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Should bike-sharing continue operating during the COVID-19 pandemic? Empirical findings from Nanjing, China

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ABSTRACT

Introduction: Coronavirus disease 2019 (COVID-19) has triggered a worldwide outbreak of pandemic, and transportation services have played a key role in coronavirus transmission. Although not crowded in a confined space like a bus or a metro car, bike-sharing users are exposed to the bike surface and take the transmission risk. During the COVID-19 pandemic, how to meet user demand and avoid virus spreading has become an important issue for bike-sharing.

Methods: Based on the trip data of bike-sharing in Nanjing, China, this study analyzes the travel demand and operation management before and after the pandemic outbreak from the perspectives of stations, users, and bikes. Semi-logarithmic difference-in-differences model, visualization methods, and statistic indexes are applied to explore the transportation service and risk prevention of bike-sharing during the pandemic.

Results: Pandemic control strategies sharply reduced user demand, and commuting trips decreased more significantly. Some stations around health and religious places become more important. Men and older adults may be more dependent on bike-sharing systems. The declined trips reduce user contacts and transmission risk. Central urban areas have more user close contacts and higher transmission risk than suburban areas. Besides, a new concept of user distancing is proposed to decrease transmission risk and the number of idle bikes.

Conclusions: This paper is the first research focusing on both user demand and transmission risk of bike-sharing during the COVID-19 pandemic. This study evaluates the mobility role of bike-sharing during the COVID-19 pandemic, and also provides insights into curbing the viral transmission within the city.

1. Introduction

Coronavirus disease 2019 (COVID-19) is an infectious disease caused by the Severe Acute Respiratory Syndrome coronavirus 2 (SARS-CoV-2), and was first discovered in Wuhan, China, in December 2019. Because of the alarming levels of spread and severity, the World Health Organization has characterized COVID-19 outbreak as a pandemic (World Health Organization, 2020). As of August 3,
2021, COVID-19 pandemic has caused 199,251,741 confirmed cases and 4,241,509 deaths (Johns Hopkins University, 2021). Compared with survivors, the deaths are more likely to have chronic medical illnesses and are older (Yang et al., 2020). SARS-CoV-2 could remain infectious in aerosol for hours and on the surfaces of stainless steel and plastic for up to 3 days (van Doremalen et al., 2020). Transmission of COVID-19 can occur through droplets and touching the surface with the coronavirus. COVID-19 poses a huge challenge for the travel demand and service safety of urban transportation.

Shared micro-mobility (SMM) is the latest trend of urban transportation, and bike-sharing is the core component of SMM. The SMM refers to shared-use fleets of small, manually or electrically powered vehicles (National Association of City Transportation Officials, 2020). Examples include electric scooter sharing, station-based bike-sharing (SBS), dockless bike-sharing (DBS), and electric bike-sharing. The SMM plays a key role in urban transportation amidst this pandemic. Unlike public transport and taxi, bike-sharing provides services in open spaces and causes fewer safety concerns. During the COVID-19 shutdown period, bike-sharing in Wuhan became the most frequently used travel mode and provided healthcare staff essential mobility services (CNR News, 2020). However, some cities and companies still stopped SMM services after the outbreak because of the safety concerns about virus transmission. Lime and Bird suspended their services of bike-sharing and electric scooter sharing in many cities worldwide (Plautz, 2020; Gauquelin, 2020). The SMM faces a tough trade-off between operational service and health safety during COVID-19.

COVID-19 has caused a global health crisis in the past months, and transportation service has been profoundly affected as a result. However, there are very few studies exploring the role of bike-sharing during the pandemic. And pandemic control measures on urban transportation still lack research. Furthermore, the outbreak coincided with the 2020 Chinese New Year (CNY) holiday, making it difficult to assess the impact of the pandemic on bike-sharing. This paper estimates the travel demand and transmission risk of bike-sharing during COVID-19 using the trip data of Nanjing Public Bicycle. This paper aims to help promote the SMM operation and reduce virus transmission risk, by comprehensively analyzing bike-sharing service from multiple perspectives of users, stations, and bikes. To the best of our knowledge, this paper is the first research focusing on both user demand and transmission risk of bike-sharing during the COVID-19 pandemic.

This paper is divided into seven sections. Following the introduction, the second section presents the literature review about COVID-19 and transportation. The third section describes the data sources and processing procedures. The fourth and fifth sections present the travel demand change based on station and user perspectives. The sixth section analyzes the COVID-19 transmission risk through shared bikes. The last section presents the conclusion and discussion.

2. Literature review

Pandemic control strategies have been applied to contain and mitigate the COVID-19 outbreak. These measures include quarantine of infected cases, self-isolation, social distancing (Chen et al., 2020), cleaning touched surfaces, and wearing personal protective equipment (PPE) such as masks and gloves (BBC News, 2020). Effective contact tracing and case isolation is enough to control COVID-19 outbreak in most scenarios (Hellewell et al., 2020). The social distancing strategy could be effective to reduce transmission and mitigate the pandemic (Fong et al., 2020).

Transportation service is a key factor that leads to the rapid spread of COVID-19, and restricting transportation is useful in slowing the pandemic spreading. Zhang et al. (2020) find that frequencies of high-speed trains and air flight services out of Wuhan are significantly related to the amount of infected cases. Because of the strong relationship between aviation services and pandemic spreading, air travel data are used to estimate the true size of Italian outbreak (Tuite et al., 2020). Chinazzi et al. (2020) confirm that international travel restrictions slow virus spreading around the globe. Tian et al. (2020) find that suspending public transport is related to the reduction of COVID-19 cases.

There have been some exploratory studies about the impacts of COVID-19 on transportation, but urban transportation and shared mobility are rarely considered. Suau-Sanchez et al. (2020) discover that the impact of COVID-19 on international air transport has been stronger than that on domestic airlines. Loske (2020) finds that the increasing freight volume for dry products in retail logistics depends on the increase of infected cases. Mogaji (2020) recognizes that transportation in Lagos, Nigeria was affected by this pandemic, including increased travel cost, shortage of travel mode, and traffic congestion.

Some studies have discussed transport supply during COVID-19 from a qualitative perspective. Budd and Ison (2020) propose the concept of Responsible Transport for post-COVID management, and stress that the individuals should assess the risk of their trips and take action accordingly. Musselwhite et al. (2020) suggest that reducing hypermobility of the transportation network and focusing on local connectivity could address virus threat. De Vos (2020) recommends that cycling can maintain satisfactory levels of health and wellbeing, and active travel should be encouraged to cope with the problems of social isolation and limited physical activity.

COVID-19 can be transmitted through aerosol and surface, so bike-sharing in open spaces is much safer than public transport and taxi in confined spaces. Bike-sharing increases its modal share among all travel modes and provides critical mobility services during the outbreak (CNR News, 2020). But the transmission risk through these shared vehicles has not been evaluated quantitatively. Extensive studies about bike-sharing have explored improving the planning and operation of bike-sharing, to provide better services for users. Previous studies about bike-sharing can be generally classified into three categories: (1) user demand (Wang et al., 2018; Biehl et al., 2019; Cheng et al., 2020; Reilly et al., 2020; Chen et al., 2021); (2) bike rebalancing (Caggiani et al., 2018; Bruck et al., 2019; Huang et al., 2020); and (3) parking allocation (Lin et al., 2018; Loidl et al., 2019; Hua et al., 2020).

Most existing papers on bike-sharing are about normal operation, and there are only very few papers focusing on bike-sharing amidst the COVID-19 pandemic. Teixeira and Lopes (2020) find the possible evidence on a modal transfer from the subway to bike-sharing in New York City during COVID-19. Nikiokos et al. (2020) conduct a questionnaire survey of 223 people in Thessaloniki, Greece, and the results show that COVID-19 does not affect the user amount of bike-sharing. The user demand and operational
service of bike-sharing during the COVID-19 pandemic remains to be studied.

3. Data

3.1. Data sources

Nanjing is the capital of Jiangsu Province and one of the megacities in China. It has a population of 8.5 million, and a city area of 782.3 square kilometers. Nanjing Public Bicycle (NPB) started the SBBS service in 2013. As of February 2020, NPB had 53,200 bikes and 1500 stations in operation. Nanjing has three DBS companies including Mobike, Didibike, and Hellobike, with a total of 350,600 free-floating bikes. The visualization of the service supply of bike-sharing is shown in Fig. 1. The DBS distribution is based on the position of each DBS bike at midnight. The distributions of NPB stations and DBS bikes are much overlapped, except for some locations in the suburban area.

In Nanjing, the first covid-19 case was found on January 23, 2020. The last case in Nanjing was found on February 18, 2020, and there were no cases from then to the end of 2020. Nanjing’s urban transportation suffered the biggest impact in February 2020, and the monthly trips compared with 2019 falling by 90.6% in metro, 93.0% in bus, and 90.3% in taxi. The trip decline is largely due to people’s extreme concern about levels of hygiene on public transport (Beck and Hensher, 2020). After February, Nanjing’s urban transportation gradually recovered. In October 2020, the monthly trips compared with 2019 falling by 12.4% in metro, 27.8% in bus, and 12.4% in taxi. For Nanjing, February 2020 is the most critical and most affected month during the COVID-19 pandemic.

Four years of SBBS trip data from March 2016 to February 2020 are provided by Nanjing Public Bicycle Company Limited. The raw SBBS dataset has 146.7 million trip records, with a file size of 19.9 GB. The fields of NPB trip data include: user ID, bike ID, departure time, arrival time, origin station, and destination station. The personal data of all 590,500 users during the four years were also provided, including user ID, gender, and age. The personal data are anonymized after data desensitization. Besides, the station list displays station name, latitude, and longitude. The latitude and longitude of NPB stations use the WGS-84 coordinate system.

Four weeks of DBS trip data are provided by Nanjing Transportation Bureau. The two fortnights consist of two weeks in January 2020 and two weeks in February 2020. The raw DBS dataset has 4.8 million trip records, with a file size of 598 MB. The fields of DBS trip data include: bike ID, company ID, departure time, arrival time, origin longitude, origin latitude, destination longitude, and destination latitude. The personal information of DBS users was not provided.

Points of interest (POI) data were obtained from Auto Navi Map to explore the relationship between land use and bike-sharing. Auto Navi Map is one of the most popular digital map companies in China. There are 65,848 POIs in the obtained data, including: company (43,225), school (3,946), residence (7,906), shopping (3,077), scenery (2,683), religion (318), health (4,693). Health POIs are subdivided into five categories: general hospital (380), specialty hospital (615), community hospital (1,520), animal hospital (318), and pharmacy (1,860).

3.2. Development period of bike-sharing

Under the influence of various factors, the operation status of bike-sharing is constantly changing. The monthly trip and user amounts of SBBS in Nanjing are shown in Fig. 2. The four years are accordingly divided into four development periods: (1) SBBS expanding period, from March 2016 to February 2017; (2) DBS shock period, from March 2017 to August 2017; (3) stable period, from
September 2017 to December 2019; (4) COVID-19 shock period, from January 2020 to February 2020.

In SBBS expanding period, user demand for SBBS grew rapidly, with a substantial increase in supply facilities. During that period, bike amount increased from 28,000 to 39,000 with an increase rate of 39%, and trip amount increased by an average of 122,800 per month. Increasing the supply of bikes and stations has a positive effect on promoting travel demand for bike-sharing. In the DBS shock period, SBBS suffered strong competition with DBS. There was a significant decline in SBBS travel demand after the DBS promotion. In August 2017, Nanjing government banned allocating new DBS bikes because of bike over-supply, and then the SBBS operation has stabilized. In the stable period, SBBS survived the tide of DBS and still met extensive user demand. For example, SBBS attracted 323,600 users and generated 29.6 million trips in 2019. Besides, user demand is mainly affected by seasonal factors. User demand in spring and fall is the highest, and user demand in summer is lower. User demand in winter is the lowest because of the cold weather and the CNY holiday.

COVID-19 has a huge impact on bike-sharing services. The amounts of trip and user have decreased significantly, and the decline was much greater than that in previous winters. The detailed analysis will be explained in the subsequent sections.

3.3. Study period and spatial object

On January 20, 2020, Professor Nanshan Zhong, the leader of the high-level expert group of China’s National Health Commission, affirmed the person-to-person transmission of SARS-CoV-2 (The Beijing News, 2020). The news immediately had a widespread impact in China. Jiangsu Province initiated a first-level response to public health emergencies, which lasted from January 25 to February 24 in 2020. And 2020 CNY was January 25, which coincided with the COVID-19 outbreak. The impacts of COVID-19 and CNY need to be distinguished.

The detailed study period and corresponding trip amount are shown in Table 1. February 2020 is the most critical and most affected month, so the study period of COVID-19 impact is the post-period 2020/2/2–2020/2/15. The pre-period 2020/1/5–2020/1/18 will serve as the benchmark before the outbreak. In the pre-period, there is no COVID-19 case found in Nanjing; in the post-period, there are a few COVID-19 cases found in Nanjing almost every day.

The post-period is the second and third weeks after the 2020 CNY, and the pre-period is the second and third weeks before the 2020 CNY. The data analysis of previous years’ trips shows that travel demand would decrease before and after a week of the CNY, so the CNY impact can be ignored in the pre-period and post-period. Therefore, the pre-period and post-period are suitable for the before and after study of COVID-19 in Nanjing. Besides, the corresponding periods of 2017 are also analyzed to consider seasonal factors, because the weather conditions around 2017 CNY and 2019 CNY are similar.

The spatial object of SBBS is the NPB station. The spatial object of DBS is the virtual station. Voronoi diagrams and buffer are combined to identify DBS virtual stations. Voronoi diagram of a given set of sites is the partition of a plane into regions close to each site. Firstly, the DBS service in Nanjing is partitioned into Voronoi regions centered by NPB stations. Then a 250-m buffer of each NPB station and the corresponding Voronoi region are fused to get the intersection, which is the service area of each NPB station and corresponding virtual station. The service areas of all stations account for only 16% of Nanjing city areas, but covered 70% of DBS trips. It indicates that virtual station results are the suitable space objects of DBS analysis. The spatial distribution of virtual stations is shown in Fig. 3(b).

![Fig. 2. Development periods of bike-sharing in Nanjing.](image-url)
4. Demand analysis: station perspective

4.1. Trip decline at station level

The difference-in-differences (DID) model is one of the most powerful and popular methods to evaluate the impact of extraordinary events and policy implementations. The DID model has been used in bike-sharing studies to evaluate various events’ impacts (Wang and Zhou, 2017; Wang and Lindsey, 2019; Fan and Zheng, 2020). To estimate the influence of COVID-19 on SBBS trip, the traditional DID model and the semi-logarithmic DID model are both applied in the data analysis. The traditional DID model is represented in

Fig. 3. The decrease rate of bike-sharing trips. (a) The decrease rate of trips in SBBS stations. (b) The decrease rate of trips in DBS virtual stations.
Equation (1), and the semi-logarithmic DID model is represented in Equation (2). The comparison of before-after periods and treatment-control groups are combined in the empirical methodology. CNY is the basis for judging the before or after period. Observations of year 2017 are used as a control group, and observations of year 2020 are a treatment group.

\[ Y_i = \phi_i + \beta \text{Year} + \delta \text{Post} + \gamma \text{Year} \times \text{Post} + \epsilon_i \]  
(1)

\[ \ln Y_i = \phi_i + \beta \text{Year} + \delta \text{Post} + \gamma \text{Year} \times \text{Post} + \epsilon_i \]  
(2)

where the dependent variable \( Y_i \) is the daily trip of Nanjing SBBS (in 1000 trips), and the dependent variable \( \ln Y_i \) is the logarithm of the daily trip. The vector \( \phi_i \) is a set of time-related dummy variables reflecting the time-varying trend, including the distance to CNY and the day of week. Parameter \( \beta \) is a treatment group effect of different years. The dummy variable Year is defined as 1 for observations of year 2020, and 0 for observations of year 2017. Parameter \( \delta \) is the post-period effect after CNY. The dummy variable Post is defined as 1 for post-period after CNY, and 0 for pre-period before CNY. Parameter \( \gamma \) captures the impact of COVID-19 outbreak on SBBS demand.

The Semi-logarithmic DID model is found to be better than the traditional DID model. Because R-squared of semi-logarithmic DID model with 0.964 is larger than that of traditional DID model with 0.931. In the estimated results of the semi-logarithmic DID model, the estimated values of \( \beta, \delta \), and \( \gamma \) are \(-1.079, -0.060, -1.289\) respectively. The impact of different events on SBBS trips could be estimated by the values of these parameters. The SBBS trips in 2020 decreased by 66% compared to 2017, which can be interpreted as the DBS shock. The post-period effect after CNY would reduce SBBS trips by 6%. The most important finding is that the SBBS trips in Nanjing fell by 72% because of the COVID-19 impact. COVID-19 outbreak is the biggest challenge for SBBS during the four-year operation, followed by the DBS impact.

The semi-logarithmic DID model of \( i \)-th SBBS station is represented in Equation (3). Decrease rate of trip amount is the negative value of relative deviation between actual value during COVID-19 outbreak and expected value assuming no COVID-19. Due to the lack of 2017 DBS data, the formulas for calculating the decrease rate of SBBS and DBS are different. The expected trips of the SBBS station assuming no COVID-19 are represented in Equation (4). The expected trips of the DBS virtual station assuming no COVID-19 are the trips in the fortnight before 2020 CNY. The decrease rate of SBBS trip \( d_i \) is represented in Equation (5), and the decrease rate of DBS trip \( v_i \) is represented in Equation (6).

\[ \ln Y_{i,t} = \alpha_i + \beta_i \text{Year} + \delta_i \text{Post} + \gamma_i \text{Year} \times \text{Post} + \epsilon_{i,t} \]  
(3)

\[ \ln Y_{i,2020\text{post}} = \alpha_i + \beta_i \text{Year} + \delta_i \text{Post} + \epsilon_{i,t} \]  
(4)

\[ d_i = \frac{Y_{i,2020\text{post}} - Y_{i,2021\text{post}}}{Y_{i,2021\text{post}}} \]  
(5)

\[ v_i = \frac{X_{i,2021\text{pre}} - X_{i,2021\text{post}}}{X_{i,2021\text{pre}}} \]  
(6)

where \( \ln Y_{i,t} \) is the logarithm of SBBS trip in \( i \)-th station. Other variables and parameters in Equation (3) are similar to those in Equation (1), except \( \alpha_i \) capturing the individual fixed effects at the station level. For the \( i \)-th station, \( Y_{i,2020\text{post}} \) is the expected amount of SBBS trips assuming no COVID-19, and \( Y_{i,2020\text{post}} \) is the actual value of SBBS trips. \( X_{i,2021\text{pre}} \) is the expected value of DBS trips assuming no COVID-19, and \( X_{i,2021\text{post}} \) is the actual value of DBS trips.

The decrease rate of SBBS trips at the station level during the COVID-19 outbreak is shown in Fig. 3(a). SBBS trips at all stations have declined to varying degrees, and most stations have experienced a drop of around 70%. Xuanwu, Gulou, and Qinhai districts are close to the city center and are the urban area of Nanjing. Qixia, Jianye, and Yuhua districts are suburban areas. Jianye and Qixia districts are the regions hit hardest by the pandemic. The station ratio with a high decrease rate in suburban areas is much larger than that in urban areas. Urban area is relatively less impacted by COVID-19, and suburban area is relatively more impacted. But there are some hot spots in the suburban area with a lower decrease rate.

Because of the COVID-19 impact, the DBS trip in Nanjing fell by 82%, which is larger than that of SBBS (72%). And 78% of DBS virtual stations’ decrease rate is higher than the corresponding SBBS station. DBS is more severely affected by the pandemic than SBBS in most regions. As shown in Fig. 3(b), DBS trips at all virtual stations have declined to varying degrees. DBS in the Jianye district is hit hardest by the pandemic among all districts. The DBS virtual stations with a high decreased rate coincide with the metro route, which suggests that the integrated trip mode of bike-sharing-metro has been greatly affected by the pandemic. Because the metro is a confined space and has a higher transmission risk, the public is not prone to take the metro. The major role of bike-sharing in urban transportation has changed from cooperating with public transport to independently providing mobility services.

4.2. Land use and travel change

Land use could be represented by the distribution of POIs, which is closely related to travel purpose. The POI index is defined as the average amount of each type of POI near each trip, as shown in Equation (7). The POI index is proposed to show the relationship between travel demand and land use. The changes in POI index before and after the COVID-19 outbreak can reflect changes in the travel purpose of bike-sharing users. For example, a decrease in the company POI index indicates that users are less likely to use bike-sharing services for commuting.
where \( I_k \) is the POI index of k-th type; \( Y \) is all trips; \( O_y \) and \( D_y \) are the y-th trip’s origin station and destination station; \( p_y(S) \) is the amount of the k-th type of POI at the service area of station \( S \).

According to the POI index results in Table 2, the SBBS users’ travel demands for commuting have decreased significantly, and the DBS users’ travel demands for commuting and school have decreased significantly. SBBS’s school trips increased and DBS’s school trips decreased. Many school-related SBBS users may be school staff who still work during the outbreak, while the school-related DBS users are students and parents who need not go to school. The travel demand of SBBS and DBS for shopping and scenery has increased slightly. In both SBBS and DBS systems, the travel demand for health, religion, and residence has increased significantly. So areas near residential, religious, and health POI require more frequent disinfection by bike-sharing companies. Besides, the residential POI index is about leaving or returning home, and its increase indicates a decrease in the diversification of travel purposes.

Healthcare service is very important during the pandemic. In both SBBS and DBS systems, the travel demand for pharmacy (buying medicines) has increased the most during the COVID-19. The trip increase for community hospital is the second-highest for SBBS, and the trip increase for specialized hospital is the second-highest for DBS. Trip amount change near animal hospital is relatively insignificant. General hospital has a fever clinic and usually is crowded with many people, so higher transmission concerns have led to smaller trip increase. Areas near hospitals or pharmacies should receive key guarantees for service supply and bike disinfection.

5. Demand analysis: user perspective

5.1. Travel characteristics

The travel characteristic indexes of bike-sharing are shown in Table 3. The number of SBBS users has dropped by 67%, and the travel frequency of remained SBBS users has decreased by 12%. The main reason is that the social distancing strategy encourages people to stay at home as much as possible in response to the pandemic. But the decrease in travel frequency does not mean that bike-sharing has become less important. Before and after the COVID-19 outbreak, the daily trips of Nanjing Metro fell from 3,172,000 (pre-period) to 156,000 (post-period), with a drop of 95%. And bike-sharing trips in Nanjing only fell by 72% for SBBS and 82% for DBS. Considering the higher decrease rate of other transport modes, bike-sharing has played a more important role in urban transportation during the pandemic.

The average travel distance of SBBS increased by 32%, and the average travel distance of DBS increased by 16%. As a COVID-19 response strategy, public transport in Nanjing has reduced service frequency and shortened service time. Therefore, some long-distance travel demands are satisfied by bike-sharing especially SBBS. This also confirms the previous finding that bike-sharing-metro mode declined because of the COVID-19 impact. A possible reason for this trip decline is that most bike-sharing-metro trips are for commuting purposes (Ma et al., 2018) but commuting is greatly impacted by the pandemic. Network density (value range is 0–1) is the ratio of the actual number of connections (origin-destination pairs) to all possible connections (Wise, 2014), which can reflect the network connectivity of user travel. The larger network density, the higher network connectivity. Network density of SBBS and DBS decreased by 45% and 43% respectively, reflecting the great decline in network connectivity.

The temporal characteristics of bike-sharing trips are shown in Fig. 4. There are significant morning peak and evening peak for bike-sharing before the pandemic. The morning peak is 7 a.m.–9 a.m. and the evening peak is 5 p.m.–7 p.m. These peaks became less

### Table 2

| POI index change of SBBS and DBS.\(^a\) |
|-----------------|-----|-----|-----|-----|-----|-----|
| POI index       | Company | School | Residence | Shopping | Scenery | Religion | Health |
| SBBS 2020 pre   | 19.191  | 1.334 | 3.533 | 1.440 | 0.952 | 0.036 | 2.258 |
| SBBS 2020 post  | 18.500  | 1.430 | 3.917 | 1.565 | 1.041 | 0.039 | 2.548 |
| Relative deviation of SBBS POI index | –3.6% | 7.2% | 10.9% | 8.7% | 9.3% | 10.0% | 12.8% |
| DBS 2020 pre    | 28.414  | 1.866 | 4.096 | 1.890 | 1.478 | 0.040 | 2.774 |
| DBS 2020 post   | 26.072  | 1.670 | 4.521 | 1.993 | 1.498 | 0.043 | 3.092 |
| Relative deviation of DBS POI index | –8.2% | –10.5% | 10.4% | 5.5% | 1.4% | 9.0% | 11.5% |

| (b) POI index change of different health POIs |
|-----------------|-----|-----|-----|-----|-----|
| POI index       | General hospital | Specialist hospital | Community hospital | Animal hospital | Pharmacy |
| SBBS 2020 pre   | 0.283 | 0.486 | 0.507 | 0.162 | 0.821 |
| SBBS 2020 post  | 0.316 | 0.542 | 0.576 | 0.169 | 0.945 |
| Relative deviation of SBBS POI index | 11.7% | 11.5% | 13.7% | 4.5% | 15.2% |
| DBS 2020 pre    | 0.427 | 0.632 | 0.609 | 0.161 | 0.945 |
| DBS 2020 post   | 0.473 | 0.714 | 0.665 | 0.165 | 1.075 |
| Relative deviation of DBS POI index | 10.8% | 13.1% | 9.1% | 2.4% | 13.7% |

\(^a\) The larger values of the relative deviation of POI index have been bolded. It shows that some travel purposes have become more important after epidemic outbreak.
obvious during the pandemic, reflecting a huge decrease in commuting travel. The peak phenomenon of DBS is more significant than that of SBBS before the outbreak, indicating that commuting travel accounts for a larger proportion of DBS trips. After the outbreak, the temporal characteristics of DBS and SBBS become similar. So DBS is more affected by COVID-19 than SBBS. No matter before or after the outbreak, the travel demand on weekdays is higher than the travel demand on weekends. It should be noted that the vertical axis of the four subgraphs in Fig. 4 are different, and the colors of each sub-graph cannot be compared with the others. For example, although the color of Fig. 4 (a) is lighter than that of Fig. 4 (b), the trip amount of SBBS 2020 pre is much higher than that of SBBS 2020 post.

5.2. Gender and age group

Due to the lack of DBS user information, the analysis of gender and age focuses on SBBS user travel. The travel speed of males (7.6 km/h) and females (7.2 km/h) has not been changed by the pandemic. The bike-sharing users are divided into five age groups: teenage (13–18 years old), youth adult (19–28 years old), adult (29–39 years old), middle age (40–59 years old), and the elderly (≥60 years old). The female and male trips of different ages are shown in Fig. 5. Before the COVID-19 outbreak, the trips of females and males are roughly equal, except that the elderly trips of females are less than that of males. But the middle age trips of females are also less than that of male after the outbreak. The female trip proportion fell from 47% to 43%, which shows that women are more impacted by the

| Characteristics      | SBBS 2020 pre | SBBS 2020 post | DBS 2020 pre | DBS 2020 post |
|----------------------|--------------|---------------|-------------|--------------|
| Daily trips (1000 trips) | 52.3         | 15.1          | 214.0       | 38.3         |
| User amount (1000 users) | 118.5        | 39.0          | –           | –            |
| Travel frequency (trips/week) | 3.09         | 2.72          | –           | –            |
| Travel distance (km)   | 1.32         | 1.74          | 1.25        | 1.45         |
| Travel time (min)      | 14.5         | 18.3          | 9.5         | 13.1         |
| Travel speed (km/h)    | 7.40         | 7.54          | 8.57        | 8.12         |
| Network density        | 0.097        | 0.054         | 0.115       | 0.065        |

Note: Due to lacking user information, DBS’s user amount and travel frequency are not listed.

![Fig. 4. Temporal patterns of bike-sharing trips.](image-url)
pandemic than men. One possible explanation could be that men may be more dependent on bike-sharing than women.

The SBBS travel changes for different age groups are shown in Table 4. The proportion of teenage users is the lowest, and their travel demands are also the hardest hit by the COVID-19. The user proportions of youth adult and adult have slightly decreased, and their trip decline is relatively small. The proportion of middle-aged and elderly users has increased, and their trip amount has been least affected by the pandemic. The travel frequency of middle age and the elderly are also the highest during the pandemic. These findings show that middle-aged and elderly people are the key groups of SBBS users and have a strong dependence on bike-sharing services. Middle-aged and elderly users should get more attention from bike-sharing companies, especially elderly users who are more susceptible and vulnerable to the coronavirus.

The POI index is used to analyze the relationship between land use and the SBBS trips of various age groups. The relative deviation of the POI index is shown in Table 5. The importance of shopping and health especially pharmacy has increased significantly in trips of all age groups, while the importance of commuting travel has decreased significantly in all age groups. Teenage users have significantly reduced travel for school, scenery, and religion, but other age groups have increased travel for these purposes. During the pandemic, teenagers avoid going to general hospitals and specialized hospitals, which may result from parents’ safety concerns. The travel purposes of youth adult and adult users are greatly affected by COVID-19. But the travel purposes of middle age and elderly users are less affected by the pandemic.

6. Risk analysis: bike perspective

6.1. Transmission risk and bike usage interval

Unlike the confined space of metro or car, bike-sharing service is provided in the open space. So the main concern of virus transmission risk is the close contact by touching the bike surface. Bike usage interval is defined as the time interval between former user travel and latter user travel of the same bike, which also is the time interval of the user contact. According to this definition, the amount of bike usage interval is equal to the amount of user contacts. Bike usage interval can be used to characterize the user contacts and the transmission risk.

During the COVID-19, SBBS bike turnover rate decreased from 1.7 trips per day to 0.8 trips per day, and DBS bike turnover rate decreased from 1.0 trips per day to 0.4 trips per day. The decrease of bike turnover rate directly leads to the duration increase and amount decrease of bike usage interval. After the COVID-19 outbreak, the average value of SBBS bike usage interval increased from 8.7 h to 14.4 h, and the average value of DBS bike usage interval increased from 12.5 h to 23.7 h. The daily amount of SBBS user contacts decreased from 46,600 times to 11,700 times, and the daily amount of DBS user contacts decreased from 199,400 times to 31,200 times. The user contacts of all companies in Nanjing is 42,900 times per day. Nanjing has four bike-sharing companies, NPB, Mobike, Hellobike, and Didibike. The bike disinfection of one company is about 20,000 times per day, so the bike infection of all four companies could exceed the amount of user contacts.

When riding a bike, users will touch the handlebars and seats, which are made of stainless steel and plastic. Considering that the virus’s half-life is about 6 h on these materials (van Doremalen et al., 2020), we tentatively choose 6 h as the safety threshold for bike usage interval. If a bike usage interval is less than the safety threshold, a user close contact occurs. The concept of the user close contact

Fig. 5. The SBBS trip amount in relation to gender and age.
is used to measure transmission risk. The more user close contacts, the higher transmission risk. After the COVID-19 outbreak, the daily amount of SBBS user close contacts decreased from 33,400 times to 6800 times, with a decrease rate of 80%. And the daily amount of DBS user close contacts decreased from 115,400 times to 14,000 times, with a decrease rate of 88%. The decrease rate of user close contacts is higher than that of bike-sharing trips (SBBS: 80% vs. 72%, DBS: 88% vs. 82%). The spatial distribution of user close contacts is shown in Fig. 6. There are more user close contacts in central urban areas than that in suburban areas, which means a higher risk of virus transmission. The high-risk places should be given priority in bike disinfection.

Table 4
The SBBS trip changes of different age groups before and after COVID-19.†

| Age group | User proportion 2020 pre | 2020 post | Travel frequency (weekly trips) 2020 pre | 2020 post | Decrease rate of trip amount |
|-----------|--------------------------|-----------|----------------------------------------|-----------|-----------------------------|
| Teenage   | 1.1%                     | 0.4% ↓    | 2.55                                   | 1.78      | 90.6%                       |
| Youth adult| 4.9%                     | 4.7% ↓    | 3.01                                   | 2.63      | 72.2%                       |
| Adult     | 22.4%                    | 18.8% ↓   | 2.86                                   | 2.47      | 76.1%                       |
| Middle age| 49.8%                    | 51.4% ↓   | 3.05                                   | 2.80      | 68.9%                       |
| The elderly| 21.9%                    | 24.6% ↑   | 3.46                                   | 2.79      | 70.2%                       |
| All       | –                        | –         | –                                      | 3.09      | 72.0%                       |

† The significant values in the same column are bolded. It shows that middle-aged and elderly people are the key user groups.

Table 5
The relative deviation of SBBS POI index of different age groups.†

| POI          | Teenage | Youth adult | Adult | Middle age | The elderly | All     |
|--------------|---------|-------------|-------|------------|-------------|---------|
| Company      | –17.1%  | –4.6%       | –6.9% | –3.1%      | –2.6%       | –3.6%   |
| School       | –10.5%  | 9.5%        | 12.8% | 6.4%       | 3.4%        | 7.2%    |
| Residence    | 10.2%   | 15.7%       | 19.9% | 8.5%       | 7.6%        | 10.9%   |
| Shopping     | 13.5%   | 13.5%       | 12.2% | 8.1%       | 5.7%        | 8.7%    |
| Scenery      | –16.7%  | 21.6%       | 21.0% | 6.5%       | 4.4%        | 9.3%    |
| Religion     | –4.7%   | 42.9%       | 15.7% | 6.4%       | 7.2%        | 10.0%   |
| Health       | 7.4%    | 17.1%       | 18.8% | 10.9%      | 10.8%       | 12.8%   |
| General hospital | –23.4% | 15.4%       | 21.5% | 6.3%       | 14.4%       | 11.7%   |
| Specialist hospital | –17.9% | 17.9%       | 21.8% | 8.3%       | 9.1%        | 11.5%   |
| Community hospital | 2.6% | 21.1%       | 18.7% | 12.2%      | 11.5%       | 13.7%   |
| Animal hospital | 27.7% | 8.5%        | 5.6%  | 2.5%       | 6.4%        | 4.5%    |
| Pharmacy     | 37.5%   | 16.2%       | 19.0% | 15.0%      | 11.1%       | 15.2%   |

† The significant values in the same row are bolded. It shows the huge changes in the travel purposes of youth people and adults.
6.2. Service supply and user distancing

Service supply of bike-sharing consists of bike supply and operational resources. The statistic indexes of service supply and transmission risk in bike-sharing are shown in Table 6. Bike supply is more sufficient as the travel demand declines during the COVID-19 pandemic. Idle bike ratio is the ratio of bikes that have not been used in a certain period to the overall bike supply. The higher the idle bike ratio, the greater bike over-supply. The idle bike ratios of SBBS and DBS both are 42% before the outbreak, that is, only 58% of the bikes are used in these two weeks. After the outbreak, the idle bike ratio becomes even higher and bike over-supply becomes more serious. These idle bikes should be activated to meet travel demand and used to avoid user close contacts.

Bike repositioning is the most important part of operational resource supply. Bike repositioning is to solve the imbalance between travel demand and bike supply, especially in the morning and evening peaks. The amount of bike repositioning experiences a huge reduction after the COVID-19 outbreak, because travel demand greatly decreases and the peak phenomenon becomes insignificant. As shown in Table 6, SBBS bikes are daily repositioned 6300 times before the pandemic and 1400 times after the outbreak, with a decrease of 78%. DBS bikes are daily repositioned 72,400 times before the pandemic and 10,900 times after the outbreak, with a decrease of 85%. The decrease rate of bike repositioning amount is large than that of bike-sharing trip. During the pandemic, the company’s repositioning objectives should shift from increasing bike efficiency to reducing transmission risk. The decline of repositioning amount results in a relative surplus of operational resources, and more operational resources could be devoted to bike disinfection.

Besides, we propose a new concept of user distancing to help avoid transmission risk. User distancing is an application of social distancing strategy and user information-sharing in shared micro-mobility. User distancing in bike-sharing is to ensure that bike usage interval should remain above the safety threshold and user close contacts should be avoided. The potential user of each bike is informed of the travel end time of the previous user and decides her/his travel behavior accordingly. For example, if the parking duration of a bike to be used is shorter than the safety threshold, the user will be informed that the bike is unavailable for travel and encouraged to ride another idle bike or a bike with enough parking duration. If bikes are parked in the high-demand area and require efficient turnover, the operation staff should be arranged to patrol the area and ensure timely disinfection. The relative surplus of bike supply and operational resources promotes the feasibility of user distancing strategy. The user distancing strategy can reduce the bike disinfection workload, reduce operational cost and increase the turnover efficiency of idle bikes.

7. Conclusion and discussion

After the COVID-19 outbreak, many cities insist on providing bike-sharing services, while some other cities have decided to suspend this service. Travel demand and transmission risk are the main concerns and the key basis for urban decision-making. Based on the trip data of SBBS and DBS in Nanjing, this study explored the usage pattern of the bike-sharing system during the pandemic from three perspectives: station, user, and bike. This paper provides a valuable case study of providing SMM service during the pandemic.

From the perspective of the station, bike-sharing has been greatly impacted by COVID-19, and travel demand for each (virtual) station has decreased differently. The decrease rate of SBBS trips (72%) is lower than that of DBS trips (82%), meaning that SBBS is less affected by the outbreak. During the pandemic, bike-sharing provides more independent and longer-distance transportation services, rather than integrated services with public transport such as bike-sharing-metro mode. Besides, trips for commuting have greatly decreased, but trips for health and religion have increased significantly.

From the user perspective, bike-sharing has become more important during COVID-19, and middle-aged and elderly people are more dependent on this service. At the same time, the network connectivity and peak phenomenon of bike-sharing have been weakened. Women are more impacted than men, especially middle-aged females. The travel purposes of youth adult and adult have a marked decrease in commuting travel and an important increase in tourism, religion, and health travel. Middle-aged and elderly people are key user groups of SBBS, and their trip decline and travel purpose change are the smallest among all age groups.

From the bike perspective, the decline of travel demand reduces user contacts, and adequate bike disinfection can avoid the risk of virus transmission. Less travel demand and weaker peak phenomenon contribute to reducing transmission risk. The decline of user close contacts in SBBS and DBS is 80% and 88%. Transmission risk in the central urban areas is higher than that in the suburban areas. Under the influence of COVID-19, the service supply including bike supply and operating resource is relatively surplus. Bike-sharing companies can encourage users to ride idle vehicles to keep user distancing, and accordingly transfer more resources to bike disinfection.

During the pandemic, SMM such as bike-sharing can both provide safe service and avoid transmission risk, with appropriate control strategies. Chinese cities such as Nanjing and Wuhan insisted on providing bike-sharing services during COVID-19. While the pandemic in these cities has been effectively controlled and there is no report about bike-sharing spreading virus. These successful practices prove that bike-sharing can simultaneously meet travel demand and avoid safety risks. The answer to our research question is that cities with good management are encouraged to maintain SMM services including bike-sharing during the outbreak.

COVID-19 is unlikely to end in the short term, considering that the Delta variant and other potential variants are more contagious and create a huge challenge of curbing the pandemic. The pandemic control strategies in the long term need to be considered. Strict strategies such as city shutdown adopted earlier are not sustainable in the long term. Social life will continue to recover, and travel restrictions will gradually be relaxed. With increased travel, people contacts will become more intensive. Therefore, how to effectively control the virus transmission risk in the long term is a huge challenge. Reliable, low-cost, and flexible pandemic control strategies in urban transportation should be explored. For example, we have proposed that companies can adopt the user distancing strategy based on activating idle vehicles. Besides, users should be encouraged to wear PPE and disinfect bikes before riding, and maintain these habits for a longer time.
Table 6
The resource supply and transmission risk in bike-sharing.

| Sample      | Bike supply (1000 bikes) | Idle bike ratio (%) | Bike repositioning (1000 times daily) | User close contact (1000 times daily) |
|-------------|--------------------------|---------------------|----------------------------------------|---------------------------------------|
| SBBS 2020 pre | 53.2                     | 41.5                | 6.3                                    | 33.4                                  |
| SBBS 2020 post | 64.9 ↑                   | 1.4 ↓               | 6.8                                    | 68.1 ↓                                |
| DBS 2020 pre  | 350.6                    | 41.6                | 72.4                                   | 115.4                                 |
| DBS 2020 post | 71.9 ↑                   | 10.9 ↓              | 14.0                                   | 110.9                                 |

Author statement

Mingzhuang Hua: Conceptualization, Writing- Original draft preparation, Methodology, Funding acquisition. Xuewu Chen: Conceptualization, Data curation, Supervision, Resources. Long Cheng: Formal analysis, Writing- Reviewing and Editing, Visualization. Jingxu Chen: Writing- Reviewing and Editing, Funding acquisition.

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