, in-store retail, vehicle sales, retail rental, repair services, cleaning services, and commercial building management.
07/08	Phase three reopening	Indoor dining at restaurants and bars at 50% capacity and personal care services.
07/22	Phase four reopening	Low-risk outdoor activities at 33% capacity and low-risk indoor activities at 25% capacity

[a] *New York Forward*. New York State Government. https://forward.ny.gov/. Accessed October 24, 2020.

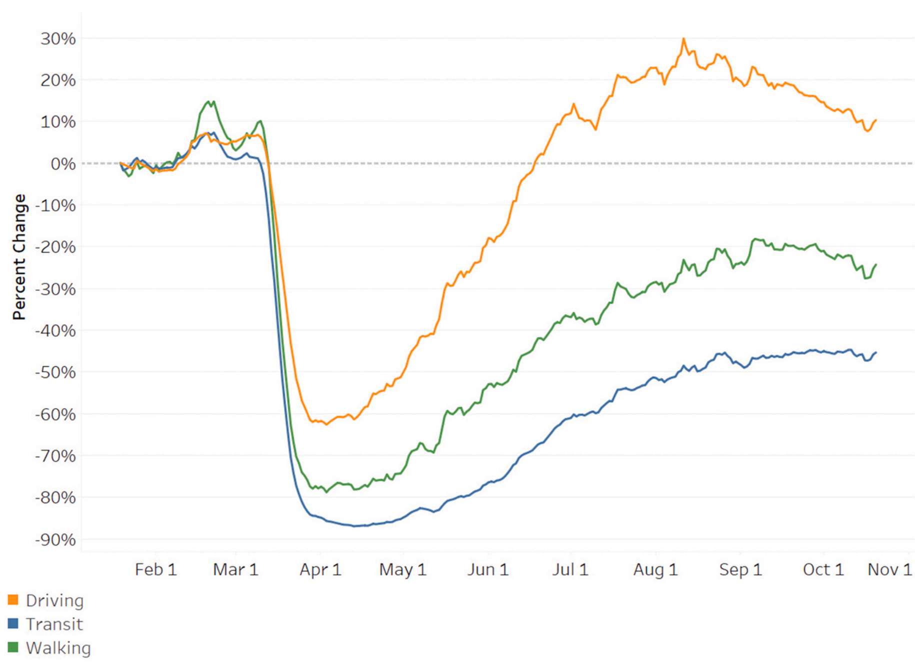

Fig. 1. New York City Mobility Trends.

On March 25th, the Metropolitan Transportation Authority (MTA) adopted an "Essential Service Plan,"[3] limiting the capacity and service hours of the subway. On the same day, the city's bike sharing system, Citi Bike, launched the "Critical Workforce Membership Program,"[4] offering free rides for 30 days for healthcare, transit employees, and first responders. On May 7th, the State announced a four-phase reopening plan for economic activity. The city entered phase one and two of the reopening in June, then phase three and four in July, loosening restrictions on business and outdoor activities.[5] These actions and policies to slow the spread of the pandemic are reflected by the performance of the transportation system, including the ridership changes for bikeshare and the subway, which is the focus of this study.

2. Literature review

Bikeshare systems allowing users to rent a bicycle for a short time period are widely available in many cities. There is a large literature examining patterns of bikeshare usage. Much of this prior work

[3] *MTA Implements "NY Essential Service Plan" to Move Healthcare Workers, First Responders and Other Essential Personnel on Frontlines of the COVID-19 Crisis*. MTA. http://www.mta.info/press-release/mta-headquarters/mta-implements-%E2%80%9Cny-essential-service-plan%E2%80%9D-move-healthcare-workers. Accessed July 27, 2020.

[4] *Citi Bike Critical Workforce Membership Program*. Citi Bike. https://www.citibikenyc.com/critical-workforce-membership-press-release. Accessed July 27, 2020.

[5] *COVID-19: RESTART Guidance for Businesses*. NYC Government. https://www1.nyc.gov/site/doh/covid/covid-19-businesses-and-facilities.page. Accessed July 27, 2020.

investigates the relationship with sociodemographic factors, the built environment, land use, weather conditions, and public transit. Of primary interest for our study is the sensitivity to weather conditions. The usage of bikeshare varies seasonally, with higher ridership in warmer months. Studies also reveal use differences between subscribers and casual users. Casual users usually take longer trips than subscribers. The trip purpose of casual users is more likely to be leisure related, while subscribers are more likely to use bikeshare for work trips (DeMaio, 2009; Fishman, 2016; Fishman et al., 2013).

Bikeshare can be either a complement or a substitute for public transit trips. For example, Noland et al. (2016) found that subway stations near bikeshare stations were correlated with increased bikeshare ridership in New York City, stressing the importance of linking bikesharing and transit. An origin-destination analysis of Capital Bikeshare in Washington, D.C. also found that proximity to subway stations increased usage rates of bikeshare stations (Ma et al., 2015). Bikeshare can compete with public transit as well, corroborated by studies showing a reduction in bus use in New York City (Campbell and Brakewood, 2017). Our work examines whether subway trips have shifted to bikeshare during the pandemic.

In general, an increase in bikeshare ridership is correlated with good weather, while bad weather (rain and snow) tends to reduce ridership. Precipitation is regarded as the most negative weather factor. Warmer temperatures also have a positive association with ridership (Heinen et al., 2010). Gebhart and Noland (2014), examined bikeshare trips in Washington, D.C., finding fewer trips were made in adverse weather conditions, including rainy days, higher wind speeds, high humidity and lower temperatures. A study in Toronto found that bikeshare ridership was negatively associated with humidity, precipitation, and snow on the ground (El-Assi et al., 2017). In a case study of a Korean city, Kim (2018) included the temperature-humidity index (THI) as a discomfort index and found that it was negatively correlated with daily bikeshare demand. Temperatures over 30 °C reduced bikeshare usage. An, Zahnow, Pojani, and Corcoran (2019) analyzed the bikeshare-weather relationship and concluded that a higher temperature (up to 28 °C) was associated with more cycling trips, regardless of the built and natural environment characteristics. None of this is surprising, but the advent of bikeshare systems and the data they produce has allowed research to quantify the impacts of weather on cycling.

Weather can also have an affect on subway and transit usage. Guo, Wilson, and Rahbee (2007), using the Chicago Transit Authority (CTA) bus and rail system as a case, found that temperature was a significant positive factor while precipitation and wind were significant negative factors. Fog had a negative effect with a 90% confidence level. The study also showed that bus ridership was more sensitive to weather than rail. Singhal, Kamga, and Yazici (2014) confirmed the negative impacts of rain and snow on transit ridership and found that ridership on weekends is more likely to be affected by weather than weekday counterparts. Although given the abundance of case studies, we are unaware of any studies that have compared the significance and magnitude of the impact of weather conditions on bikeshare and subway usage simultaneously. Therefore, comparing the impact of weather patterns on bikeshare and subway ridership is a contribution of this paper, although we primarily use these as control variables to isolate the effect of the pandemic response on ridership.

The incorporation of bikeshare within a comprehensive urban transport system may improve the resilience of the system. Bikeshare is versatile and requires less investment in infrastructure and capital than public transit, making it less vulnerable and more resilient to disasters and crises. Studies have shown that during the 2002–2004 SARS outbreak in China, there was a considerable drop in subway ridership and an increase of e-bike ridership (Wang, 2014; Weinert et al., 2007). For the COVID-19 pandemic, several case studies have already been conducted. Chai, Guo, Xiao, and Jiang (2020) performed co-location analysis between bikeshare usage and POIs (Point of Interest) to assess the impact of the pandemic in Beijing. When COVID-19 was contained in Beijing, bikeshare usage gradually rebounded. Areas where technology companies were located had the largest reduction in bikeshare usage as many employees in this industry began working at home. A thematic analysis of an online survey reveals that Sydney residents observed more bicyclists and showed positive attitudes toward bicycling, during the COVID-19 lockdown restrictions (Lock, 2020). Li et al.(Li et al., 2020) examined four types of micro-mobility services (docked bikes, docked e-bikes, dockless e-bikes, and dockless e-scooters) in Switzerland during the COVID-19 pandemic and found trips of longer duration increased. Teixeira and Lopes (2020) analyzed Citi Bike data in March 2020, at the start of the pandemic, and showed that Citi Bike in New York City was more resilient in comparison to the subway system with smaller ridership reductions and a rise in average trip duration. We extend this analysis in New York city by examining data from January to September for two years (2019 and 2020) and estimating a time-series model with the inclusion of weather and policy variables, allowing us to compare the full progression of bikeshare and subway usage during the pandemic to the previous year.

The study presented here builds on prior research in two ways. First, we corroborate the impact of weather on bikeshare and subway ridership, although primarily as a control variable. Second, we examine the mobility trends at the city-level, using New York City as a case study. We use a time series analysis to analyze factors influencing bikeshare and subway ridership during the COVID-19 pandemic. To our best knowledge, this is the first time-series comparison study of bikeshare and subway use patterns during the pandemic. For policy makers, our results suggest that bikesharing has been a valuable alternative to assist with social-distancing for those who still must travel in New York City.

3. Background on Citi Bike and the subway

New York City's (NYC) bikeshare system, Citi Bike, was launched in July 2013 and continues to expand annually. Citi Bike riders broke a daily ridership record of over 100,000 trips in September 2019. As of September 2020, the Citi Bike system, with about 15,000 bikes and 1000 stations, covers Manhattan and a small portion of Brooklyn and Queens, with plans for further expansion. Citi Bike also operates in Jersey City, New Jersey, but these are not included in our study. Full details on pricing and maps showing the extent of the system are available here: https://www.citibikenyc.com/.

NYC's subway system, is one of the oldest and largest public transit systems in the world, connecting communities in four boroughs of NYC, Manhattan, Bronx, Queens, and Brooklyn, with one line on Staten Island. The subway system has 472 stations and operates 24 h a day. It had a daily ridership of roughly 5.5 million and an annual ridership of about 1.698 billion in 2019, the largest ridership in the country. Further information, including maps and fares, are easily found on the Metropolitan Transportation Authority (MTA) website: https://new.mta.info/

Table 2
Data sources.

Dataset	Provider	Source link
Citi Bike usage	NYC Bike Share	https://www.Citi.Bikenyc.com/system-data
Subway usage	Metropolitan Transportation Authority	http://web.mta.info/nyct/facts/ridership
Weather	NOAA, National Weather Forecast Office	https://w2.weather.gov/climate/xmacis.php?wfo=okx
Positive test	NYC Department of Health	https://www1.nyc.gov/site/doh/covid/covid-19-data.page
NYC policy response to COVID-19	NYC government COVID-19 Citywide Information Portal	https://www1.nyc.gov/site/coronavirus/index.page

Table 3
Summary statistics.

Variable	Mean	Count (for dummy variable)	Std Dev /Percent	Min	Max
Citi Bike all trips, 2020	52,952		23,370	3999	101,462
Citi Bike casual user trips, 2020	12,793		9724	337	36,734
Citi Bike subscriber trips, 2020	40,159		15,745	3662	70,344
Subway ridership, 2020	1,794,401		1,744,135	212,947	5,602,978
Average temperature (° F), 2020	60.06		16.21	22.50	87.00
Total precipitation (inches), 2020	0.11		0.30	0	2.54
Snowfall (inches), 2020	0.01		0.13	0	2.10
Average wind speed (mph), 2020	5.10		2.18	1.20	12.75
Weekday, 2020		186	70%	0	1
Stay-at-home order		78	29%	0	1
Phase 1 reopening		14	5%	0	1
Phase 2 reopening		14	5%	0	1
Phase 3 reopening		14	5%	0	1
Phase 4 reopening		71	27%	0	1
Citi Bike all trips, 2019	59,292		20,980	10,291	98,755
Citi Bike casual user trips, 2019	8730		6965	260	39,899
Citi Bike subscriber trips, 2019	50,562		16,969	9778	82,822
Subway ridership, 2019	4,696,150		1,269,535	1,971,816	6,094,418
Average temperature (° F), 2019	58.88		18.10	9.00	88.50
Total precipitation (inch), 2019	0.14		0.30	0	1.82
Snowfall, 2019	0.01		0.13	0	2.10
Average wind speed (mph), 2019	8.75		4.94	1.57	27.00
Weekday, 2019		186	70%	0	1

Note: Each variable has 267observations. All the numerical variables are by day. The whole study period is from July 1, 2019 to 9/30/2019 and from June 1, 2020 to 9/28/2020. We match by days of the week and our time trend variable for 2019 and 2020, begins on at the first Monday of the year (July 1, 2019 and June 1, 2020, respectively). Note that 2020 was a leap year, thus the 2019 data ends on 9/30/19, while the 2020 data ends two days earlier (9/28/20).

4. Data

A variety of data sources were acquired to compile a dataset of bikeshare and subway usage, weather conditions, and policy responses to the COVID-19 pandemic. Table 2 lists the provider and source links for our data. Table 3 lists the summary statistics for all variables.

We downloaded Citi Bike trip data from January to September in 2019 and 2020, respectively, from the Citi Bike website. The original dataset includes trip start time and end time, pick-up station name and return station name, demographics of the users, including gender and age, and whether the user is a subscriber or casual user. Subscribers pay $169 per year for unlimited 45-min rides on a Citi Bike, after which Citi Bike charges annual subscribers $0.15 per minute. Casual users pay $3 for one trip of less than 30 min, or pay $12 for a one-day pass, or $24 for a 3-day pass. The latter two options offer free rides for the first 30 min. If a user rides for longer than 30 min at a time, an additional $4 every 15 min is charged.[6] The literature indicates that travel patterns of subscribers and casual users are different (Fishman, 2016; Noland et al., 2016). Thus we estimate models for these two user types separately. We aggregated the daily data to total trips, trips by user type, for both years. We aligned the data to start on the first Monday of the year, so weekend effects are consistent in each series with 267 days for each year. We obtained subway turnstile data from the MTA website from which we summed the total daily entries by station and then aggregated station totals into daily ridership totals.

Daily weather data is from the National Oceanic and Atmospheric Administration (NOAA). This includes temperature (maximum, minimum, and average), precipitation, snowfall, humidity, and wind speed (maximum, minimum, and average). The selection of these weather conditions is based on previous research findings on the impact of weather on bikesharing and transit (An et al., 2019; Gebhart and Noland, 2014; Guo et al., 2007; Martinez, 2017; Singhal et al., 2014). The weather data was recorded at the NYC Central Park observation station, which is closest to most Citi Bike docking stations, relative to other weather observation stations. We included snowfall considering that New York City observed heavy snowfall in early spring in 2019 but a very warm spring with little snowfall in 2020.

We also acquired the daily counts of confirmed COVID-19 cases from the NYC Department of Health thus charting the mobility trends and severity of the coronavirus pandemic. The dates of the critical events such as the stay-at-home order, phase one reopening, and phase two reopening were accessed from the NYC government website.

5. Methods and analysis strategy

Since we use daily time-series data, simple OLS models will suffer from serial correlation. We are also using counts of trips as our dependent variable; these would typically be modeled with a Negative Binomial model, but these assume independence for each day. Thus we use the log of our counts to approximate a normal distribution and estimate Prais-Winsten models to control for serial correlation.

We estimate four models for each year. These include total daily subway trips, total daily bikeshare trips, and trips taken by subscribers and casual users. Control variables include daily weather conditions, dummy variables for weekdays versus weekends/holidays, and the pandemic policy variables. The holidays are Martin Luther King Jr. Day, President's Day, Memorial Day, Independence Day, and Labor Day. For the weather variables we selected average temperature, total precipitation, snowfall, and average wind speed; other weather variables were highly correlated with these and each other. We hypothesized that the stay-at-home order and subsequent reopening phases had significant impacts on travel behavior thus we included them in the 2020 models.

6. Descriptive analysis results

To investigate the pandemic's impact on bikeshare ridership, Fig. 2 compares Citi Bike trips taken from the beginning of January to the end of September in 2019 and 2020. The darker trend lines are the 7-day moving average of daily Citi Bike trip counts. Citi Bike trips in the first half of 2019, shown as blue lines, increased from about 30,000 to approximately 70,000 per day. This increase is likely due to warmer weather. In comparison, 2020 witnessed a significant drop in Citi Bike

[6] *Citi Bike Pricing Plans*. Citi Bike. https://www.citibikenyc.com/pricing. Accessed July 20, 2020.

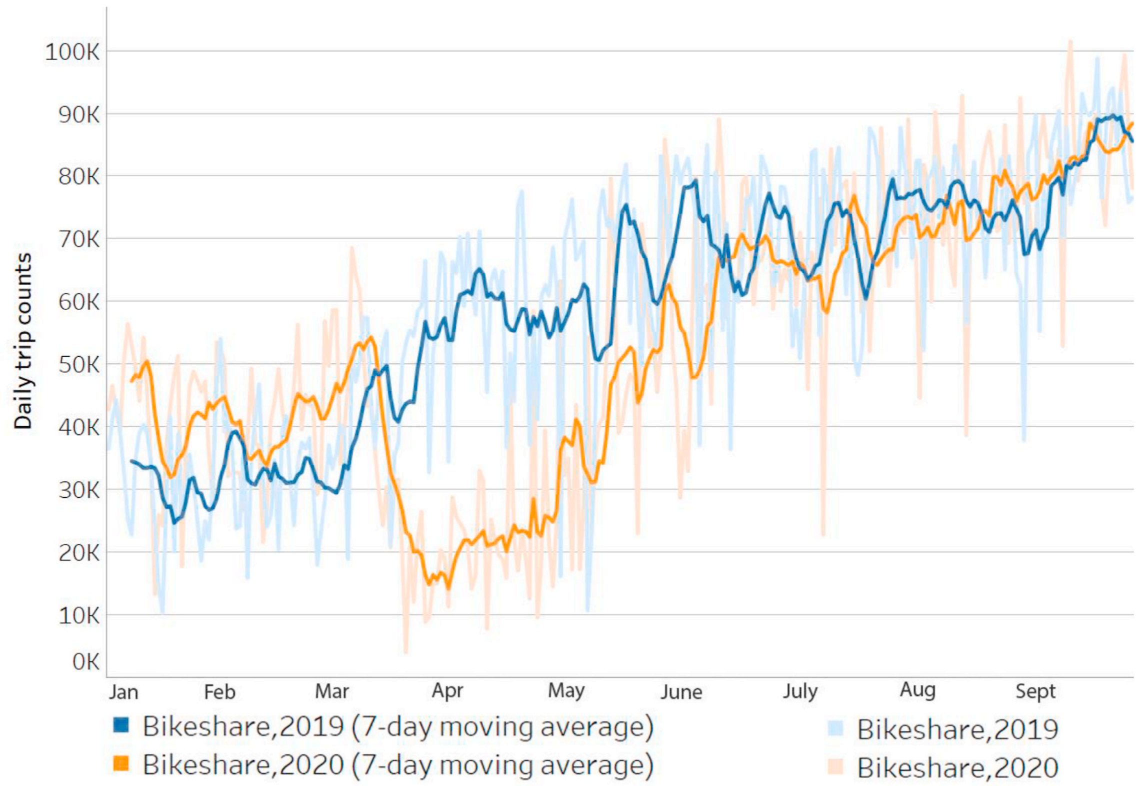

Fig. 2. Citi Bike daily trip counts in 2019 and 2020.

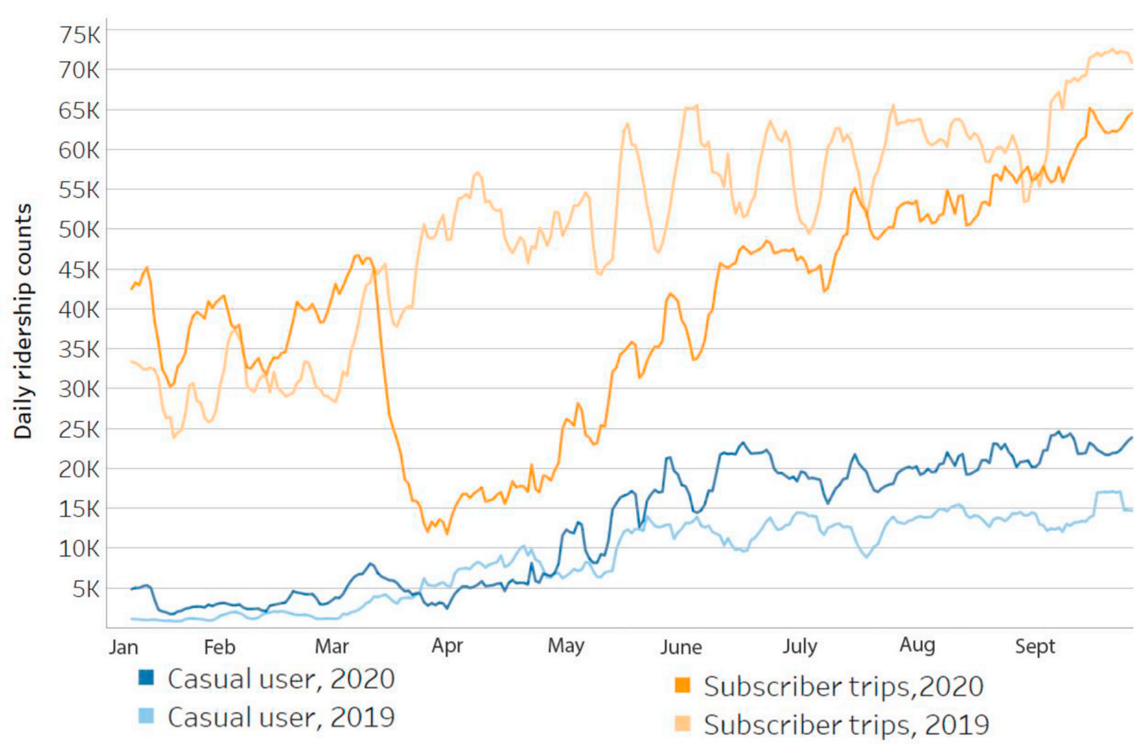

Fig. 3. Citi Bike trip counts by user type in 2019 and 2020.

trips in March, for example, trip counts fell by roughly 71% from 68,509 trips on March 9 to 19,830 on March 22. Citi Bike ridership started to recover in early April. From April to September, in 2020, the total number of Citi Bike trips increased, recovering to about 90,000 daily trips at the end of September, similar to counts in September 2019.

Fig. 3 displays the changes in Citi Bike ridership by user type. Most trips are made by subscribers in both years. The number of trips made by subscribers dropped substantially in March 2020 then steadily increased

Table 4
Number of Citi Bike trips by trip duration in 2019 and 2020.

		number of trips less than 30 min	number of trips between 30 and 60 min	all trips	ratio of longer trips/ shorter trips
2019	January	918,183	44,787	966,153	4.88%
	February	891,125	47,980	942,594	5.38%
	March	1,238,884	79,484	1,325,759	6.42%
	April	1,614,763	131,627	1,761,926	8.15%
	May	1,745,017	158,240	1,921,023	9.07%
	June	1,913,777	186,180	2,125,370	9.73%
	July	1,979,627	176,946	2,181,064	8.94%
	August	2,119,483	197,601	2,344,224	9.32%
	September	2,225,078	195,237	2,444,900	8.77%
2020	January	1,173,619	60,974	1,239,359	5.20%
	February	1,085,204	55,743	1,145,519	5.14%
	March	940,786	111,997	1,066,026	11.90%
	April	535,597	123,661	679,988	23.09%
	May	1,122,094	300,698	1,479,407	26.80%
	June	1,427,991	350,862	1,842,706	24.57%
	July	1,735,245	314,207	2,105,808	18.11%
	August	1,926,725	342,321	2,329,514	17.77%
	September	2,099,388	333,796	2,488,225	15.90%

after March, while the number of trips by casual users remained relatively stable in March and at similar levels to 2019. There are more casual users in 2020 than in 2019 from May to September, despite fewer visitors and tourists being in the city during the pandemic. This suggests that more people are trying out Citi Bike, perhaps eventually deciding to subscribe and use it on a regular basis.

Table 4 compares the number of shorter bikeshare trips, with a duration of less than 30 min, and longer trips with durations between 30 min and 60 min. In 2019, the ratio of longer trips increased each month from January to June, probably due to warmer weather and longer daylight hours. However, following the stay-at-home order which went into effect in March 2020, the ratio was about double the 2019 ratio. The ratio increased, with the largest value of 26.80% in May, then decreased in the following months, perhaps as people returned to the subway as the immediate crisis subsided (see Fig. 4). Thus, there was an increase in the number of longer trips, relative to the corresponding values in 2019. This result suggests that bikeshare use replaced other modes of travel for longer trips, in particular subway trips, though perhaps decreasing as the fear of the pandemic lessened.

A seven-day moving average of daily subway usage is displayed in Fig. 4 for both 2019 and 2020, as well as daily totals. The pattern of weekday and weekday usage is seen in the daily totals. Subway daily ridership in 2019 remained relatively constant across the months. In comparison subway ridership in 2020 decreased by approximately 94% from 4,826,491 on March 10 to 279,110 on March 29. Since early April, subway ridership has gradually increased, though it still remains at a much lower level than in 2019.

These trends in 2020 are summarized in Fig. 5 and compared with the trend lines of COVID-19 cases and deaths. The upper chart presents bikeshare and subway usage patterns. The lower chart shows the count of confirmed cases by date of diagnosis and deaths by date of death from the coronavirus. The trend of daily deaths lagged about one week behind that of daily confirmed cases. The peak of new cases and deaths was on April 6th, with 6378 new cases and 597 COVID fatalities on that day. After April 6th, these two indicators decreased in response to the shelter-at-home order issued on March 20. Even prior to this order, ridership on the subway and bikeshare was dropping, most likely due to businesses moving employees to working at home for their own protection.

Bikeshare ridership dropped less than subway ridership, with a 70% decline versus about 95% throughout the month of March. With the severity of the pandemic decreasing in about mid-April, the ridership on both has increased, but subway ridership remains very low. The following analysis will examine how the policy response to the pandemic affected ridership, while controlling for weather and weekdays vs. non-workdays.

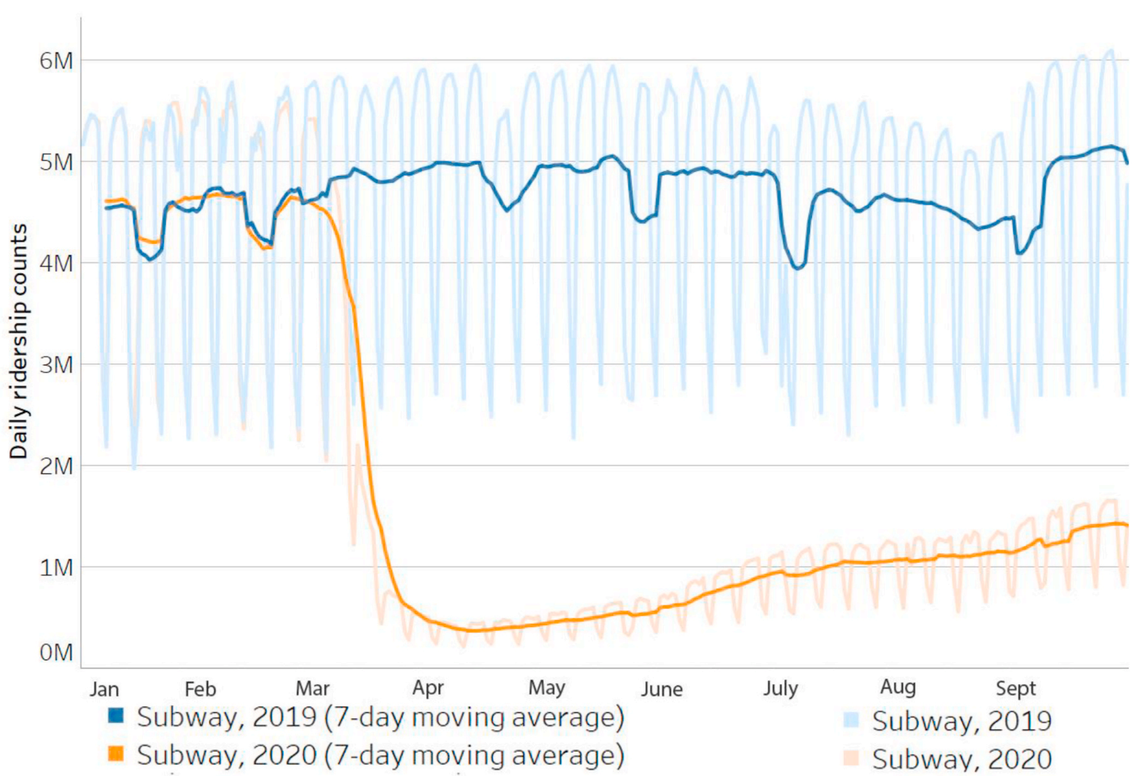

Fig. 4. Subway daily ridership in 2019 and 2020.

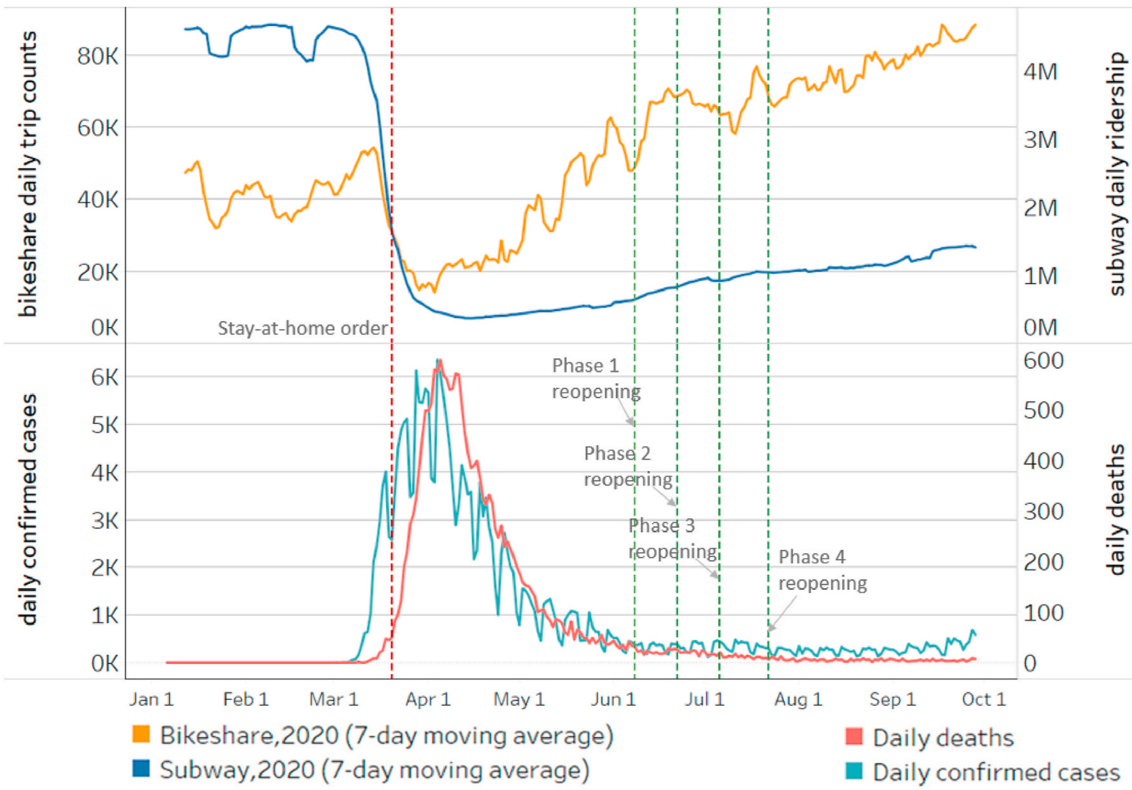

Fig. 5. Citi Bike daily trip counts and subway daily ridership, and the COVID-19 daily cases and deaths.

7. Modelling results

We estimated a Prais-Winsten model to control for serial correlation in our times series. Independent variables included weather conditions, weekdays, and COVID-19 policy responses. The model results are shown in Table 5. The table includes the coefficient, the t-value for each independent variable as well as Rho, Durbin-Watson statistic, and adjusted R-squared for each model. A Durbin-Watson statistic equal to 2, minimizes serial correlation, and all our models show improved performance on this statistic, the one exception being our subway ridership model with DW = 2.76. According to the values of the adjusted R-squared, the subway models explain more variation than Citi Bike models. For example, the model for subway ridership in 2020 accounts for about 89% of the total variance in the dependent variable. All models show an improvement in the Durbin-Watson statistic when serial correlation is controlled for.

We use weather as a control variable to isolate the impact of the COVID policy on both subway and bikeshare use. Not surprisingly, bikeshare use is more sensitive to weather conditions than for subway usage. Colder temperatures and more precipitation decrease bikeshare use. In our 2019 analysis (model 4), a small increase in temperature is associated with a small increase in subway use, while precipitation reduces usage. Both effects disappear for subway use in 2020 (model 2). This is likely due to the overall reduction in subway use and especially in discretionary trips with subway users being mainly those essential workers who have no choice. Snowfall is only significant for Citi Bike use in 2020. Heavier snow decreases bikeshare travel. Wind speed has a negative impact on bikeshare and subway ridership in 2020, though the coefficient for the subway model is very small.

The weekday variable is significant for subway use in both 2019 and 2020, that is, more subway use occurs on weekdays relative to weekends and holidays. This is likewise true for Citi Bike in 2019, but there is a small negative effect in 2020, i.e., fewer Citi Bike trips on weekdays than weekends and holidays in 2020. This result indicates that bikeshare travel behavior on weekdays and weekends/holiday has changed during the pandemic. This may reflect changes in subscriber versus casual use, which we examine further below.

The objective of the stay-at-home order was to reduce community spread of the coronavirus. Results show that this policy was highly effective at reducing both subway and bikeshare usage. The stay-at-home order had a larger negative impact on Citi Bike trip counts than subway ridership. Surprisingly, the phase 1 reopening still had a negative effect on subway usage, albeit at 90% confidence level. For Citi Bike there is a similar effect that continues into the phase 2 reopening, suggesting some reduction in Citi Bike use as the economy reopened, possibly due to increased vehicle traffic. The trends we see in Fig. 5 showing an increase in bikeshare use, are likely due to improved weather conditions. This may also reflect a shift from subway use.

We also estimated four sets of Prais-Winsten models to distinguish usage patterns of bikeshare subscribers and casual users in 2019 and 2020. The results are presented in Table 6. Temperature and precipitation are significant in all models, with the same tendency shown in Table 5 that higher temperatures and less rain increases trips. These two weather factors have a stronger impact on causal user trips than subscriber trips. Comparing the coefficients in 2019 and 2020, we see that temperature has similar impacts on subscriber trips in 2019 and 2020 but a smaller impact on casual user trips in 2020 than in 2019. Precipitation has a larger effect on subscriber trips and a smaller effect on casual user trips in 2020 than in 2019. Snowfall and wind speeds are significant for both subscribers and casual users in 2020, both showing a negative association. These two weather factors are not significant in the 2019 models.

In 2019, subscriber bikeshare trips were higher on weekdays, while casual user trips were lower. This is consistent with a pattern of subscribers being commuters and casual users using the bikes for recreation. While in 2020, casual users are still less likely to ride on on weekdays, the positive association with subscriber trips vanishes; this is consistent with the reduction in commute trips associated with the pandemic.

Table 5
Models for Citi Bike trips and subway ridership in 2019 and 2020.

Dependent Variable	Model 1	Model 2	Model 3	Model 4
	ln (Citi Bike20)	ln(subway20)	ln(Citi Bike19)	ln(subway19)
	coefficient/ t-stat	coefficient/ t-stat	coefficient/ t-stat	coefficient/ t-stat
Temperature	0.020***	0.001	0.019***	0.001*
	(7.18)	(0.33)	(17.86)	(2.54)
Precipitation	−0.567***	−0.030	−0.516***	−0.067***
	(-11.02)	(-1.58)	(-15.00)	(-3.56)
Snowfall	−0.343**	−0.005	0.009	0.008
	(-2.91)	(-0.12)	(0.23)	(0.45)
Wind speed	−0.028**	−0.008*	−0.004	0.003*
	(-3.01)	(-2.19)	(-1.19)	(2.19)
Weekday	−0.080*	0.583***	0.215***	0.665***
	(-2.14)	(38.56)	(8.74)	(53.22)
Stay-at-Home-Order	−0.582***	−0.425***		
	(-7.08)	(-3.36)		
Phase 1 reopening	−0.262	−0.297		
	(-1.75)	(-1.68)		
Phase 2 reopening	−0.337*	−0.115		
	(-2.10)	(-0.53)		
Phase 3 reopening	−0.196	−0.006		
	(-1.22)	(-0.02)		
Phase 4 reopening	−0.051	0.050		
	(-0.44)	(0.18)		
constant	10.016***	13.875***	9.729***	14.767***
	(63.55)	(34.57)	(112.55)	(389.64)
Observations	267	267	267	267
Rho	0.44	0.98	0.38	0.07
Durbin-Watson (original)	1.15	0.54	1.32	1.88
Durbin-Watson (final)	2.11	2.76	2.11	2.00
Adj_R^2	0.69	0.89	0.80	0.92

Note: *p < 0.05, **p < 0.01, ***p < 0.001. t statistics in parentheses.

Table 6
Models for Citi Bike subscriber and casual user trips in 2019 and 2020.

Dependent Variable	Model 1	Model 2	Model 3	Model 4
	ln (subscriber20)	ln(casual20)	ln(subscriber19)	ln(casual19)
	coefficient/ t-stat	coefficient/ t-stat	coefficient/ t-stat	coefficient/ t-stat
Temperature	0.016***	0.039***	0.016***	0.051***
	(6.31)	(10.26)	(14.90)	(22.46)
Precipitation	−0.517***	−0.749***	−0.462***	−0.817***
	(-11.53)	(-10.27)	(-14.96)	(-13.02)
Snowfall	−0.315**	−0.443**	−0.005	−0.005
	(-3.07)	(-2.65)	(-1.54)	(-0.77)
Wind speed	−0.026**	−0.034*	0.006	−0.011
	(-3.11)	(-2.56)	(0.15)	(-0.14)
Weekday	0.047	−0.546***	0.353***	−0.536***
	(1.44)	(-10.44)	(15.81)	(-11.72)
Stay-at-home order	−0.700***	0.195		
	(-8.99)	(1.83)		
Phase 1 reopening	−0.406**	0.478*		
	(-2.91)	(2.43)		
Phase 2 reopening	−0.413**	0.204		
	(-2.77)	(0.96)		
Phase 3 reopening	−0.255	0.321		
	(-1.71)	(1.51)		
Phase 4 reopening	−0.123	0.508**		
	(-1.13)	(3.28)		
Constant	9.972***	7.089***	9.699***	6.151***
	(69.92)	(33.11)	(118.03)	(35.17)
Observations	267	267	267	267
Rho	0.48	0.39	0.44	0.49
Durbin-Watson (original)	1.07	1.24	1.21	1.13
Durbin-Watson (final)	2.15	2.11	2.12	2.18
Adj_R^2	0.72	0.75	0.82	0.79

Note: *p < 0.05, **p < 0.01, ***p < 0.001. t statistics in parentheses.

The stay-at-home order has a significant negative impact on subscriber trips in 2020 but has no effect on casual user trips. Subscribers, who usually ride for work-related purposes, likely shifted to working from home or lost their jobs. In comparison, there is a slight increase in trips for casual users, at a 90% confidence level. This suggests some increase in recreational activity, though other phases have no effect until the phase 4 reopening. We tested models without the reopening phases and results are largely similar.

All models for the two user types are statistically significant. The 2019 models explain higher variation based on the adjusted-R^2 (82% and 79% for subscriber and casual user models respectively) compared to their counterparts in 2020 (72% and 75%).

8. Discussion and conclusions

Our study has examined the impact of the COVID-19 pandemic on bikeshare and subway usage patterns in New York City, via data visualization and time-series modeling. Our findings have implications for policy during a crisis as well as during recovery from the pandemic.

Our analysis results suggest that the bikeshare system is more resilient than the subway system. Both were severely impacted by the pandemic and witnessed major ridership reductions, with a substantial drop (95%) in subway ridership and about a 70% reduction in bikeshare trip counts, relative to prior to the coronavirus outbreak. Citi Bike saw an increase in longer trips between 30 and 60 min, suggesting some shifting from the subway, perhaps due to fear of contagion. After the peak of the pandemic in New York City, the number of Citi Bike trips gradually recovered to the corresponding level in 2019. In contrast subway ridership is only at about 30% of its pre-crisis level of ridership (as of September 30, 2020).

Our weather variables were used primarily to control for day-to-day variation in ridership. The results, however, are revealing about potential behavioral changes, especially for subway users. While it is not unexpected to see bikeshare usage sensitive to weather conditions, casual user trips are affected more by adverse weather conditions. While subway use tends to be lower on rainy days, this effect disappears in 2020, likely reflecting the absence of discretionary trips which would be more sensitive to weather conditions.

Our key policy variables are the stay-at-home order and the four phases of reopening policies. The stay-at-home order is significant, reducing bikeshare and subway ridership substantially. However, the reopening phases have more modest effects. Further research is needed to determine how the subway can recover its ridership, but we suspect this is largely due to employees continuing to work at home. Bikeshare ridership, on the other hand, is largely back to pre-COVID levels. However, additional work is needed to determine if the pattern of trips between stations, and at different times of day has changed. There is some evidence for increases in commute trips and shifts from the subway, as demonstrated by longer trip durations.

One limitation of our study is that we do not know how MTA service reductions affected ridership. These reductions were due to both staff shortages (due to COVID) and reductions in ridership.[7] During the phase four reopening regular service returned, except for the subway remaining closed between 1:00am and 5:00am for cleaning[8] This may have added to people avoiding the subway if there were long waits at stations. Unfortunately, precise data on service schedules is not archived on the MTA website and so is not available for analysis. While the stay-at-home policy clearly affected travel, we don not know how job losses

[7] *Subway Service Is Cut by a Quarter Because of Coronavirus*. The New York Times, https://www.nytimes.com/2020/03/24/nyregion/coronavirus-nyc-mta-cuts-.html

[8] *Reopen News: Subway and bus service updates in New York City*. Eyewitness News. https://abc7ny.com/reopen-nyc-mta-subway-covid-19/6232748/.

also may have led to reductions in commuting trips which led to reduced service. Increased levels of working at home also have reduced ridership.

Based on the current trend, Citi Bike ridership may continue to grow with the restrictions eased. Will some users purchase their own bicycle? There has been a rush on bicycle shops during the pandemic, suggesting this is an attractive mode for those fearing to use the subway (Goldbaum, 2020). However, we cannot predict how enduring these changes may be, once the pandemic is over. Batty (2020) believes that there will be a new normal in all aspects, but what this new normal will look like is still unclear.

As abundant data on the transport system and the pandemic impact becomes available, further research can complement our analysis to examine the details of the impact of the pandemic on travel behavior. In particular, we need to understand changes in telecommuting patterns, car-sharing, non-motorized travel (beyond bikeshare) as well as the impacts on public transit. Investigation of whether there was a modal transfer from subway riders to bikeshare users and whether bikesharing complements or substitutes subway patronage can be examined via individual survey data. Case studies in other cities with comprehensive bikeshare systems such as Washington, D.C. and Chicago, can provide a clearer and more general picture of the impact of the pandemic on bikeshare and public transit.

Our findings pose several implications for policymakers and transportation planners. Our findings suggest that bikeshare systems add to the resiliency of transportation systems. New York City has seen bicycles come out of the closet during other crises, including the 1980 transit strike (Chan, 2005) and after Superstorm Sandy ("Bikes keep NYC rolling through hard times," 2020) in 2012. This provides evidence of additional benefits of active transportation and for better bicycling infrastructure. Potentially, new guidelines for resilient transportation systems with the inclusion of bikeshare systems and other micro-mobility options are needed in the post-pandemic era. Cities are also finding ways to use streets to provide social distancing for walkers and space for outside dining ("Oakland Slow Streets," 2020). Probably the most effective policy to encourage more bikeshare (and cycling) use is providing protected infrastructure (Pucher and Buehler, 2008).

Our analysis has demonstrated the disruption to regular travel habits, and the potential for adaptation to new travel habits, which can be a precursor to behavior change. In the 1980 public transit strike in New York City, citizens were forced to walk and bike with subway and bus service unavailable (Chan, 2005). In this event, travel habits changed due to the disruption of the transport system. However, the devastating pandemic results in a much longer disruption. Given the unique characteristics of the impact of the pandemic, we raise questions for planners and policy makers: How can we build towards a more resilient transport system? How can future transport systems respond to new travel behaviors?

Author statement

The authors confirm contribution to the paper as follows: study conception and design: Wang, Noland; data collection: Wang; analysis and interpretation of results: Wang, Noland; draft manuscript preparation: Wang, Noland. All authors reviewed the results and approved the final version of the manuscript.

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