 doi:10.20944/preprints202209.0049.v1

Article

Bikeshare Interactions with Other Transportation Modes During the COVID Pandemic

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ABSTRACT: In this paper, bikeshare data in Chicago on weather-friendly days in 2019 and 2020 were analyzed to investigate the variation in bikeshare travel before and during the pandemic. Our results show that bikeshare trips during the pandemic were much longer than prior to the pandemic. The increased rate of bikeshare usage was unbalanced spatially and varied significantly for different user types. Specifically, bikeshare was used significantly more by casual users than by subscribers, and the increase occurred much more in the outskirts of the city. The increase in bikeshare travel was associated with a reduction in travel by ride-hailing and public transit, especially in the urban periphery. The correlation of bikeshare use with the bus system was much less significant than with the rail system. Bike lanes/facilities had a mixed effect on bikeshare travel. Weekend bike trips increased in areas where there was no bike lane. Weekday trips, on the contrary, increased in the vicinity of bike greenways.

Keywords: Bikeshare; COVID; interaction of multiple modes

INTRODUCTION

During the COVID-19 pandemic, the world observed a dramatic drop in the volumes of all traffic modes. For example, automobile traffic volumes alone dropped by 40% to 60%. Due to the need to abide by social distancing and the concerns about infection, travelers tended to switch to travel modes with lower exposure to the virus. Bikeshare, due to its open-in-the-air and natural distancing features, became popular. While the reduction of traffic volume was quite similar across the world for personal vehicles, our study concentrates on the changes in bikeshare usage. Specifically, we identify the variation in bikeshare usage during the pandemic and its interaction with other travel modes, by attempting to answer the following questions: How did bikeshare travel vary during the pandemic? How did bikeshare interact with other travel modes? Did all the modes have a similar reduction? Will there be a possibility to motivate travelers to use bikeshare after the pandemic in connection with transit that will be equitable and has minimal impacts on our environment? To answer these questions, this paper obtained and analyzed the travel data of multiple transportation modes before and during the pandemic. Our goal was to identify the variation of bikeshare travel during the COVID-19 pandemic, explore its correlation with other modes, especially public transit, and propose possible policies that can stimulate bikeshare usage. The results of this paper will help policy makers better understand the travel behavior of bikeshare users so that they can make effective policies to create a more sustainable and equitable traffic system post pandemic.

In terms of the paper layout, we first present the state-of-the-art literature on the topic, we then present the data analysis and results and conclude with the findings and conclusions of the study.

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BACKGROUND AND LITERATURE REVIEW

Bikeshare has developed rapidly since its first appearance as the "white bike" in Amsterdam in the 1960s. Currently, there are 7,469 docking stations and 36 dock-less bikeshare systems in the U.S. Since bikeshare is relatively low in cost and has a minimum carbon footprint, it can be a promising solution for the equity and environmental problems of the traffic system. To better understand the behavior of bikeshare users and promote the usage of bikes, many previous studies have investigated patterns related to bikeshare travel, users, weather impacts, interaction of bikeshare with other modes, and other policy- or economics-related topics. Due to the focus of this paper, we will concentrate our literature review on studies that have investigated the relationship between bikeshare and other transportation modes.

Kong et al. found that bikeshare trips can be grouped into three types in regard to their relationship with public transit: modal substitution (MS), modal integration (MI), and modal complementation (MC). Bike trip patterns vary by weekend/weekdays and subscribers/casual users. MI trips are typically shorter in distance and occur during the weekdays. MC and MS are more dominant compared to MI. MC often happens during times when public transit is not available. MS made by casual users is much more than subscribers [1]. Welch et al. investigated the role of the built environment and other factors affecting travelers' choices of travel modes. Their conclusions found that cost is an important factor. In addition, higher job diversity, lower density of roads and intersections are positively linked to shared modes (ridesharing or bikeshare) [2]. Shaheen et al. analyzed survey data from four cities and found that bikeshare will both increase and decrease the usage of buses and rail. The percentage of travelers who indicated that they use less public transit due to bikeshare is more than the percentage of users who said they increased public transit travel in three of the cities, Montreal, Toronto, and Washington, D.C. The only one of the four in which more travelers indicated that their usage of public transit increased was the Twin Cities (Minneapolis and Saint Paul, Minnesota). The authors believed that this difference was caused by the density of the city and existing level of service provided by public transit [3]. A more detailed analysis using the same survey data was conducted by Martin and Shaheen. They found that in Washington, D.C., those shifting toward bus and rail transit live on the urban periphery, whereas those living in the urban core tend to use public transit less. In Minneapolis, the shift toward rail extends to the urban core, while the modal shift for bus transit is more dispersed. The conclusion drawn by the authors is that public bikeshare may be more complementary to public transit in small to mid-size cities and will become a substitution for public transit in larger and denser cities [4]. To analyze the impact on car substitution of bikeshare, Fishman et al. used survey data where bikeshare users from five cities around the world were asked, "Thinking about your last journey on bike share, which mode of transport would you have taken had it not existed?". They concluded that for 2012, bikeshare usage was responsible for a decrease in car travel of 115,826 km in Melbourne and 632,841 km in London. However, with the truck mileages generated from rebalancing the bikes at different stations, the authors found that motor vehicle support services traveled 344,446 km more than the vehicle kilometers of travel avoided when bikeshare replaces car use [5]. Jappinen et al. used data collected from Journey Planner, a public internet service provided by Helsinki Region Transport, to provide information about the optimal route between a given origin and destination by public transit at a given time of a day to study the potential travel time savings that can be offered by bikeshare. Their analysis concluded that a bikeshare system would decrease public transportation travel times. On average, travel time would be 6 minutes shorter when combining public transit with bikeshare than when using public transit alone. The time savings, however, vary according to location. In the city center area, the difference is smaller. The busiest stations were found to be near the railway and metro stations. The authors concluded that it is possible that a large-scale bikeshare system can complement a traditional public transit system [6]. Singleton et al. concluded that transit and cycling were short-term mode substitutes but might be long-term complements [7]. Campbell and Brakewood concluded that bikeshare competed with buses and resulted in a 2.42% decrease in bus trips per thousand docks along a bus route [8]. Ma et al., however, drew the opposite conclusion regarding the relationship between rail and bikeshare. They believe that a 10% increase in annual bikeshare ridership contributed to a 2.8% increase in average daily Metrorail ridership [9]. Fuller et al. studied the bikeshare trips during a transit strike in Philadelphia. Their results showed that in the face of a major transportation constraint, large-scale adoption of biking as a transportation mode is possible. Although after the strike bikeshare usage decreased to normal levels. The authors believe that by enhancing the service on rebalancing bikes, the bikeshare program usage among less-frequent users is likely to increase [10]. Saberi et al. indicated that when the public transportation is constrained, a large-scale adoption of cycling can occur, indicating a similarity in the pool of public transportation users and bike users [11].

Since the outbreak of COVID-19, some researchers have studied the resulting changes in travel, including bikeshare and other modes [12-14]. Hu et al. found that during the COVID-19 pandemic, bikeshare usage at stations near the city center decreased more than at stations in other places [15]. Teixeira and Lopes found about a 71% decrease in bikeshare trips in New York City. However, compared to the overall 90% drop in the subway system usage, bikeshare is believed to be resilient and rebound more quickly [16]. Using data collected from Budapest, Bucsky concluded that bikeshare became more popular during the pandemic [17]. Song et al. concluded that bikeshare systems may serve as a replacement mode when public transit services are restricted due to lockdown policies and have the potential to facilitate a disease-resilient transport system [18]. Nikiforiadis et al. analyzed some survey data from Thessaloniki, Greece, and concluded that bikeshare is now more likely to become a more preferable mode for people who were previously commuting with private cars as passengers (not as drivers) and existing bikeshare subscribers [19]. The study by Kim and Cho indicated that the COVID-19 pandemic weakened the competitive relationships between bikeshare and bus transit and modal integration between bikeshare and subway in Seoul, Korea. They concluded that bikeshare increases the overall resilience of the public transit system as an alternative to short-term bus trips as well as long-term subway trips in response to a disastrous pandemic situation [20]. Jie et al. believed that short trips between transit stations or bus stops may be replaced by shared bikes and, therefore, they concluded bikeshare may have the ability to absorb additional travel demands due to reduced capacities of public transit services [21].

As can be seen, while bikeshare is a promising mode in reducing the carbon footprint of the transportation system, it has not been fully utilized before due to the wide availability of other modes. The COVID pandemic provided us with an opportunity to study bikeshare usage when travelers needed to limit their usage of other shared modes of transportation. If we can better understand the travel behavior of bikeshare users during the COVID pandemic and provide travelers with better designed bikeshare systems, we will be able to encourage people to make a better use of bikeshare and create a more sustainable transportation system.

DATA EXPLORATION AND ANALYSIS

Since previous studies concluded that the behavior of bikeshare subscribers and casual users differs, as well as behavior on weekdays versus weekends, for the rest of the paper we separate the data into four different categories for data analysis: subscribers/casual users and weekday/weekend trips.

The following datasets were acquired:

- Bus ridership by route from the city of Chicago data portal[1]
- Rail ridership by station from the city of Chicago data portal[2]

[1] https://data.cityofchicago.org/Transportation/CTA-Ridership-Bus-Routes-Daily-Totals-by-Route/jyb9-n7fm

[2] https://data.cityofchicago.org/Transportation/CTA-Ridership-L-Station-Entries-Daily-Totals/5neh-572f

- Bikeshare data were obtained from DIVVY®. Data from 2019 were downloaded from the City of Chicago data portal[1] and the data from 2020 were downloaded from the DIVVY website.[3]
- Trips served by transportation network companies (TNCs; e.g., Uber and Lyft), downloaded from the city of Chicago data portal[4]
- Bike facilities in the city, obtained from the Chicago Department of Transportation (CDOT)

Figure 1 illustrates the existing biking facilities in the city of Chicago. Of the total system of 342 miles, neighborhood greenway and protected bike lanes take up 62 miles, buffered bike lanes 113 miles, and the rest of the facilities (shared lane or bike lane) 167 miles. In total, there are 842 bike stations with 12,904 bike docks.

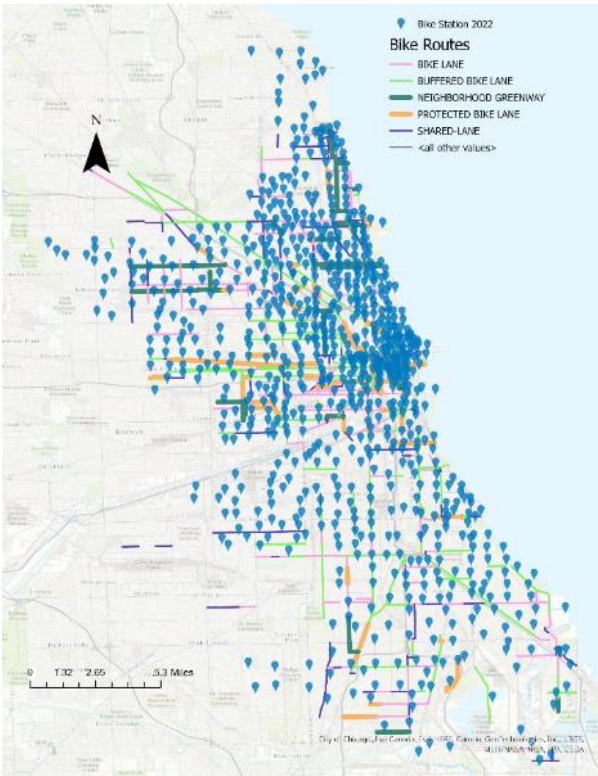


Figure 1 Bike facilities in Chicago.

Table 2 through Table 4 illustrate statistics for bikeshare, bus, rail, and ride-hailing travel. As can be seen in Table 2, bikeshare travel by casual users on weekdays increased significantly in trip frequency. No significant change was observed in trip time. Bikeshare travel by casual users on weekends decreased slightly in trip frequency but increased in trip time. For subscribers, trip frequency decreased for both weekdays and weekends. However, there was a significant increase in trip time. The standard deviation for trip time is larger for both casual users and subscribers, indicating a larger variation in the bike trips. As can be seen from Table 3, ride-hailing trips dropped significantly for both weekends and weekdays. The trip lengths increased in 2020 on both weekends and weekdays along with decreased trip times, indicating longer trips by ride-hailing users in a less-congested traffic network where the trips could be accomplished in a much shorter time. Table 4 provides bus and rail ridership. The use of public transit, for both buses and rail,

[3] https://divvy-tripdata.s3.amazonaws.com/index.html

[4] https://data.cityofchicago.org/Transportation/Transportation-Network-Providers-Trips/m6dm-c72p

 doi:10.20944/preprints202209.0049.v1

decreased significantly, especially for rail, where ridership decreased by 77% (weekends) and 81% (weekdays).

TABLE 1 Statistics for Bikeshare Trips

USER TYPE	YEAR AND DAY TYPE	AVERAGE TRIPS PER DAY	TRIP TIME MEAN (SEC)	TRIP TIME MEDIAN (SEC)	STD
SUBSRIBER	2019 Weekday	15,008	812	636	952
	2019 Weekend	9,517	972	743	1,353
	2020 Weekday	10,050	989	764	1,257
	2020 Weekend	6,579	1,215	957	1,687
CASUAL	2019 Weekday	5,118	2,307	1,506	3,258
	2019 Weekend	10,184	2,595	1,714	3,260
	2020 Weekday	7,912	2,376	1,366	4,007
	2020 Weekend	9,063	2,958	1,716	4,519

Table 3. Statistics for Ride-hailing Trips.

YEAR AND DAY	TRIPS PER DAY	TIME MEAN (SEC)	TIME MEDIAN (SEC)	TIME STD	LENGTH MEAN (MILES)	LENGTH MEDIAN (MILES)	LENGTH STD
2019 Weekday	283,945	1,132.81	914.00	808.36	5.91	3.60	6.54
2019 Weekend	314,812	985.12	827.00	652.24	5.58	3.60	6.15
2020 Weekday	104,953	993.09	838.00	654.23	6.55	4.30	7.10
2020 Weekend	107,108	923.26	781.00	600.01	6.56	4.20	7.26

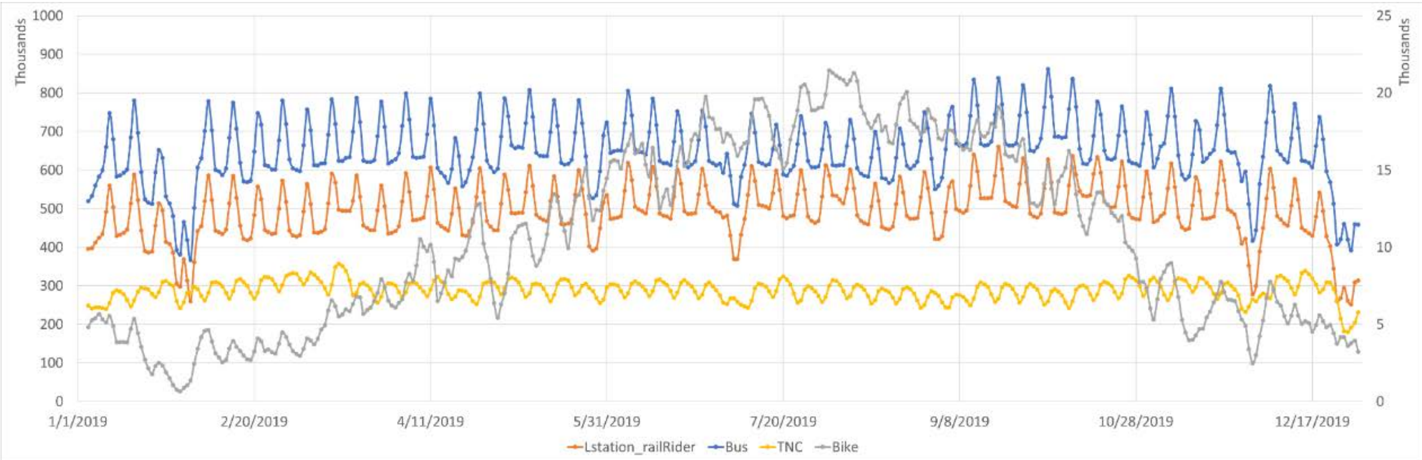
TABLE 2 Statistics for Public Transit Ridership (Per Day)

	YEAR/DAY TYPE	CITY SUM (THOUSAND)	MEAN	MAX	MIN	MEDIAN	STD
BUS (BY ROUTE)	2019 Weekday	758	6,017	23,396	4	4,281	4,281
	2019 Weekend	421	3,343	15,866	0	1,759	3,878
	2020 Weekday	306	2,431	11,546	0	1,618	2,432
	2020 Weekend	197	1,563	8,521	0	885	1,853
RAIL (BY STOP)	2019 Weekday	620	4,339	22,227	475	3,128	3,882
	2019 Weekend	326	2,281	11,396	256	1,470	2,289
	2020 Weekday	121	843	3,660	123	658	642
	2020 Weekend	74	519	2,307	75	366	431

Figure 2 shows the seven-day moving average of the number of trips made by different travel modes over 2019 (above) and 2020 (below). It describes the overall trend and changes of modes. As can be seen, in 2019 travel by bus, rail, and TNC was consistent over the whole year. Bikeshare travel, on the contrary, exhibited a seasonal variation. It started low in the first couple of months and rose during the warmer months. The volume peaked during the summer from July to September and then dropped when the temperature decreased in winter. The pandemic in 2020 changed the pattern. Bikeshare volumes dropped along with all the other modes when the pandemic hit and a shelter-in-place order was issued in March. The volume for bikeshare travel started to increase rapidly in May, while the other modes stayed low for the rest of the year. Bikeshare travel peaked and stayed high until November. This observation intrigues our interest in studying bikeshare during the pandemic in a more detailed way. We want to explore the possibility of using bikeshare as a routine commuting mode and the likelihood of using bikeshare jointly with other modes, especially public transit, after the pandemic. Because biking is dramatically affected by weather, to identify the real correlation among different modes we need to remove the effects of weather beforehand such that the travels of different modes can be compared without any bias. According to previous studies, temperature, wind speed, and precipitation are three major factors affecting bike travel [22-26]. Weather data were obtained from the Global Historical Climatology Network, a composite of climate databases from numerous sources that were merged and then subjected to a suite of quality assurance reviews.[5] Table 1 shows the weather data statistics for Chicago in 2019 and 2020. We used the following criteria as filters to identify days with good weather for bikeshare users based on previous research: temperature above 70 Fahrenheit, wind speed below 7 mph, amount of rain less than 0.1 inch/day, and no snow. Using these criteria, we extracted 66 good-weather days. Among them, 2019 had 28 days (8 weekend days and 20 weekdays) and 2020 had 38 days (9 weekend and 29 weekdays).

TABLE 3 Statistics for Weather

	YEAR	MEAN	MAX	MIN	STD	75TH PCTL	25TH PCTL
AVERAGE WIND (MPH)	2019	9.80	25.17	3.36	3.47	11.97	7.38
	2020	9.74	22.37	3.69	3.42	11.69	7.27
RAIN (INCH/DAY)	2019	0.12	2.22	0.00	0.28	0.11	0.00
	2020	0.11	3.39	0.00	0.32	0.05	0.00
AVERAGE TEMPRATURE (F)	2019	50	85	-15	20.34	68	35
	2020	53	87	6	18.69	71	37
SNOW (INCH/DAY)	2019	0.13	5.4	0	0.588	0	0
	2020	0.12	3.1	0	0.38	0	0



(a)

[5] https://www.ncdc.noaa.gov/cdo-web/search

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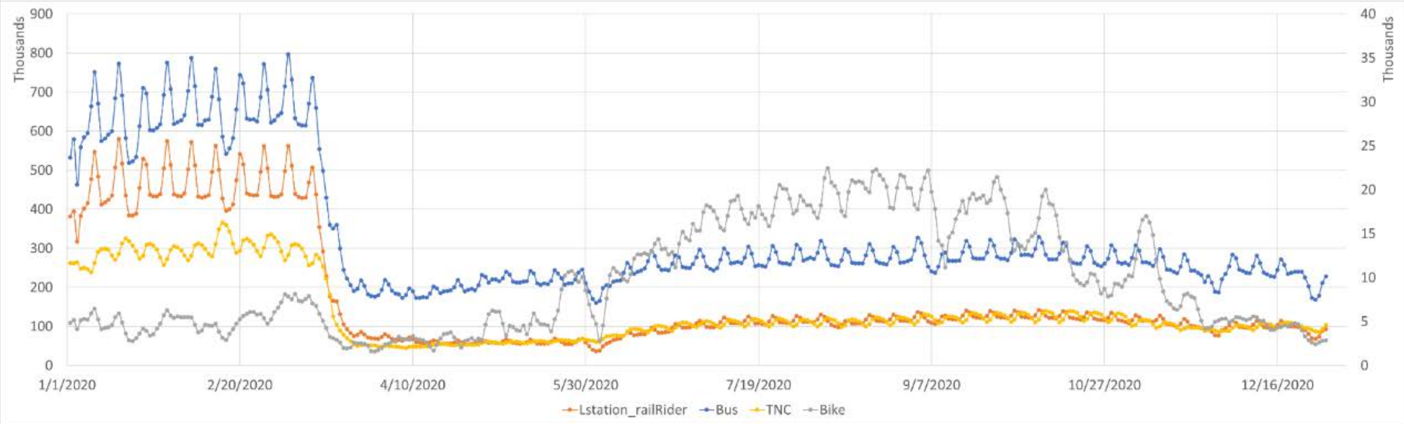

(b)

Figure 1 Trip trend by mode in (a) 2019 and (b) 2022

Intercorrelation of Bikeshare with Other Modes

We calculated the percentage of volume changes from 2019 to 2020, $Delta_{m,w,i}$, using the following equation for all the other modes besides bikeshare:

$$Delta_{m,w,i} = \frac{(Vol_{2020,m,w,i} - Vol_{2019,m,w,i})}{Vol_{2019,m,w,i}} * 100\% \qquad (1)$$

where m indicates different modes, w indicates weekdays or weekends, and i delegates the location i in which Vol_{2020} or Vol_{2019} occurred. Location i can be rail stations (for rail), bus routes (for buses), or census tract (for ride-hailing).

For bikeshare, the $Delta$ was calculated separately for casual users and subscribers and calculated using equation (2) for each bike station j.

$$Delta_{w,user,j} = \frac{(Vol_{2020,w,user,j} - Vol_{2019,w,user,j})}{Vol_{2019,w,user,j}} * 100\% \qquad (2)$$

where $user$ is either subscribers or casual users.

The histogram of $Delta$ for each mode is illustrated in Figure 3. As can be seen, rail and bus ridership decreased significantly. The majority of the rail stations had their ridership decrease by 50% to 100%. Most bus routes had their ridership decrease by 50% - 75%. A similar trend was observed for ride-hailing. The trips made by ride-hailing decreased variedly across different census tracts. Most of them had more than a 50% reduction. We divided bikeshare trips into two categories: by subscribers and by casual users. Overall, subscribers had fewer trips in 2020 than 2019. Half of the bike stations, however, had the bikeshare trips increased by subscribers. Casual users had a significant increase of trips in 2020. Some stations have double or triple the number of trips compared to 2019. The distribution of $Delta$ for casual bikeshare users ranged largely across the board from -50% to 500%. In the following section, we will investigate the spatial distribution and variations of different modes.

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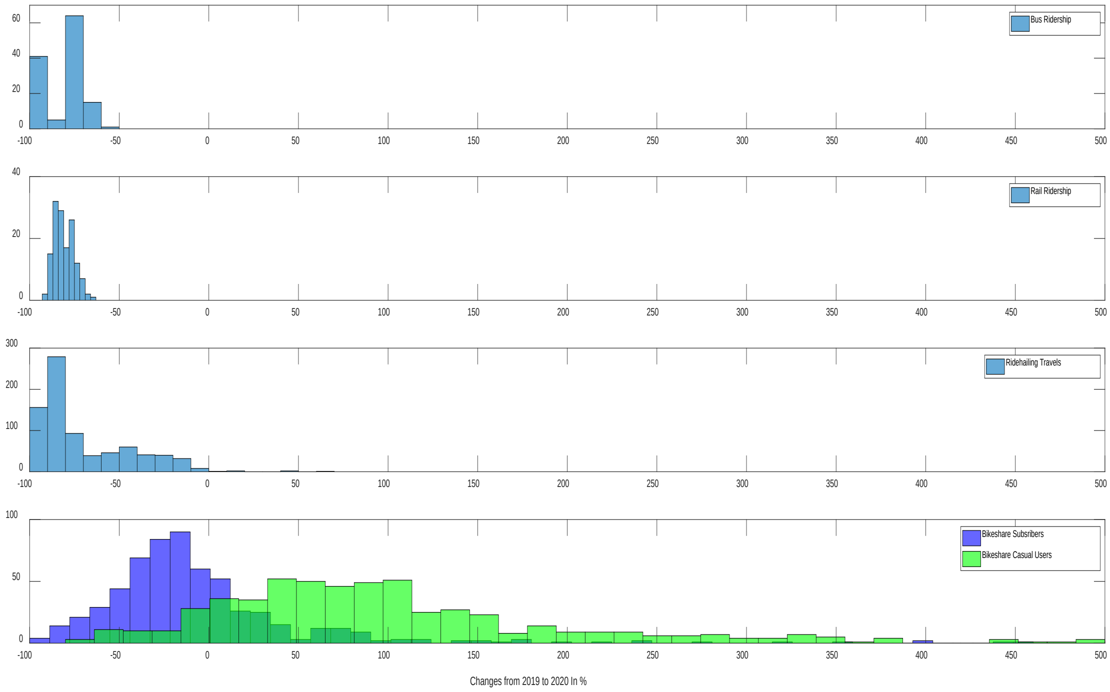


Figure 2 Histogram of changes in trip volume by mode

A difference ratio (DR) was calculated for each location i of rail station, bus route, or census tract using equation (3). DR is used to represent the relative changes (Difference in Difference) of bikeshare in relation to the change of volumes by another mode.

$$DR_{m,w,user,i} = \frac{Mean(Delta_{w,user,j\in 0.25\ mile\ of\ i})}{Delta_{m,w,i}} \qquad (3)$$

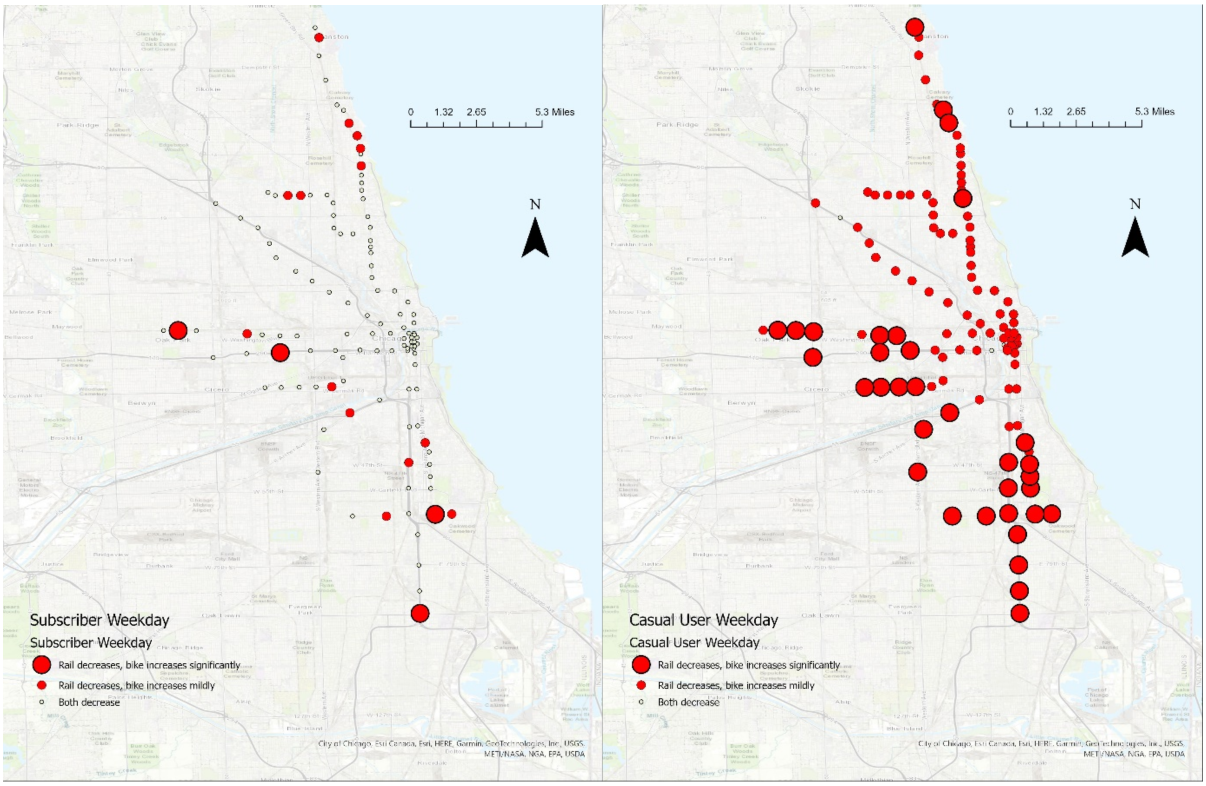
Here $Mean(Delta_{w,user,j\in 0.25\ mile\ of\ i})$ is the average of $Delta$ all the bike stations that are within 0.25 miles of a location i (rail station, a bus route, or a census tract, and the DR of mode m at location i of weekday or weekend (by casual users or subscribers) to other modes. The threshold value 0.25 mile is selected because this is a reasonable walking distance accepted by most travelers [27]. Due to the large range of the values of DR for different modes, we used different thresholds for a better visualization for the following figures. The threshold values we adopted are illustrated in Table 5. We then plotted the DR of rail, bus, and ride-hailing versus bikeshare in the figures below. Note that there is an extremely small number of locations that have both increased volumes in bikeshare and the other modes. After a careful examination, we illustrated these cases separately using different legends (as shown in blue and brown lines in Figure 5 or empty census tracts without green or red dots in Figure 6).

TABLE 4 Threshold Values for Visualization of DR

Mode	DR Threshold Value Range	Legend
Rail	<= -0.2	Rail decreases, bike increases significantly
	-0.2 - 0	Rail decreases, bike increases mildly
	> 0	Both decrease
Bus	<= -0.5	Bus decreases, bike increases significantly
	-0.5 - 0	Bus decreases, bike increases mildly
	> 0	Both decrease

Ride-hailing	<= -7	Ride-hailing decreases, bike increases significantly
	-7 - 0	Ride-hailing decreases, bike increases mildly
	> 0	Both decrease

Figure 4 illustrates the DR for bikeshare versus rail. As can be seen, the majority of the rail stations had a decrease in their ridership along with a decreased number of trips made by bikeshare subscribers (the left two panes). During weekdays, certain rail stations are surrounded by bikeshare stations with gently increased trip volumes in the northern part of the city. A few stations in the southern and western parts of the city are surrounded with bikeshare stations with significantly increased usage. For casual users, the pattern is completely different. The majority of the rail stations have bikeshare stations with increased usage associated with them, especially for weekday travel. These observations show that (1) subscribers might use bikeshare to replace some of their rail trips in the outskirt areas of the city; and (2) casual users might use bikeshare to replace the majority of their rail travel, especially during weekdays and at the periphery of the city.



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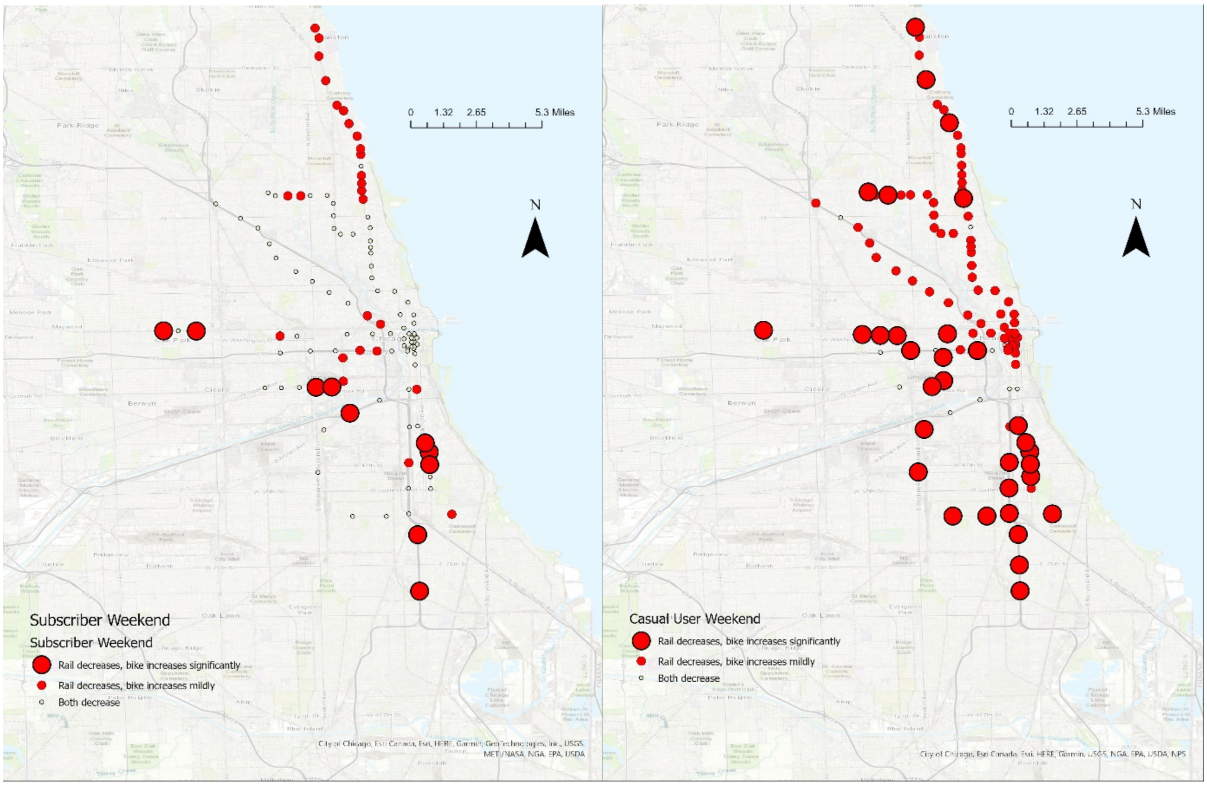

Figure 3 Rail and bikeshare (left upper: weekday subscribers; left lower: weekend subscribers; right upper: weekday casual users; right lower: weekend casual users)

Figure 5 shows the relationship between bus ridership and bikeshare usage. As can be seen, the majority of the bus routes had decreased ridership along with decreased bikeshare subscriber usage around them. The exception is located at the southern far end of the city. There are some routes in the southern part of the city that had ridership decrease but the surrounding bikeshare stations saw a significant increase in usage by subscribers, indicating that travelers used bikeshare to replace their bus rides in the remote area of the city. Casual bikeshare users increased their bikeshare trips significantly along with the decrease of bus ridership across the city for weekdays, indicating that they used bikeshare to replace bus riding during the weekdays. For weekends, the increase of bikeshare usage was not as significant as weekdays. Again, we observed that the increase of bikeshare usage in the areas other than downtown of the city, especially in the southern parts of the city, is more significant than in other areas. As can be seen, there are two sets of bus routes (in blue lines) that have increased ridership along with increased bikeshare usage (both for subscribers and casual users on both weekend and weekdays). These are promising locations that have high potential of integrating bus travels with bikeshare travels. Increasing bike stations in these areas is a valid plan for bikeshare development.

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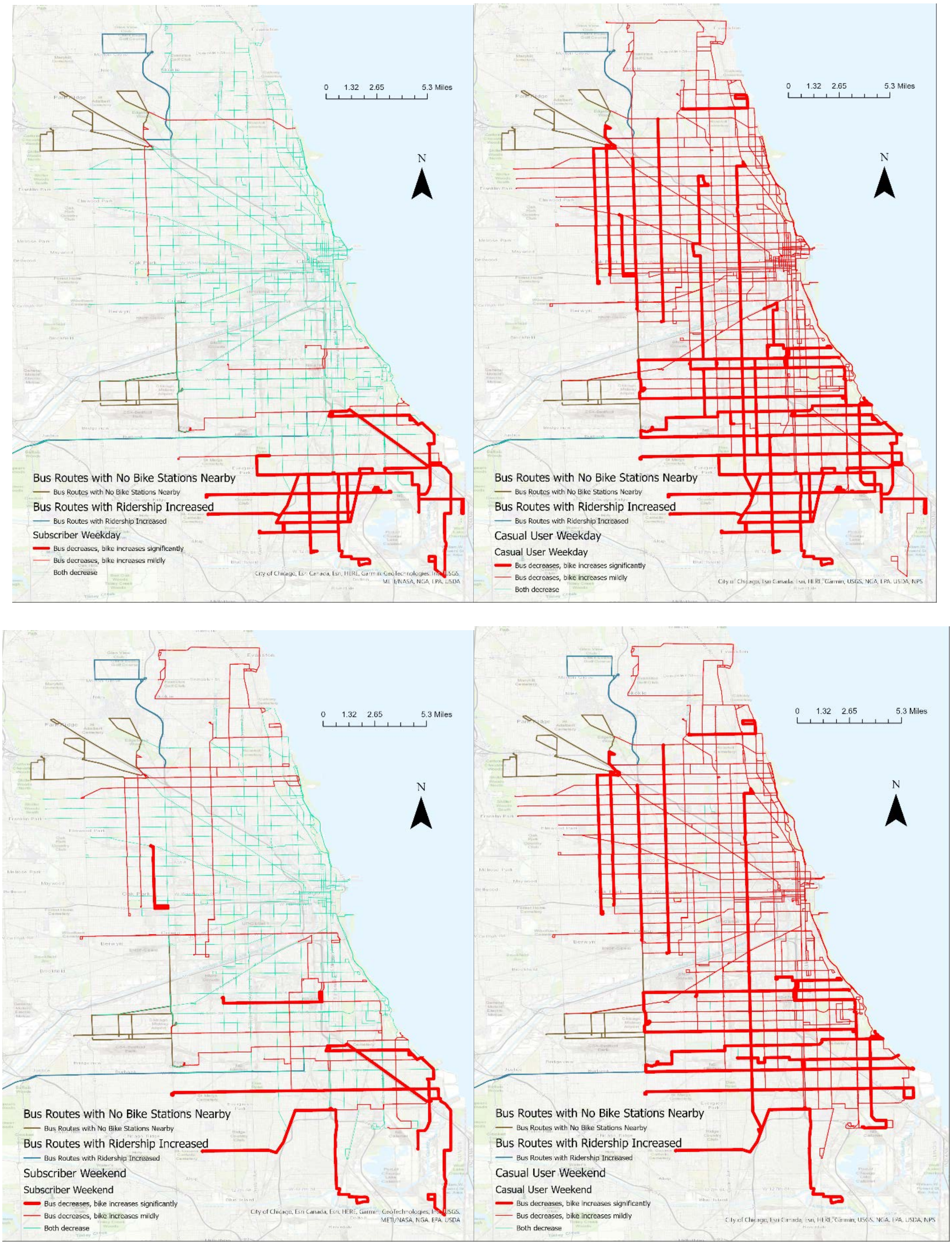
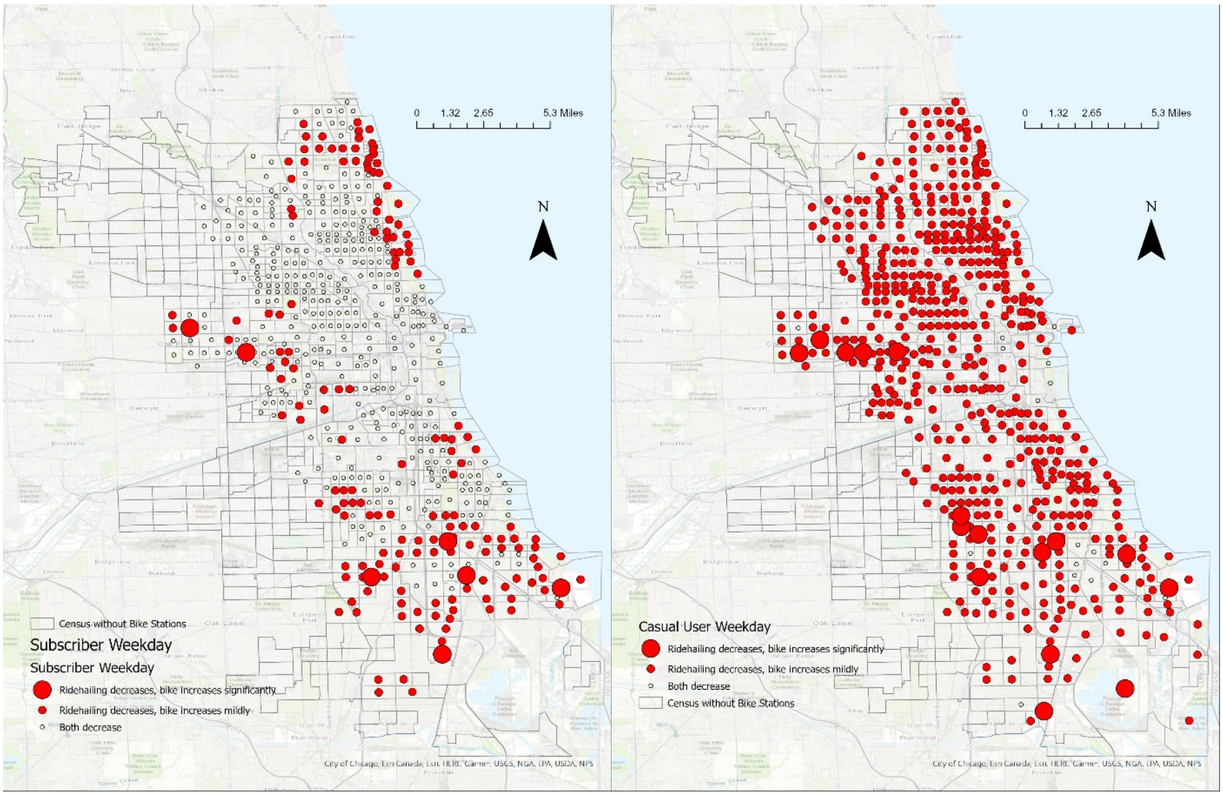


Figure 4 Bus and bikeshare (left upper: weekday subscribers; left lower: weekend subscribers; right upper: weekday casual users; right lower: weekend casual users)

Figure 6 shows the interaction between ride-hailing and bikeshare travel. Half of the census tracts have decreased ride-hailing travel along with decreased bikeshare travel by subscribers (left panes). About half of them have slightly increased bikeshare travel by subscribers along with decreased ride-hailing travel. Several census tracts in the western and southern part of the city have significantly increased bikeshare travel by subscribers. As for casual users, during weekdays the majority of the census tracts had increased bikeshare travel along with decreased ride-hailing travel. Certain tracts, the ones in west outskirts and southern part, saw significant increase in bikeshare travel along with decreased ride-hailing travel. For weekends, the increase of bikeshare is not as significant as weekdays. However, it is still evident that travelers made many more bikeshare trips than ride-hailing trips.

In summary, when comparing the changes in bikeshare travel during the pandemic versus the changes in other modes, we can see that subscriber bikeshare travel increased significantly along with the reduction of other modes in the outskirts areas of the city. Bikeshare travel by subscribers in the center area of Chicago had a similar decreasing trend as other modes. For casual users, however, weekday travel by bikeshare increased along with the reduction of other modes. There is not much spatial difference for the DR values in the downtown area, but in the southern part of the city, significant bikeshare usage increase is observed along with reduced trips of other modes. On weekends, casual users tended to make significantly more bikeshare trips, along with reduced bus, rail, or ride-hailing trips, at the outskirts of the city.

Since we are specifically interested in the relationship between bikeshare travel and the public transit trips, in the next section we will concentrate on the analysis of bikeshare trips versus travel by bus and rail.



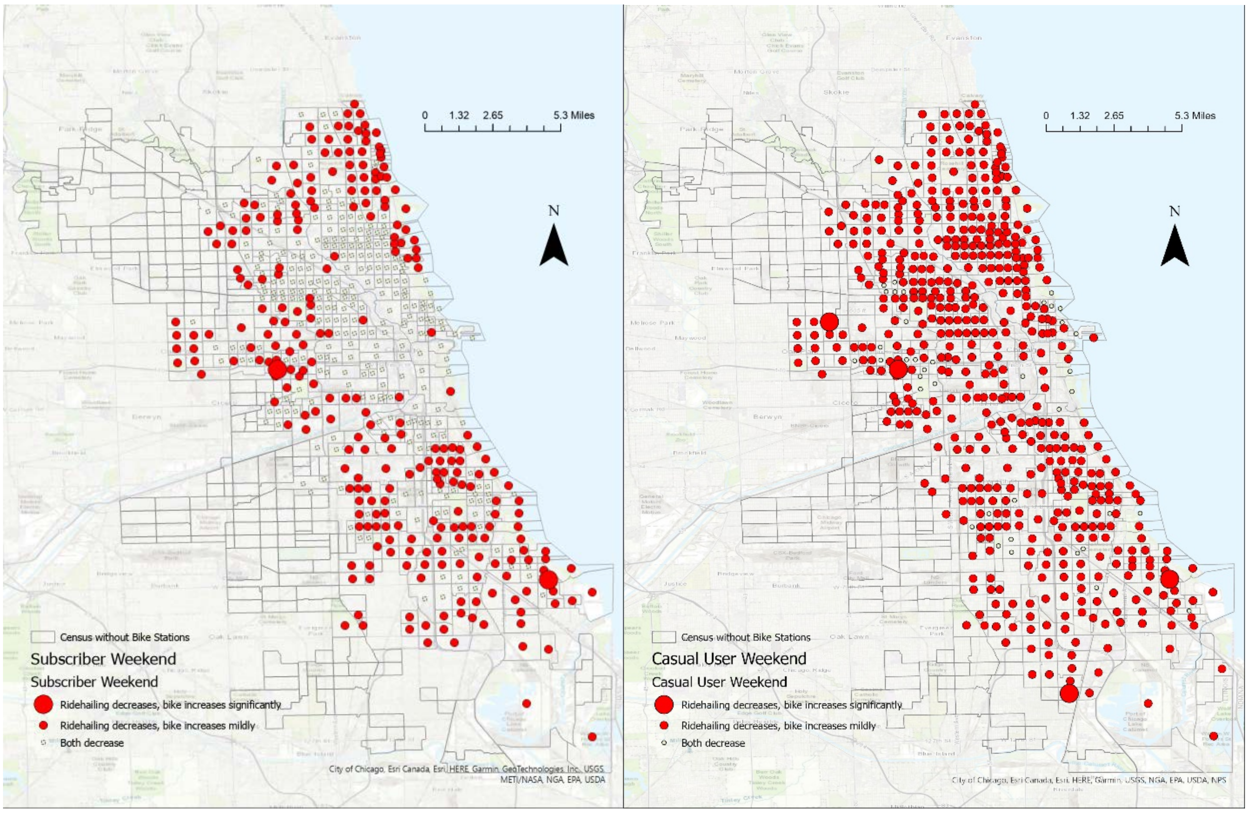


Figure 5 Ride-hailing and bikeshare (left upper: weekday subscribers; left lower: weekend subscribers; right upper: weekday casual users; right lower: weekend casual users)

Bikeshare and Public Transit

In order to enable more effective public policies that encourage travelers to maximize these sustainable and healthy travel modes, we need to explore the changes between bikeshare usage and public transit. Therefore, we spatially join the bikeshare stations to each of the following data layers: bus stops, bus routes, rail stations, and bike facilities (bike lanes shown in Figure 1). The distance of a bike station to each of the data layer features was categorized into the following five groups: < 200 feet (extremely easy access to bike stations), 200-500 feet (easy access to bike stations), 500-1,320 feet (moderately easy access to bike stations), 1,320-2,640 feet (accessible bike stations), and > 2,640 feet (remote bike stations). The $Delta_{w,user,j}$ are plotted in the boxplots from Figure 7 through Figure 11.

As can be seen from Figure 7, the bike stations that are further away from bike routes had the highest percentage increase for three categories of the user/time period. The only exception is for the subscribers on weekdays. Indeed, there is a slightly increasing trend of bikeshare usage for bike stations that are located further away from biking facilities. While observing the spatial distribution of the bike routes and bike stations, as can be seen from Figure 1, existing bike routes are not distributed evenly across the city. The downtown and northern part of the city have a much higher density of bike routes. As illustrated in the earlier section of the paper, the bike stations with higher increases are in the southern part or at the west border of the city. Therefore, this observation is consistent with the fact that stations that are at the outskirts of the city have a larger increase in bikeshare usage. Users are employing bikeshare to reach locations that were not traveled by bikeshare users before. The fact that there is no significant difference among different distance categories of bike stations to the closest bike routes for subscribers on weekdays indicates that subscribers were not affected by the availability of bike facilities/routes for their weekday travels. This is a user group that makes bikeshare trips with or without bike lanes on weekdays.

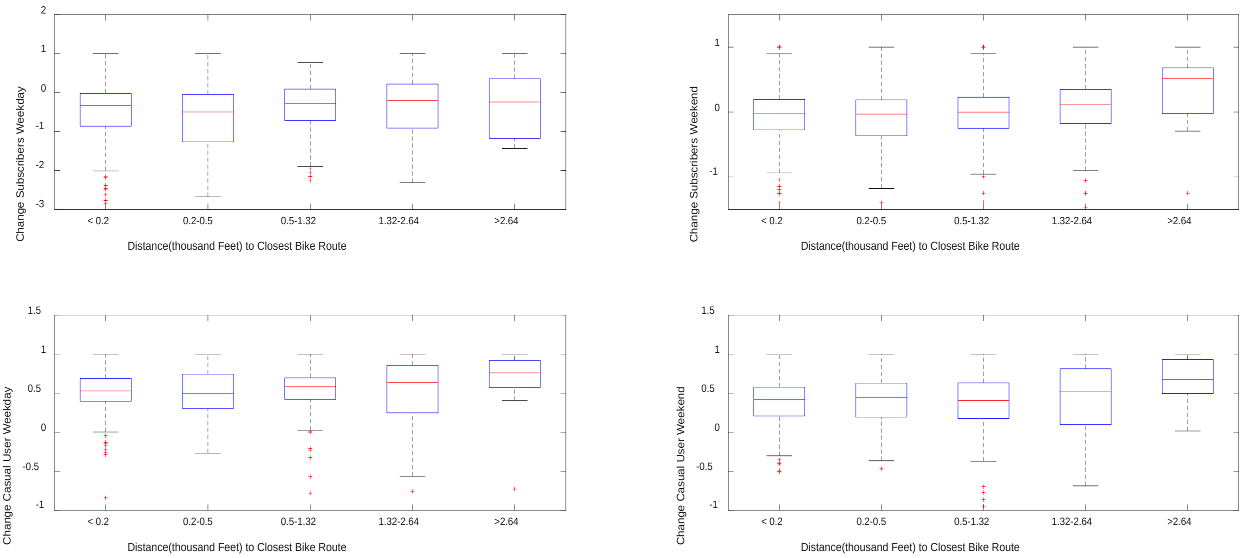


Figure 6 Changes in bikeshare trips by distance to the closest bike facilities

There were no significant differences for $Delta_{w,user,j}$ of bikeshare stations located further from or closer to bus stops and bus routes for the majority of the user and time categories (Figure 8 and Figure 9). One noticeable fact relates to the trips made by subscribers. As can be seen, the ranges for the changes of trips at bike stations that are within 0.5 miles (2.64 thousand feet) of bus stops are relatively small, indicating more consistency for subscriber trips.

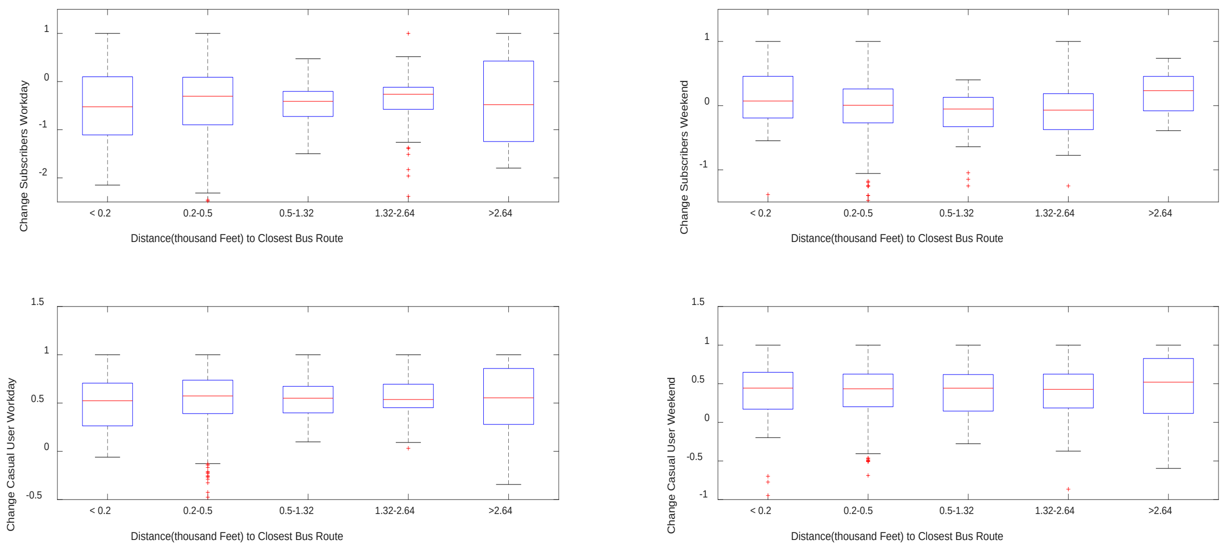


Figure 7 Changes in bikeshare trips by distance to the closest bus routes

 doi:10.20944/preprints202209.0049.v1

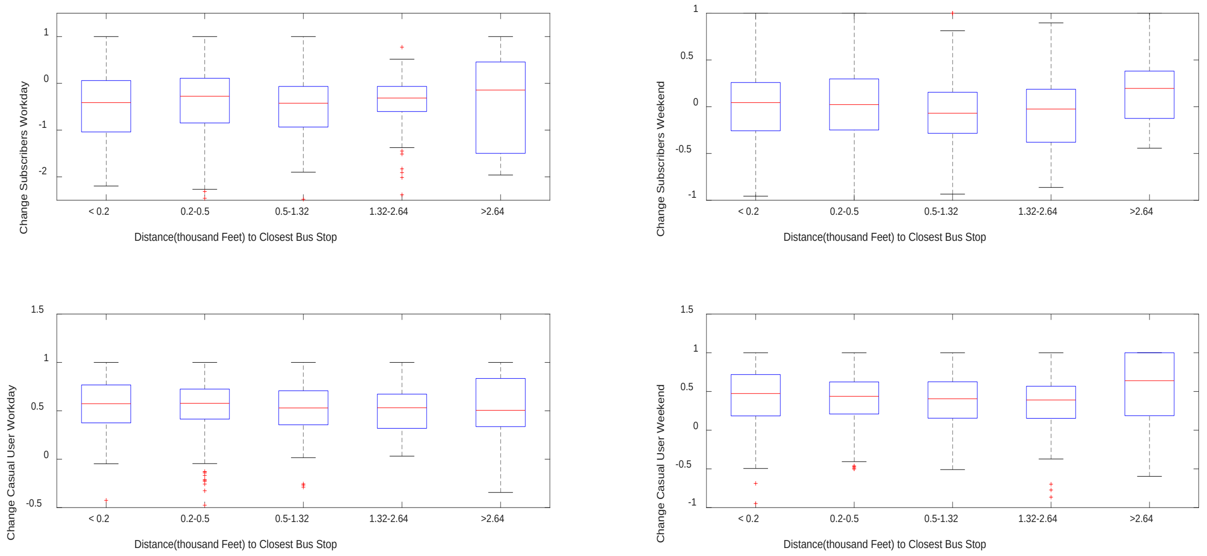


Figure 8 Changes in bikeshare trips by distance to the closest bus stops

Figure 10 shows the relationship of changes of bikeshare trips versus the distances of bike stations to rail stations. There is a concave trend as the bikeshare stations get further away from rail stations. For subscribers, the decrease of bikeshare trips becomes smaller when the bike stations are either located closer or further away from rail stations. For casual users, the increase of bikeshare trips is larger at stations that are either close or further away from rail stations. This observation indicates that bikeshare users used bikeshare more to connect with their rail trips (at bikeshare stations closer to a rail station) or replace their rail trips (at bikeshare stations further away from a rail station). Either case, we can conclude that bikeshare usage is closely related to rail travels.

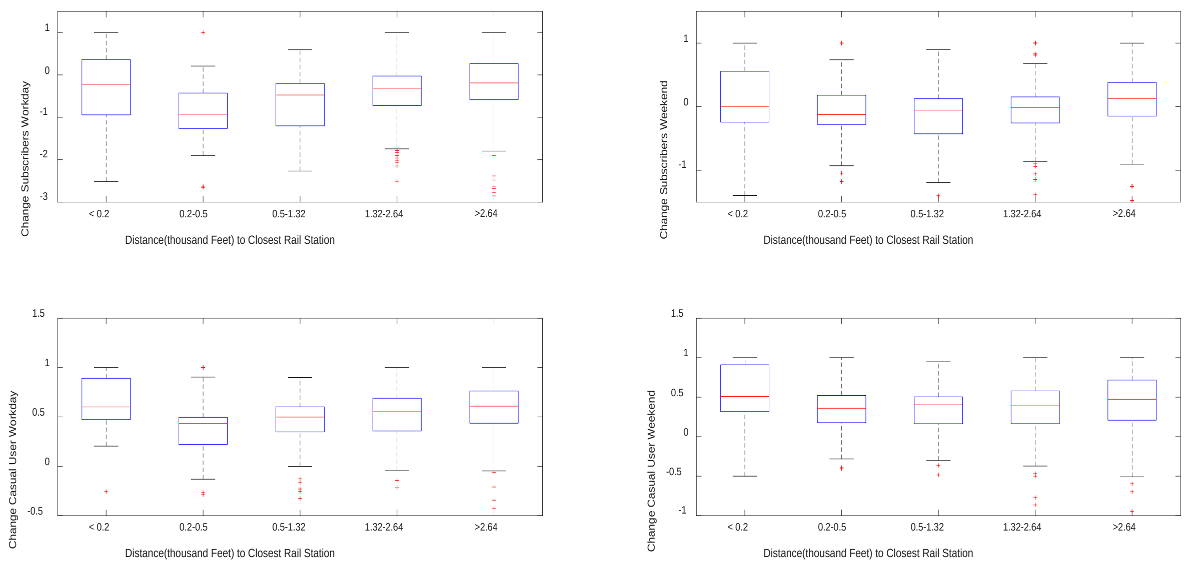


Figure 9 Changes in bikeshare trips by distance to the closest rail stops

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Figure 11 illustrates the changes at bike stations in relation to the type of the closest bike facility. If there are no bike lanes within a 2-mile distance of the bike station, that station will have "none" as the closest bike facility in the figure. As can be seen, for workdays, the largest increase occurred at bikeshare stations that have easy access to greenways. While looking at the locations of the greenways (Figure 1), we can see that the majority of the greenways are in the downtown area. We may infer that bikeshare users might use bikeshare to serve their commuting needs. However, more survey data are needed in the future to confirm this inference. For weekends, the largest increase occurred at bike stations that do not have any bike facilities close by. One plausible explanation is that weekend bikeshare trips increased more at locations that are typically remote to downtown areas that are well served by biking facilities.

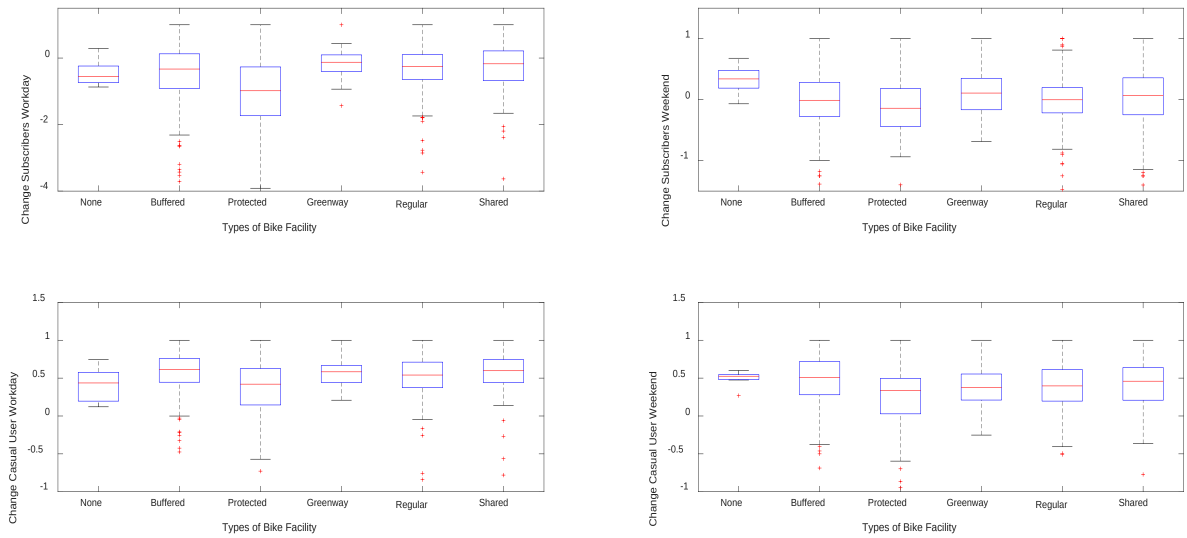

Figure 10 Changes for stations with the type of the closest bike route

("none" indicates there is no bike facility in a 2-mile radius.)

To identify all the factors that impact the changes in bikeshare trips, we conducted a 7-way analysis of variance (ANOVA) test to identify significant factors. The results are illustrated in Table 6. As can be seen, bus stops or bus routes have no impact on the changes in bikeshare usage. Whether if there is a bike facility close by, the distance of the bike station to a rail station, the user type, and the time (weekday or weekend) that the trips occurred are significant factors affecting the changes in bikeshare trips.

Table 5 ANOVA Results

	Sum Square	Degree of Freedom	Mean Square	F-test	Prob>F
Bike Facility Type*	37.95	5	7.591	10.57	0
Distance to Bike Facility	3.74	4	0.934	1.3	0.268
Distance to Bus Stop	0.73	4	0.183	0.25	0.907
Distance to Bus Route	2.32	4	0.58	0.81	0.52
Distance to Rail Station*	32.61	5	6.523	9.08	0
User type*	358.53	1	358.53	499.03	0
Weekday/Weekend*	30.03	1	30.032	41.8	0
Error	1755.91	2444	0.718		

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Total	2233.49	2468

* **Significant at 0.05**

DISCUSSION AND CONCLUSIONS

Biking is a healthy and sustainable means of travel. Bikeshares provide travelers with this mode without having to worry about the storage and transport of bikes. Although promising, bikeshare is not as widely used in the US compared to other countries in Europe. Over the past several decades, numerous studies have been conducted to design policies stimulating active transport or study the effectiveness of such policies [10, 28-32].

During the pandemic, bikeshare usage dropped along with other modes of transportation but bounced back quickly and stayed relatively high in volume. Bikeshare has proven to be a resilient and equitable mode [15] adopted by more travelers. We see the possibility of using bikeshare as a routine travel mode even after the pandemic. Therefore, it is now more important than ever to understand the behavior of bikeshare users, obstacles to using it as a routine commuting mode, feasible and effective policies that can sustain bikeshare usage, and possible rules to encourage the usage of bikeshare together with public transit.

In this paper, we studied bikeshare travel along with other non-personal-vehicle travel before and during the pandemic in the city of Chicago. By identifying variations and intercorrelation of these modes, we believe that the results can answer some of the questions regarding bikeshare travel and eventually help policy makers to design a biker-friendly traffic system. Two unique features of our study are (1) all the data analysis is based on data under biker-friendly weather conditions, which we do to exclude the biased impacts of weather on different travel modes; and (2) the dependent variable we analyzed in this paper is the relative change of different modes, $Delta$, before and during the pandemic. By using $Delta$ instead of absolute volumes, we are avoiding bias by the capacity.

Our conclusions are as follows. (1) Bikeshares are potentially acceptable in longer trips that may serve as regular commuting trips. As can be seen from our analysis, trip lengths of bikeshare subscribers on weekdays increased significantly during the pandemic. (2) Subscribers have a stable travel demand for bikeshare during weekdays. Whether the bike stations are close or not close to a public transit facility will have minimal impact the bikeshare travel of subscribers. (3) The changes in bikeshare travel are heterogeneously distributed over space: our analysis showed that the bikeshare travel increased most significantly in the more remote areas. The authors believe that travelers are using bikeshare to reach destinations that were not served as usual destinations in bikeshare travel before the pandemic. This conclusion is in accordance with the fact that bikeshare travel during the pandemic is longer [15, 33] and is consistent with previous studies [4, 11, 15]. It implies that a more connected bikeshare network can be achieved either by increasing the number of stations in remote areas, adjusting the pricing strategy, or optimizing the rebalancing strategy to favor remote areas [29]. Interventions, either fiscal or policy-related, if adopted effectively, will be helpful to increase the usage of bikeshare. (4) Bikeshare usage will be increased with effective infrastructure design and policy subsidy. Caggiani et al. and Hamidi et al. found that during a lockdown period, people living in deprived areas may need more outdoor activities than those living in wealthier areas. In our study, we also found that the bikeshare stations with the larger changes are in the southern part of the city, where the income level is relatively low. Therefore, we should take equity into consideration when planning bikeshare infrastructure [34, 35]. (5) Weekday trips increased bikeshare usage at stations associated with biking facilities (greenways) close by, while weekend trips had a higher bikeshare increase at locations without any biking facilities. This observation tells us that during weekdays with heavier traffic flow, travelers would like to use bikeshare with biking routes. However, users want to use bikeshare even without biking lanes during the weekend when the traffic volume is relatively light to reach more remote locations. If more biking facilities can be built on the outskirts of the city, it will be a positive incentive for bikeshare users on weekdays. (6) Bikeshare travel is more likely to be correlated with rail travel. There is a minimum connection of bikeshare travel with bus stops or bus routes. This conclusion is consistent with previous studies [8, 33]. We recommend a better coordination in planning rail stations and bikeshare stations since the evidence in this paper showed that travelers are likely to use bikeshare to connect/extend their rail travel or reach locations that are not served by rails.

The limitation of this study is that the results are only drawn from objective data. In the future, stated preference surveys are needed to collect data regarding the opinions and thoughts of bikeshare users; for example, what are the factors limiting further or more usage of bikeshare. Such data can be incorporated into the analysis of objective data for us to better understand the behavior of travelers and improve the resilience of the system.

ACKNOWLEDGEMENTS

This study was sponsored by The Urban Mobility & Equity Center (UMEC).

AUTHOR CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: Du and Rakha; analysis and interpretation of results: Du and Rakha; draft preparation: Du and Rakha. All authors reviewed the results and approved the final version of the manuscript.

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