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Exploring impacts of COVID-19 on city-wide taxi and ride-sourcing markets: Evidence from Ningbo, China

Jingru Yu a, Ningke Xie a, Jiangtao Zhu a, Yiwei Qian b, Sijing Zheng b, Xiqun (Michael) Chen a,⁎

a College of Civil Engineering and Architecture, Zhejiang University, Hangzhou, China
b Polytechnic Institute, Zhejiang University, Hangzhou, China

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ABSTRACT

The outbreak of the COVID-19 epidemic has brought enormous impacts and changes to human mobility. To better understand and quantify the impacts of COVID-19 on city-wide ride-sourcing and taxi markets, we present exploratory evidence on the factors such as coronavirus cases related attributes, policy-related attributes, operational status of transportation, socio-economic status related variables, demographics related variables, and other factors. Based on 5-month real-world ride-sourcing and taxi datasets in Ningbo, China, including 37-million trips, we study the temporal variations of drivers’ working characteristics and productivity of ride-sourcing and taxi fleets. The spatial heterogeneity of the impacts of COVID-19 on taxi and ride-sourcing trips is demonstrated in terms of traffic analysis zones (TAZs). Regression models are established to examine the impacts of a variety of explanatory variables, including COVID-19 related variables, on the district-level productivity of taxi and ride-sourcing services. The results show that the accumulated cured coronavirus cases, policy of closed management, operational status of mass transit, and average fee spent on transportation per capita significantly impact the productivity of the taxi and ride-sourcing fleets. This paper empirically reveals the influence of the epidemic on ride-sourcing and taxi markets and the temporal and spatial variations. The findings can support decision-making to restore the ride-sourcing and taxi markets and benefit other COVID-19 related research efforts.

1. Introduction

Since 2020, the COVID-19 pandemic has spread worldwide, causing unprecedented massive destruction to the society and economy of numerous countries. As of November 4, 2021, the total confirmed cases had reached 247,472,724 in 216 countries, areas, or territories, and the number of deaths was as high as 5,012,337 (World Health Organization, 2021). Confronted with the threat of the pandemic, most countries have adopted various measures to limit the spread of the coronavirus, including lockdown, social distancing, closing stores, schools, and other facilities.

Due to government restrictions or prohibitions on human mobility, people need to work from home or conduct online meetings, and students take classes online. Besides, with the development of the logistics industry, online shopping, takeaway, and other online consumption modes have become popular, and people can meet consumer demand without leaving home (Sheth, 2020). Therefore, travel demand is significantly reduced, which has a profound impact on the transportation industry. Meanwhile, the pandemic also leads to some changes in people’s choices of travel modes. Because of fear of being infected, people avoid going to crowded places, such as stations and shopping malls, and maintain a large social distance. Thus, people were unwilling to take public transportation, bringing a considerable decline to related industries (Google, 2020). On the contrary, private cars are favored by car owners as a safe way of travel, and cycling and walking have become popular. The pandemic has a massive impact on urban transportation, and this impact may even last for a long time after the end of the pandemic.

The taxi market and the emerging ride-sourcing market are usually affected by major events such as policy changes. For example, Shenzhen Municipal Government issued a new policy on September 16, 2019, requiring newly registered ride-sourcing vehicles to be pure electric vehicles, which blocked many drivers with fuel vehicles (Du et al., 2020). When the pandemic broke out, similar to public transit, the taxi and ride-sourcing market also suffered much. As a result of reduced travel demand, New York City taxi drivers’ salaries in March 2020 fell by

⁎ Corresponding author. B828 Anzhong Building, College of Civil Engineering and Architecture, Zhejiang University, 866 Yuhangtang Rd, Hangzhou, 310058, China.
E-mail address: chenxiqun@zju.edu.cn (X.(M. Chen).

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two-thirds or even more (The New York Times, 2020). Under the influence of the pandemic, transportation network companies, such as Uber and Lyft, were also facing tremendous pressure (PR Newswire, 2020).

Therefore, there is a need to study the COVID-19 pandemic’s impacts on urban taxi and ride-sourcing markets based on large-scale real-world datasets. This paper quantitatively analyzes the impacts of the pandemic on taxi and ride-sourcing markets based on the 5-month, 37-million taxi and ride-sourcing order data of Ningbo, China. Also, this paper reveals the effects of the pandemic on passenger demand and driver working patterns. The results indicate that the accumulated cured coronavirus cases, policy on closed management, operational status of mass transit, and travel demand of passengers significantly impact the productivity of the taxi and ride-sourcing fleets, which can support the decision-making of government to restore the ride-sourcing and taxi markets.

This paper is organized as follows. Section 2 reviews the related literature on the impacts of the COVID-19 pandemic on transportation, the impacts of major events on the taxi and ride-sourcing markets, and the working modes of drivers. Section 3 presents the COVID-19 epidemic dataset, and ride-sourcing and taxi datasets collected in Ningbo, China. Section 3 also describes the regression model and summarizes the explanatory variables and dependent variables of the regression model. Section 4 estimates the COVID-19 related factors that impact the taxi and ride-sourcing markets and presents the findings by spatial and temporal analyses. Finally, Section 5 concludes the paper and provides an outlook on future research.

2. Literature review

The demand for urban transportation is usually derived from the economic output, population, migration, employment figures, schools, and various other factors (Holmgren, 2007), among which public health emergency has become one of the greatest threats to transportation. The outbreak of the COVID-19 pandemic is a typical case of public health emergency, which has brought enormous impacts and changes to cities and lives. The pandemic has rapid and significant impacts on transportation and mobility patterns.

First, the total amount of transportation has declined worldwide. One of the most critical responses of countries worldwide to slow the spread of the pandemic restricted the movement of people, which had a considerable effect on transportation systems (Bucsky, 2020). The analysis has shown severe impacts of the coronavirus pandemic with an unprecedented ridership drop (90%) in New York City. Likewise, the city’s bike-sharing system also followed the same fate, with a 71% ridership decrease comparing to the days before the coronavirus appearance (Teixeira and Lopes, 2020). American cities have the lowest mobility indices as of the end of June 2020, with mobility indices lower than 20%. It is expected and reasonable to assume that the public response to COVID-19 will exceed SARS (Abu-Rayash and Dincer, 2020). According to the research conducted by de Haas et al. (2020) in the Netherlands, the number of trips and distance traveled dropped by 55% and 68%, respectively, compared to the fall of 2019. Because of the COVID-19 pandemic, the government put up some restrictions that halved transportation demand in Budapest, Hungary (Bucsky, 2020). In the case of Nigeria, the increased cost of transportation, lack of transportation modes, and traffic congestion were identified as the significant impact of COVID-19 on transportation (Emmanuel Mogaji, 2020). Due to the high infection risk of public transportation, residents are more likely to choose more private transportation. Reduction levels differed significantly among the various modes of transportation. Public transportation experienced the most considerable reduction in demand, while cycling and bike-sharing saw the lowest decrease (Bucsky, 2020).

Second, the taxi and ride-sourcing markets are easily affected by major events, such as policy changes and pandemics. Lee et al. (2020) found that legalization and socio-technical context were very important for the sustainable mobility of ride-sourcing services. The government has reduced the clash between ride-sourcing services and traditional services by legalizing ride-sourcing services. Under the background of the new policy that the newly registered ride-hailing vehicles should be clean energy vehicles, and the pure electric rate of ride-hailing vehicles should reach 100% by the end of 2020 in Shenzhen, China, Du et al. (2020) analyzed the influence of the new policy on drivers’ intention to leave the ride-sourcing business and found that a lack of subsidy policies would significantly reduce drivers’ acceptance for electric ride-hailing. The balance between ride-sourcing platforms and the government could be achieved by reducing government supervision costs and increasing government punishment (Sun et al., 2019). Beer et al. (2017) qualitatively compared the regulations of ride-sourcing companies between major American cities and found that it was mainly up to local governments to embrace a regulatory framework that allowed multiple transportation options to thrive. According to a recent study of 3021 people, 40% of the survey respondents said that they used ride-sourcing services less often, and 93% of people said that they used personal vehicles more because of the demand to keep a certain social distancing (Hyatt, 2020).

Third, the behavior of taxi drivers and ride-sourcing drivers is diverse and complicated due to the instability of the taxi and ride-sourcing markets. Many studies have analyzed the choice behavior and work patterns of taxi drivers and ride-sourcing drivers. It was assumed that each taxi driver exhibited such behavior, minimizing search time when cruising and maximizing net revenue (Yang et al., 2002; Yang et al., 2010). Farber (2015) found that taxi drivers were inclined to work with increases in earnings opportunities. Compared to taxi drivers, ride-sourcing drivers have a more flexible work schedule, including when and how long they work. Sun et al. (2019) put forward an econometric framework to explore the influence of hourly income rates on labor supply in the ride-sourcing market and found that driver participation and working hours were positively and significantly related to the hourly income rate. Nourinejad and Ramezani (2020) constructed a non-equilibrium model of two-sided markets to analyze the impacts of the wage and expected cruising time on the driver’s decision to take up work or leave. To grasp the characteristics of labor supply in the ride-sourcing market, Zha et al. (2018) first proposed a time-expanded network to sketch out drivers’ possible work schedules, which was the basis of the entire equilibrium model. Ke et al. (2019) also used a time-expanded network to outline the behavior of both electric vehicle and gasoline vehicle drivers in an analytical framework. Affected by the COVID-19 epidemic, the behavior of drivers has undergone significant changes compared with normal conditions. Romero and Sosa (2020) pointed out that taxi drivers were in a vulnerable position in the face of the COVID-19 epidemic due to the structure of their work. Similarly, due to the COVID-19 epidemic, ride-sourcing drivers have lost many job opportunities and financial resources. Ride-sourcing companies represented by Uber are helping drivers cope with the epidemic by formulating employment protection measures, which will also affect the work pattern of drivers (Katta et al., 2020).

In summary, there is limited literature on the impact of the COVID-19 pandemic on the taxi and ride-sourcing markets based on real-world large-scale datasets so far. This paper empirically reveals the effects of the COVID-19 epidemic on taxi and ride-sourcing markets based on real-world city-wide dataset collected in Ningbo, China. The variation tendency of passenger demand and driver working patterns before the epidemic, during the epidemic, and after the epidemic are analyzed by the analytical analysis method. Also, this paper reveals the effects of COVID-19 case related variables, policy-related variables, operational status of transportation, and demand-related variables on the productivity of the taxi and ride-sourcing fleets. This paper corroborates the evidence of significant factors that impact the productivity of taxi and ride-sourcing fleets during the epidemic, which can support decision-making for government to regulate the taxi and ride-sourcing market during the epidemic.
3. Data and method

3.1. COVID-19 epidemic data

The COVID-19 epidemic monitoring platform\(^1\) provides public available and comprehensive epidemic data in Ningbo, China. The epidemic dataset used in this study includes the temporal and spatial information of COVID-19 cases from December 1, 2019, to April 30, 2020. Specifically, the dataset includes the following fields: date, newly confirmed cases, newly cured cases, cumulative confirmed cases, cumulative cured cases, and hospitalized cases. Besides, epidemiological, statistical features about gender, age, and the disease spot are also included. Along with the epidemic dataset, the Geographic Information System (GIS) data of the City of Ningbo were obtained, in which the city is divided into 707 traffic analysis zones (TAZs).

Fig. 1 shows the daily number of COVID-19 cases during the epidemic in Ningbo, Zhejiang Province, China. There were 157 confirmed cases between January 23, 2020, and April 30, 2020. On January 23, 2020, the first five confirmed cases appeared in this area, then Zhejiang Province launched the first-level response to major public health emergencies. The daily number of newly confirmed coronavirus cases peaked on January 29, 2020, with 21 cases. The first cured case left the hospital on January 31, 2020. Since February 20, 2020, there have been no more confirmed cases by April 30, 2020. On February 9, 2020, the inflection point of the COVID-19 epidemic appeared, and the number of hospitalizations began to decline. Fortunately, the confirmed cases were all cured, and the number of hospitalized cases was cleared to zero on March 9, 2020. Fig. 2 presents the spatial distribution of COVID-19 cases in TAZs during the COVID-19 crisis in Ningbo, China. Among all of the 707 TAZs in this city, confirmed COVID-19 cases have appeared in 47 TAZs.

Since our target is to examine the impact of COVID-19 on the ride-sourcing and taxi markets, it is helpful to review the major events. Fig. 3 presents the timeline of critical COVID-19 events related to Ningbo, China. Firstly, the lockdown measure was carried out on January 24, 2020. Going further still, the lockdown measure was issued with enforcement on February 4, 2020. As for traffic management measures, metro was stopped on February 6, 2020. The inflection point of the epidemic came on February 9, 2020. As the epidemic eased, the corresponding measures were adopted. The metro was fully restored to normal operations on March 9, 2020. Restoring the production and living order was encouraged on March 21, 2020, and further strengthened on March 23, 2020. Consequently, the ride-sourcing and taxi datasets during the period are selected for exploring the impact of the COVID-19 epidemic on the markets.

\(\text{\footnotesize \(^1\) Available at https://wxyq.nbsghy.com.}\)
3.2. Ride-sourcing and taxi data

As shown in Table 1, the ride-sourcing and taxi order datasets used in this study are collected from the Bureau of Transportation in Ningbo, China, between December 1, 2019, and April 30, 2020. Each piece of the order information includes the following attributes: LicenseId, CompanyId, OrderId, DepTime, DestTime, DriveTime, FactPrice, and DriveMile.

Table 1 provides the monthly total number of orders of ride-sourcing and taxi, respectively. The 5-month real-world ride-sourcing and taxi datasets in Ningbo, China, include more than 37-million trips in total. There are substantial variations. The number of orders drops about 23.71% for ride-sourcing and 21.92% for taxi during January 2020 compared with December 2019. Further, the number of orders hits bottom during February 2020. Then during April 2020, it bounces back to 62.15% for ride-sourcing and 54.56% for taxi compared with December 2019.

Fig. 4 shows the daily number of active taxi and ride-sourcing drivers in Ningbo, China.

Fig. 5. The daily number of active taxi and ride-sourcing drivers in Ningbo, China.

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Fig. 4 shows the daily number of taxi and ride-sourcing drivers between January 1, 2020, and April 30, 2020. Fig. 5 presents the urban mobility trend by taxi and ride-sourcing during the COVID-19 crisis, quantifying ride-sourcing and taxi orders. The data confirmed that mobility by taxi and ride-sourcing dropped significantly after the epidemic outbreak. Moreover, the market began to restore to a normal level after the number of hospitalized cases had been cleared to zero.
3.4.1. Explanatory variables

Comparing the productivity with and without the COVID-19 epidemic, the explanatory variables are comprehensively considered in this study: COVID-19 epidemic related causes and other factors. The explanatory variables are used to estimate the productivity reduction of taxi and ride-sourcing fleets by COVID-19 related variables. The explanatory variables are used to capture the policy effect during the epidemic, the socio-economic status related variables, and the demographics related variables. The explanatory variables are used to measure the productivity of the taxi and ride-sourcing fleets.

Given the datasets above, this paper attributes them to a range of COVID-19 related causes and other factors. The explanatory variables are summarized in Table 3. The following explanatory variables are comprehensively considered in this study:

### Table 3

| Variable                        | Description                                      |
|---------------------------------|--------------------------------------------------|
| COVID-19 case related variables |                                                  |
| New confirmed cases             | Daily number of newly confirmed coronavirus cases |
| New cured cases                 | Daily number of newly cured coronavirus cases     |
| Sum cured cases                 | Daily number of accumulated cured coronavirus cases |
| Hospitalized cases              | Daily number of hospitalized coronavirus cases    |
| Policy-related variables        |                                                  |
| Closed management               | 0: No closed management; 1: Closed management issued without penalty or without specifying enforcement; 2: Closed management issued and enforced with warning, and a possible fine for repeated offense. |
| Normal order                    | 0: No policy on restoring the production and living order; 1: Policy on restoring the production and living order issued; 2: Policy on restoring the production and living order strengthened. |
| Operational status of transportation |                                                  |
| Mass transit                    | 1: If the operation of mass transit is normal; 0, otherwise |
| Highway                         | 1: If the operation of highway is normal; 0, otherwise |
| Socio-economic status related variables |                                |
| Traffic fee per capita          | Average fee spent on transportation per capita in each administrative region |
| Average consumption per capita  | Average consumption expense spent per capita in each administrative region |
| Demographics related variables  |                                                  |
| Population                      | Population in each administrative region          |
| Population density              | Population density in each administrative region |
| Other factors                   |                                                  |
| Weekend or not                   | 1: If the day is weekend; 0, otherwise            |

### Table 4

| Index     | Description                                      |
|-----------|--------------------------------------------------|
| AHOT      | Average hourly occupied trips                    |
| AHDt      | Average hourly distance traveled (km)            |
| AHTT      | Average hourly time traveled (h)                 |
| AS        | Average speed of occupied trips (km/h)          |

(a) COVID-19 case related variables. Based on the COVID-19 epidemic datasets, the daily newly confirmed cases, newly cured cases, cumulative confirmed cases, cumulative cured cases, hospitalized cases are taken into consideration as COVID-19 case related variables.
(b) Policy-related variables. During the outbreak of the COVID-19 epidemic, several policies on travel restrictions were issued to reduce the risk of virus transmission. We use policy-related variables (e.g., closed management and normal order) to capture the policy effect during the epidemic on taxi and ride-sourcing markets.
(c) Operational status of transportation. The government imposed traffic restrictions on highways and public transportation in response to the outbreak. For instance, on January 29, 2020, a temporary closure was imposed on 19 expressway entrances and exits in Ningbo. After the outbreak eased, the control was removed entirely by February 19, 2020.
(d) Socio-economic status related variables. Specifically, each administrative region’s traffic fee per capita and average consumption per capita are selected as socio-economic status related variables.
(e) Demographics related variables. Travel demand plays a vital role in affecting the supply in ride-sourcing and taxi markets. The population and population density in each administrative region influence travel demand, and they are taken into consideration as demographics related variables.
(f) Weekend or not. There are differences in the travel mode between weekdays and weekends. The productivity of the taxi fleet and ride-sourcing fleet vary on weekdays and weekends.

3.4.2. Productivity indices

The taxi and ride-sourcing markets go through the COVID-19 epidemic outbreak stage, epidemic remission stage, and market recovery stage between December 30, 2019, and April 30, 2020. The overall productivity of the ride-sourcing and taxi varies across the effect of the epidemic.

To measure the productivity of the taxi and ride-sourcing fleets, Nie (2017) developed several productivity analysis indices. As shown in Table 4, four productivity indices are adopted in our study. The occupied trips refer to the trips carrying passengers. The total working hours of a taxi driver and ride-sourcing driver consist of the time spent on occupied trips and the time spent on vacant trips searching for passengers. The average capacity utilization rate is estimated by distance (AHDt) and by time (AHTT). To capture the time-of-day effect, the datasets are further disaggregated into the three time periods: peak hours (7 AM - 9 AM and 4 PM - 7 PM); mid-of-day period (9 AM - 5 PM); off-peak hours (7 PM - 7 AM). AHOT is defined as the number of average hourly orders for each online driver. AHDt is defined as the sum of DriveMile divided by Duration, if the drivers are online during peak hours, Duration = 4 h; if they are online during off-peak hours, Duration = 12 h; otherwise, Duration = 8 h. AHTT is defined as the sum of DriveTime divided by Duration. The average speed is defined as the sum of DriveMile divided by the sum of DriveTime. The productivity indices of the taxi fleet and ride-sourcing fleet are calculated for different daytime periods, and the results will be shown in Section 4.1.
3.4.3. Multivariate linear mixed regression

To quantify how productivity indices of ride-sourcing and taxi fleets responded to different factors during the COVID-19 epidemic, we study the longitudinal changes in the productivity indices by establishing a regression model. Multivariate linear mixed regression is applied to examine the COVID-19 epidemic effects on the productivity of taxi and ride-sourcing fleets. The overall error distribution of the linear mixed-effects model is assumed to be Gaussian, and heteroskedasticity within groups can also be modeled. Compared with linear regression, the model takes heterogeneity among the administrative regions into consideration. Also, the interpretable results are essential in supporting decision-making with statistical evidence for government policy development to restore the productivity of ride-sourcing and taxi markets to the period before the epidemic. The multivariate linear mixed-effects model on day $d$ can be formulated as follows:

$$ Y(d) = \beta_0 + \beta'X(d) + \mu_0 + \epsilon(d) \quad (1) $$

where $Y(d)$ is the productivity index of the taxi fleet (or the ride-sourcing fleet) on day $d$; $X(d)$ is a column vector of the aforementioned explanatory variables; $\beta$ is a column vector of the model parameters for the associated explanatory variables, which has the same dimension as $X(d)$. The superscript represents the transpose. $\beta_0$ is the intercept of the regression model. This is regarded as the portion of productivity without the influence of the COVID-19 epidemic. $\epsilon(d)$ is an error term following the normal distribution with zero mean and a finite variance. $\mu_0$ is a random intercept that varies among the administrative regions.

4. Results and findings

4.1. Temporal analysis of drivers’ working characteristics

According to epidemic datasets, the five-month datasets are divided into three stages: before pandemic stage (from December 1, 2019, to January 19, 2020), outbreak and lockdown stage (from January 20 to February 20, 2020), and recovery stage (from February 21 to April 30, 2020). Because of the COVID-19 epidemic, travel demand has shrunk by a wide margin. As a result, drivers’ working characteristics are affected significantly. This section shows the variation tendency of taxi and ridesourcing drivers’ daily travel distance, daily orders, and daily income during the three stages by the statistical analysis method.

Fig. 6 presents the probability distributions of average daily travel distance for active taxi drivers and ride-sourcing drivers in each stage from December 2019 to April 2020. More than 7% of both taxi drivers and ride-sourcing drivers have nearly zero travel distance. Also, affected by the COVID-19 epidemic, the proportions of ride-sourcing drivers and taxi drivers with travel distance greater than 120 km decline significantly. For taxi drivers, the curves of Stage 1 and Stage 3 show a clear peak at around 110 km and 50 km, respectively. Compared with Stage 1, the travel distance of taxi drivers reduced to 68.62% of the distance before the epidemic due to travel restrictions and lockdown policies. While during the pandemic recovery period, the travel distance reduced to 63.28%, which is less than that during the pandemic outbreak and lockdown stage. Because the taxi drivers with daily travel distance more than 120 km during the outbreak and lockdown stage is more than that of the pandemic recovery period. In Stage 1 and Stage 3, the mean daily travel distance of taxi drivers is 111.79 km and 100.34 km, respectively, while the mean daily travel distance is 88.57 km in Stage 2. Compared with Stage 1, the travel distance of ride-sourcing drivers reduced to 79.23% of the travel distance before the epidemic. While during the pandemic recovery period, the travel distance recovered to
Fig. 8. Distributions of average daily income of active taxi drivers and ride-sourcing drivers in 3 stages.

Fig. 9. Distributions of monthly working days of active taxi and ride-sourcing drivers.
89.76% as the epidemic was brought under control in Stage 3.

Fig. 7 shows the probability distribution of the average daily orders for active taxi and ride-sourcing drivers for each stage from December 2019 to April 2020. As shown in Fig. 7(a), the curve of Stage 1 shows prominent unimodal characteristics, peaking around 18 daily orders. In terms of taxi drivers, their average daily orders decrease sharply from 18.32 in Stage 1 to 9.81 in Stage 2, almost 50%. As shown in Fig. 7(b), the average daily orders more than 15 decrease significantly in Stage 2 and Stage 3 for ride-sourcing drivers. In Stage 2, affected by travel restrictions and lockdown policies, the average daily orders fall to around 12. After pandemic recovery, the average daily orders increase over 15. With the ease of pandemic, the ride-sourcing and taxi markets gradually recover. In Stage 3, the average daily orders recover to 58.13% and 86.99% for taxi and ride-sourcing, respectively. Still, it had not recovered to the level before the epidemic.

Fig. 8 shows the distributions of the daily income of ride-sourcing drivers and taxi drivers in the three stages. In Stage 2 and Stage 3, the mean daily income of taxi drivers is CNY 293.65 and CNY 273.88, respectively, while the mean daily income before the pandemic is CNY 444.18. For taxi drivers, the curves of Stage 1 and Stage 3 show a clear peak at around CNY 400 and CNY 200, respectively. Fig. 8 shows a sharp decrease in the probability of drivers with a daily income of more than CNY 400 in Stage 2. Compared with Stage 1, the daily income of taxi drivers in Stage 2 reduced to 66.56% of the daily income before the epidemic. Even after easing the restrictions (in Stage 3), the mean daily income was still –37.92% less than before the pandemic. For ride-sourcing drivers, the mean daily income is CNY 351.32 and CNY 299.49 in Stage 1 and Stage 3, respectively. Compared with Stage 1, the mean daily income of ride-sourcing drivers in Stage 2 reduced to 86.97% of the distance before the epidemic. Surprisingly, both the mean daily income of ride-sourcing drivers and taxi drivers during Stage 2 are more than that during Stage 3.

There is an apparent difference between ride-sourcing drivers and taxi drivers. Before the epidemic, the average daily travel distance, average daily orders, and average daily income of taxi drivers are all more than that of ride-sourcing drivers due to the more flexible working pattern of ride-sourcing drivers. Generally, the ride-sourcing drivers consist of different types of drivers (e.g., full-time drivers, and part-time drivers). However, during the outbreak and lockdown stage and recovery stage, the average daily travel distance, average daily orders, and average daily income of taxi drivers are all less than that of ride-sourcing drivers, which reveals that taxi drivers are affected more significantly. For taxi drivers, the average daily orders decline sharply by almost 50%. In Stage 3, the recovery of ride-sourcing is more obvious. That implies the ride-sourcing market was affected less significantly and can recover from epidemic more quickly.
Fig. 9 illustrates the probability distribution of the monthly working days of active taxi and ride-sourcing drivers from December 2019 to April 2020. As shown in Fig. 9(a), many taxi drivers tend to work for more than 25 days in December 2019, and a large proportion of them even reached 30 days (about 23%). The proportion of ride-sourcing drivers who work 30 days is about 12%, less than taxi drivers. As the confirmed cases first appeared on January 23, 2020, numerous drivers could not continue working. Therefore, the proportion of drivers who worked for more than 25 days was significantly reduced in January 2020. As shown in Fig. 9(b), the proportion of drivers whose working days are between 15 and 25 days increases and forms a peak. In February 2020, the proportion of drivers with more than 15 working days dropped significantly. As the taxi and ride-sourcing markets gradually recovered in March 2020, the proportion of drivers working more than 15 days increased. As of April 2020, the proportion of ride-sourcing drivers working for 30 days was higher than before the epidemic, while it was smaller for taxi drivers. The reasons are that taxi operations have not fully recovered, order demand cannot be met because of insufficient supply and more ride-sourcing drivers are willing to work for more days.

4.2. Spatial analysis

In this section, we proceed to examine whether the impact of the COVID-19 pandemic on taxi and ride-sourcing trips demonstrates any spatial heterogeneity on the level of TAZs. Each trip corresponds to a unique order ID, origin TAZ, destination TAZ, starting and ending time, and is matched to TAZ in terms of the origin TAZ.

Fig. 10 shows the distribution of the origin and destination of taxi and ride-sourcing orders on January 24, 2020, which is the first day after Ningbo launched the first-level response and the first five confirmed COVID-19 cases delivered. Fig. 11 presents the distribution of desire lines among TAZs. The noticeable deviation between taxi and ride-sourcing is that passengers far from the city center tend to choose ride-sourcing than taxi.

Using the average daily trips on weekdays from December 30, 2019, to January 10, 2020, as the benchmark (the period without the COVID-19 epidemic in Ningbo, as per the previous analysis), the relative difference of the daily trips on weekdays are computed for each TAZ and each week. Fig. 12 and Fig. 13 show how the average number of daily trips by taxi and ride-sourcing changes in each TAZ on weekdays over the six weeks (between January 13 and February 21, 2020), respectively. The TAZs of cases with symptom onset are circled by red lines, according to retrospective data released. The information primarily relies on patient recall after confirmation of COVID-19. Therefore, the onset time was usually earlier than the time when cases were confirmed. The changes in average daily taxi trips per TAZ for taxi and ride-sourcing begin to have negative growth from the middle area and gradually spread to the surrounding areas. The TAZs with confirmed cases were also concentrated in the middle of the city, indicating the spread effect of the epidemic. It also shows that the normal economy and transportation can be restored earlier in the less affected suburbs. There is a sharp drop
in the trips during week-2, which indicates that travel demand was affected significantly from week-2. As shown in Fig. 12(e–f) and Fig. 13 (e–f), in the TAZs without COVID-19 cases, travel demand by taxi (or ride-sourcing) recovered more quickly than those with positive COVID-19 cases when the activities and travel were gradually resumed.

Moreover, a plot of cumulative TAZs based on the relative change in taxi and ride-sourcing trips (as per the previous analysis) is used to measure the spatial heterogeneity. As shown in Fig. 14, it implies that about 90% of TAZs experience a drop in the total taxi trips and ride-sourcing trips during week-2. Besides, the ratio for ride-sourcing is higher than that of taxi. The leftward shift in a curve on this plot suggests that more TAZs encounter negative changes in the total trips. Therefore, more TAZs experience negative changes in ride-sourcing trips than taxi between January 20 and February 7, 2020. As one may read from the plot, in week-4, more than 90% of TAZs occur over a 50% drop in the total taxi trips. Whereas ride-sourcing trips of all TAZs were dropped more than 50%, indicating that the decline in the ride-sourcing ridership had become more significant.

### 4.3. Productivity analysis

The city-level daily productivity indices of the taxi and ride-sourcing fleets are estimated in the three periods: peak hours (7–9 a.m. and 5–7 p.m.), mid-of-day period (9 a.m. - 5 p.m.), and off-peak hours (7 p.m. - 7 a.m.) from December 2019 to April 2020. Moreover, the datasets are further aggregated on weekdays to present the trend of the weekly variation.

Fig. 15 shows the variations in the average number of hourly occupied trips (AHOT) of taxi and ride-sourcing fleets on weekdays between December 2, 2019, and April 24, 2020. The first observation from these plots is that taxi AHOT during the mid-of-day period is more than that of peak hours before the COVID-19 epidemic, whereas ride-sourcing AHOT during peak hours is more than that of mid-of-day. Surprisingly, taxi AHOT during peak hours is more than that of off-peak hours between January 27 and March 13, 2020. It is because the emergency capacity dispatching of cruised taxis was enhanced by the transportation department since the temporary suspension of public transportation.

Taking AHOT of the taxi fleet during peak hours as an example, it peaked during January 13-17, 2020, i.e., 1.14 trips/hour. As shown in Fig. 15(a), after the first five confirmed cases appeared in this city on January 23, 2020, it dropped about 44.73% to 0.63 trips/hour during January 27-31, 2020. Further, it appeared to hit bottom (0.56 trips/hour) during February 24-28, 2020, after closed management in all communities issued by the government. Then it bounced back to 0.75 trips/hour during March 23-27, 2020, because of the policy on the orderly opening of public places issued on March 23, 2020. Fig. 15(b) presents AHOT of the ride-sourcing fleet. The temporal trend is similar to the taxi fleet.

Fig. 16 reveals that the variation tendency of AHDT (km) is similar to AHOT. For instance, taxi AHDT during peak hours reached the maximum during January 13–17, 2020, i.e., 7.64 km, while ride-sourcing AHDT reached 9.38 km. After the first five confirmed cases appeared in this city on January 23, 2020, taxi AHDT dropped about 20.54% to 6.07 km during January 27–31, 2020. Subsequently,
following closed management in all communities issued by the government, it hit bottom (4.68 km) during February 24–28, 2020. Then it bounced back to 5.15 km during March 23–27, 2020, owing to the orderly opening of public places. The variation range of AHDT for the taxi fleet is smaller during peak hours than other periods due to the relatively stable distance of commuting trips. This taxi feature is more evident than ride-sourcing, which indicates that trips by taxi have a more unified purpose on commuting in peak hours. It also shows that most of the non-commuting trips are completed by ride-sourcing.

During the week of April 20–24, 2020, ride-sourcing AHDT restored to 8.68 km, 92.53% of the peak value before the epidemic, while taxi AHDT had restored only 69.89%. Moreover, ride-sourcing AHDT during peak hours and the mid-of-day period is much higher than that in off-peak hours, but this variation for taxi is not apparent, which may be related to the distinct characteristics of drivers of these two markets.

Average speeds across all periods are significantly higher from January 20 to April 24, 2020, than the previous periods without the epidemic. This improvement is related to the ban on traveling in the city. Overall, the average speed of occupied trips peaked during January 27–31, 2020. As shown in Fig. 18, for taxi service, it was 36.83 km/h in peak hours, 37.54 km/h in the mid-of-day period, and 40.48 km/h in off-peak hours. Additionally, during the epidemic, as expected, the variations in the average speed are much smaller. Furthermore, the average speed during peak hours is lower than that of other periods, and it is the highest during off-peak hours, which is related to road traffic states. After February 14, 2020, the variation tendency shows the reduction of average traveling speed in peak hours is more than that of other periods, indicating that traffic flow increases on the road network, and the working mode gradually shifts to offline.

Fig. 14. Cumulative distributions of TAZs affected by relative daily taxi trip changes.

| Week       | Relative trip change (%) | Cumulative probability |
|------------|--------------------------|------------------------|
| Week-1     | -100 to 0                | 0.0                    |
| Week-2     | -100 to 0                | 0.0                    |
| Week-3     | -100 to 0                | 0.0                    |
| Week-4     | -100 to 0                | 0.0                    |
| Week-5     | -100 to 0                | 0.0                    |
| Week-6     | -100 to 0                | 0.0                    |

During the week of April 20–24, 2020, ride-sourcing AHTT experienced a sudden jump during February 3–7, 2020. Concerning ride-sourcing AHTT during peak hours, it peaked during January 13–17, 2020. Again, AHTT began to drop sharply during January 20–24, 2020, after the first five confirmed cases occurred on January 23, 2020. In the end, it bounced back to 0.35 h during April 20–24, 2020, which is close to the value before the epidemic.

Average speeds across all periods are significantly higher from January 20 to April 24, 2020, than the previous periods without the epidemic. This improvement is related to the ban on traveling in the city. Overall, the average speed of occupied trips peaked during January 27–31, 2020. As shown in Fig. 18, for taxi service, it was 36.83 km/h in peak hours, 37.54 km/h in the mid-of-day period, and 40.48 km/h in off-peak hours. Additionally, during the epidemic, as expected, the variations in the average speed are much smaller. Furthermore, the average speed during peak hours is lower than that of other periods, and it is the highest during off-peak hours, which is related to road traffic states. After February 14, 2020, the variation tendency shows the reduction of average traveling speed in peak hours is more than that of other periods, indicating that traffic flow increases on the road network, and the working mode gradually shifts to offline.
4.4. Regression analysis results

Peak hours are the busiest period during the day for ride-sourcing. The data show that the average waiting time for ride-sourcing service is 6.7 min during AM peak (7–9 a.m.) and 9.4 min during PM peak (5–7 p.m.). The value of the productivity index during the peak period is one of the most important indices of ride-sourcing and taxi service evaluation. Since the productivity indices have a similar trend of temporal variation, the average hourly travel distance of occupied trips and average speed (km/h) of occupied trips are selected as representatives to explore the effects of different factors. The regression results of average hourly occupied trips and average hourly time traveled are shown in the appendix. In the models developed for the taxi and ride-sourcing fleets to examine the factors’ effects on productivity during epidemic, the district-level productivity indices during peak hours serve as the dependent variables. The COVID-19 related variables, policy-related variables, operational status of transportation, socio-economic status related variables, demographics related variables, and other variables are included as independent variables. The dependent variables and independent variables are estimated by the taxi and ride-sourcing orders from January 20 to April 30, 2020. The period covers the epidemic outbreak and lockdown stage and recovery stage in Ningbo, China.

The multivariate linear mixed regression model is adopted to analyze the effects of explanatory variables on the productivity of the taxi fleet and ride-sourcing fleet. The model parameters are estimated by maximum likelihood estimation (MLE). The results for modeling average hourly distance traveled of the taxi fleet and ride-sourcing fleet are summarized in Table 5 and Table 6, respectively. The second column (coefficient) shows the estimated values of β₀ (intercept) and β (coefficients of different variables). Intercept β₀ is the amount of AHDT to be observed when all explanatory variables are zero. This portion of AHDT is regarded as base AHDT, which is not explained by the independent variables. Therefore, it represents the travel distance without the influence of the COVID-19 epidemic. Estimate of Sd(_cons) refers to the estimated standard deviation of random intercept.

From the results in Table 5, we gain the following insights:

- Intercept β₀, SumCure, Weekendornot, TrafficFee, and Density are all significant factors at the significance level of 0.01. MassTransit is a significant factor at the significance level of 0.05. ClosedManagement is a significant factor at the significance level of 0.1.
- The daily number of accumulated cured coronavirus cases has negative effects on the productivity of the taxi fleet. It is recognized as a strongly significant factor at the significance level of 0.001.

![Fig. 15. Average hourly occupied trips per vehicle on weekdays.](image-url)
• Closed management has negative effects on the productivity of the taxi fleet because of the restrictions on residents’ trips during the epidemic period.
• Normal operations of mass transit harm the productivity of taxi, which implies that people tend to choose public transportation instead of taxi because of the higher reliability and better efficiency of rail transit during peak hours.
• WeekendOrNot is recognized as a significant factor associated with a negative coefficient due to the decreased travel demand for commuting trips on weekends during 7–9 a.m. and 5–7 p.m.. Moreover, unnecessary non-commuting trips during the epidemic are not recommended.
• Average fee per capita spent on transportation in each administrative region is also recognized as a significant factor. There is significant positive correlation between TrafficFee and taxi productivity, which reveals that the traffic fee spent on trips by taxi is higher in the regions with higher traffic fee.
• However, there is significant negative correlation between population density and taxi productivity which reveals that trips by taxi are less frequent in the regions with higher population density.

From the results in Table 6, we gain the following insights:

• Intercept $\beta_0$, Hospitalized, SumCure, NormalOrder, MassTransit, WeekendOrNot, TrafficFee, and Density are all significant factors at the significant level of 0.01.
• The estimated standard deviation of random intercept among different districts is 0.295.
• The coefficient associated with normal operations of mass transit is generally more than twice of WeekendOrNot. It implies that the marginal effect of normal operations of mass transit on AHDT is more than twice as that of WeekendOrNot.
• The coefficient associated with MassTransit in the model for ridesourcing is less than that of the model for taxi, which indicates that taxi is affected by mass transit more significantly than ridesourcing during the epidemic. Besides, ride-sourcing is less significantly affected by WeekendOrNot and the number of cumulative cured cases.
• The absolute value of the coefficients associated with density for ridesourcing is less than that of taxi, which implies that the marginal effect of population density for ride-sourcing is less than that of taxi.
• The absolute value of the coefficients associated with TrafficFee for ride-sourcing is more than that of taxi, which indicates that the positive correlation between TrafficFee and AHDT of ride-sourcing are more significant than that of taxi.

Fig. 16. Average hourly distance traveled distance on weekdays.
The results for modeling the average speed of the taxi fleet and ridesourcing fleet are summarized in Table 7 and Table 8, respectively. The second column shows the estimated values of $\beta_0$ (intercept) and $\beta$ (coefficients of different variables). Intercept $\beta_0$ is the amount of AS to be observed when all explanatory variables are zero. This portion of AS is regarded as base AS, which is not explained by the independent variables. Therefore, it represents the traveling speed without the influence of the COVID-19 epidemic.

From the results in Table 7, we gain the following insights:

- Intercept $\beta_0$, Hospitalized, Normalorder, Weekendornot, Trafficfee, Population, and Density are all significant factors at the significance level of 0.01. Newcase and Masstransit are significant factors at the significance level of 0.1.
- The estimated standard deviation of random intercept among different districts is 0.427.
- The estimated standard deviation of random intercept among different districts is 0.427.
- The daily number of newly confirmed coronavirus cases and accumulated hospitalized coronavirus cases have positive effects on the speed of the taxi fleet. The efficient traffic state is due to the restrictions on residents’ trips during the epidemic period.
- Policy on restoring the production and living order has negative effects on the average traveling speed of taxi.
- Normal operations of mass transit have positive effects on traveling speed, revealing the subway share part of the passenger flow and alleviating traffic congestion during peak hours.
- Weekendornot is recognized as a strongly significant factor associated with a positive coefficient due to the efficient traffic state during 7–9 AM and 5–7 PM on weekends.
- There is a significant positive correlation between Trafficfee and the traveling speed of taxi, which implies that the traffic state is more effective in regions with higher traffic fee.
- There is a significant negative correlation between the population in each administrative region and the traveling speed of taxi, which is the same for population density.

From the results in Table 8, we gain the following insights:

- Intercept $\beta_0$, Hospitalized, Normalorder, Masstransit, weekendornot, Trafficfee, and Population are all significant factors at the significance level of 0.01. Sumcure is a significant factor at the significant level of 0.05. Closed management is a significant factor at the significant level of 0.1.
- The p-value of the LR tests is more than the level of significance 0.05. There is no significant variation in the random intercepts among different regions.
- The coefficient associated with normal operations of hospitalized is generally more than twice the one of Sumcure. It implies that the
marginal effect of the number of hospitalized COVID-19 cases on AS is more than twice as that of the number of COVID-19 cases.

- The coefficient associated with MassTransit in the model for ridesourcing is more than that of the model for taxi. Besides, the average traveling speed of the ride-sourcing fleet is affected by WeekendOrNot more significantly.
- The value of the coefficients associated with population for ridesourcing is less than that of taxi, which implies that the marginal effect of population for ride-sourcing is less than that of taxi.

4.5. Discussions

The COVID-19 epidemic has caused unprecedented massive destruction to society and economy all over the world. Transportation is one of the fields that severely suffered from this misfortune, whereas taxi and ride-sourcing markets during the epidemic have not been studied or verified by real-world data. Based on the 5-month city-wide datasets of taxi and ride-sourcing platforms, we provide evidence on how COVID-19 related factors influence taxi and ride-sourcing markets. The datasets go through the COVID-19 epidemic outbreak stage, epidemic remission stage, and market recovery stage. Furthermore, based on the real-world ride-sourcing dataset in China, our study gains insights into how the real-world taxi and ride-sourcing market react to the epidemic and offers a valuable reference to the rest of the world.

The variation tendency of driver working pattern before the epidemic, outbreak and lockdown stage, and recovery stage are analyzed by the statistical analysis method. Nearly 9% of taxi drivers have nearly zero travel distance. Affected by the COVID-19 epidemic, the proportion of ride-sourcing drivers with a travel distance greater than 120 km declines. Surprisingly, both the mean daily income of ride-sourcing drivers and taxi drivers during the epidemic outbreak stage are more than that during the remission stage. This may be caused by the sharply decreased number of drivers. The analysis also verifies the difference in the influence on taxi and ride-sourcing by the epidemic. In terms of the temporal analysis, traveling distance, daily orders, and daily income of taxi drivers are affected more significantly than ride-sourcing drivers. Besides, the ride-sourcing market can recover from the epidemic more rapidly.

As for the spatial analysis results, we find that the decline in the ridesourcing ridership on the spatial scale was more significant than taxi influenced by the epidemic. Besides, when the activities and travel were gradually resumed, travel demand by taxi (or ride-sourcing) recovered more quickly in TAZs without confirmed cases than those with positive COVID-19 cases. The noticeable deviation between taxi and ride-
sourcing is that passengers tend to choose ride-sourcing to travel a longer distance than taxi. The majority of trips that departed from and arrived at fringe areas of the city were served by ride-sourcing.

In terms of the city-level productivity analysis, productivity indices AHOT, AHDT, and AHTT of the ride-sourcing fleet have almost been positive effects on AHDT of both ride-sourcing and taxi fleets. Besides, the average fee of ride-sourcing is that passengers tend to choose ride-sourcing to travel a longer distance than taxi. The majority of trips that departed from and arrived at fringe areas of the city were served by ride-sourcing. Furthermore, productivity indices AHOT, AHDT, and AHTT of the ride-sourcing fleet are greater than those of the taxi fleet during peak and mid-of-day periods but lower during off-peak hours. It indicates that taxi drivers and ride-sourcing drivers have different working schedules, and ride-sourcing drivers are less likely to work during off-peak hours.

Exploring the COVID-19 related factors influencing taxi and ride-sourcing markets based on the comprehensive dataset is beneficial to provide evidence for decision-making of the government. We present exploratory evidence on the factors, including the coronavirus cases related attributes, policy-related attributes, operational status of transportation, socio-economic status related variables, demographics related variables, and other factors. The results imply that normal operations of mass transit and Weekends have negative effects on AHDT of both ride-sourcing and taxi fleets. Besides, the average fee spent on transportation per capita in each administrative region has positive effects on AHDT of both ride-sourcing and taxi fleets. The daily number of newly confirmed coronavirus cases and accumulated

| Table 5 | Regression results for modeling average hourly distance traveled of the taxi fleet. |
|----------|---------------------------------------------|
| Independent variable | Coefficient | Standard error | z-statistic | p > | z |
| Newcase | −0.006 | 0.017 | −0.332 | 0.740 |
| Newcure | 0.002 | 0.027 | 0.069 | 0.945 |
| Hospitalized | −0.003 | 0.003 | −0.799 | 0.424 |
| Sumcase | −0.008*** | 0.002 | −4.520 | 0.000 |
| Closedmanagement | −0.394** | 0.208 | −1.901 | 0.057 |
| Normalorder | 0.064 | 0.124 | 0.515 | 0.606 |
| Maxtransmit | −0.718** | 0.344 | −2.088 | 0.037 |
| Highway | 0.014 | 0.032 | 0.043 | 0.966 |
| Weekends | −0.300*** | 0.106 | −2.824 | 0.005 |
| Trafficfee | 3.03e-04 | 0.000 | 4.013 | 0.000 |
| Population | −2.99e-07 | 0.000 | −0.997 | 0.319 |
| Density | −0.001*** | 0.000 | −5.221 | 0.000 |
| Intercept (β₀) | 5.600*** | 0.822 | 6.815 | 0.000 |

**| Random-effects parameters | Estimate | Standard error | 95% Confidence interval |
|----------|---------------------------------------------|
| Sd(cons) | 0.179 | 0.073 | [0.081, 0.379] |
| Sd(residual) | 1.153 | 0.033 | [1.090, 1.220] |

| N | 612 |
| Log-likelihood | 959.401 |

LR test vs. linear model: chibar2(01) = 7.14 Prob ≥ chibar2 = 0.0038.  
* Significant at 10%. ** Significant at 5%. *** Significant at 1%.

| Table 6 | Regression results for modeling average hourly distance traveled of the ride-sourcing fleet. |
|----------|---------------------------------------------|
| Independent variable | Coefficient | Standard error | z-statistic | p > | z |
| Newcase | −0.003 | 0.005 | −0.648 | 0.517 |
| Newcure | 0.005 | 0.008 | 0.659 | 0.510 |
| Hospitalized | −0.004*** | 0.001 | −3.442 | 0.001 |
| Sumcase | −0.003*** | 0.001 | −5.081 | 0.000 |
| Closedmanagement | 0.010 | 0.003 | 0.015 | 0.878 |
| Normalorder | 0.318*** | 0.038 | 8.423 | 0.000 |
| Maxtransmit | −0.609*** | 0.105 | −5.794 | 0.000 |
| Highway | 0.074 | 0.099 | 0.749 | 0.454 |
| Weekends | −0.235*** | 0.032 | −7.247 | 0.000 |
| Trafficfee | 3.62e-04*** | 0.000 | 3.432 | 0.001 |
| Population | 0.000 | 0.000 | 1.314 | 0.189 |
| Density | −6.6e-04 | 0.000 | −2.982 | 0.003 |
| Intercept (β₀) | 3.898*** | 0.843 | 4.623 | 0.000 |

**| Random-effects parameters | Estimate | Standard error | 95% Confidence interval |
|----------|---------------------------------------------|
| Sd(cons) | 0.295 | 0.086 | [0.166, 0.523] |
| Sd(residual) | 0.352 | 0.010 | [0.333, 0.373] |

| N | 612 |
| Log-likelihood | −242.717 |

LR test vs. linear model: chibar2(01) = 298.75 Prob ≥ chibar2 = 0.0000.  
* Significant at 10%. ** Significant at 5%. *** Significant at 1%.

| Table 7 | Regression results for modeling average speed of the taxi fleet. |
|----------|---------------------------------------------|
| Independent variable | Coefficient | Standard error | z-statistic | p > | z |
| Newcase | 0.078** | 0.046 | 1.705 | 0.088 |
| Newcure | 0.094 | 0.072 | 1.308 | 0.191 |
| Hospitalized | 0.043*** | 0.009 | 4.710 | 0.000 |
| Sumcase | −0.007 | 0.005 | −1.455 | 0.146 |
| Closedmanagement | −0.079 | 0.059 | −1.042 | 0.887 |
| Normalorder | 2.044*** | 0.337 | −6.061 | 0.000 |
| Maxtransmit | 2.090** | 0.927 | 2.255 | 0.024 |
| Highway | 1.356 | 0.871 | 1.556 | 0.120 |
| Weekends | 2.381*** | 0.290 | 8.204 | 0.000 |
| Trafficfee | 8.42e-04*** | 0.000 | 4.491 | 0.000 |
| Population | −5.34e-06 | 0.000 | −9.373 | 0.000 |
| Density | −0.002*** | 0.000 | −4.245 | 0.000 |
| Intercept (β₀) | 31.329*** | 2.126 | 14.738 | 0.000 |

**| Random-effects parameters | Estimate | Standard error | 95% Confidence interval |
|----------|---------------------------------------------|
| Sd(cons) | 0.427 | 0.188 | [0.180, 1.012] |
| Sd(residual) | 3.108 | 0.090 | [2.937, 3.289] |

| N | 612 |
| Log-likelihood | −1550.295 |

LR test vs. linear model: chibar2(01) = 4.93 Prob ≥ chibar2 = 0.0132.  
* Significant at 10%. ** Significant at 5%. *** Significant at 1%.
hospitalized coronavirus cases have positive effects on the traveling speed of the taxi fleet due to the efficient traffic state during the epidemic outbreak period.

From the perspective of market regulation, incentive policies should be introduced to increase the dispatching capacity of taxis during peak hours and encourage more taxi drivers to work in peak hours. For transportation management, differentiated regional management should be adopted in the stage of the market recovery, and priority should be given to restoring mobility in the suburbs.

5. Conclusions

Emergency management concepts, policies, regulations, and scientific decision-making systems should be introduced to adapt to the normalization of epidemic prevention and control among transportation network companies before the effective treatment of COVID-19 comes out. This paper explores the impacts of different factors on the ride-sourcing and taxi markets during the COVID-19 epidemic. The 5-month city-wide taxi and ride-sourcing datasets with more than 37-million trips cover different stages of the epidemic. The remarkable datasets include departure/arrival geolocation of each trip order and the detailed travel description such as travel time and travel distance, making the analysis result solid and constructive. We present temporal variation of the city-level productivity of the ride-sourcing fleet and taxi fleet. The real-world datasets demonstrate the spatial heterogeneity in TAZs of the impact of COVID-19 on taxi and ride-sourcing trips. Therefore, the difference in temporal and spatial influence by epidemic is demonstrated. The multivariate linear mixed regression model is applied to examine the effects of different factors on the district-level productivity of taxi and ride-sourcing, respectively. The variables include the coronavirus cases related variables, policy-related variables, operational status of transportation, demand-related variables, and other factors. The estimation results show that regression models can estimate the explanatory variables that significantly impact the productivity of taxi and ride-sourcing, including NewCase, SumCase, MassTransit, TrafficFee, Density, and WeekendOrNot. The findings can generally support other COVID-19 related decision-making in different stages and help restore ride-sourcing and taxi markets to the status before the epidemic. The COVID-19 datasets presented were provided by the COVID-19 epidemic monitoring platform of Ningbo and used as a case study. The method in this paper can be adapted to other cities or regions to explore how the COVID-19 epidemic affects the taxi and ride-sourcing markets.

Author statement

Jingru Yu: Methodology, Data curation, Formal analysis, Validation, Writing – original draft. Ningke Xie: Formal analysis, Writing – review & editing, Investigation. Jiangtao Zhu: Data curation, Writing – review & editing, Investigation. Yiwei Qian: Data curation, Methodology. Sijing Zheng: Data curation, Writing – review & editing. Xiqun (Michael) Chen: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Appendix

Table A1

| Independent variable        | Coefficient | Standard error | z-statistic | p > |z| |
|----------------------------|-------------|----------------|-------------|-----|-----|
| NewCase                    | -0.002      | 0.001          | -1.304      | 0.192 |
| Newcure                    | 0.000       | 0.002          | -0.226      | 0.821 |
| Hospitalized               | -0.001***   | 0.000          | -4.601      | 0.000 |
| SumCase                    | -0.001***   | 0.000          | -7.218      | 0.000 |
| Closedmanagement           | -0.011      | 0.015          | -0.764      | 0.445 |
| Normalorder                | 0.072***    | 0.009          | 8.169       | 0.000 |
| Masstransit                | -0.037      | 0.024          | -1.510      | 0.131 |
| Highway                    | -0.013      | 0.023          | -0.564      | 0.573 |
| WeekendOrnot               | -0.029***   | 0.008          | -3.799      | 0.000 |
| TrafficFee                 | 6.696-08    | 0.000          | 1.276       | 0.202 |
| Population                 | 9.35e-08    | 0.000          | 0.648       | 0.517 |
| Density                    | 5.70e-05    | 0.000          | 0.571       | 0.568 |
| Intercept                  | 0.064       | 0.374          | 0.170       | 0.865 |
| Random-effects parameters  | Estimate    | Standard error | 95% Confidence interval |
| Sd(cons)                   | 0.133       | 0.039          | [0.076, 0.235] |
| Sd(residual)               | 0.082       | 0.002          | [0.078, 0.087] |
| N                          | 612         |                |             |
| Log-likelihood             | 645.692     |                |             |

LR test vs. linear model: chibar2(01) = 758.68 Prob > chibar2 = 0.000.

* Significant at 10%. ** Significant at 5%. *** Significant at 1%. 
Table A2
Regression results for modeling average hourly trips of the ride-sourcing fleet

| Independent variable | Coefficient | Standard error | z-statistic | p > |z| |
|---------------------|-------------|----------------|-------------|-----|----|
| Newcase             | -0.001      | 0.001          | -0.839      | 0.402 |
| Newcure             | 0.001       | 0.002          | 0.753       | 0.451 |
| Hospitalised        | -7.80e-04 **| 0.000          | -4.006      | 0.000 |
| Suncure             | -2.90e-04***| 0.000          | -2.714      | 0.007 |
| Closedmanagement    | -0.001      | 0.012          | -0.043      | 0.966 |
| Normalorder         | 0.062***    | 0.007          | 8.774       | 0.000 |
| Mastransit          | -0.075***   | 0.020          | -3.818      | 0.000 |
| Highway             | 0.030       | 0.018          | 1.627       | 0.104 |
| Weekendornot        | -0.054***   | 0.006          | -8.892      | 0.000 |
| Trafficfee          | 6.96e-05    | 3.69e-05       | 1.895       | 0.058 |
| Population          | 9.48e-08    | 1.12e-07       | 0.846       | 0.398 |
| Density             | -1.80e-04** | 7.76e-05       | -2.322      | 0.020 |
| Intercept (β₀)      | 0.572**     | 0.291          | 1.968       | 0.049 |

Random-effects parameters

| Estimate | Standard error |
|----------|----------------|
| Sd(_cons)| [0.059, 0.183] |
| Sd(residual)| [0.062, 0.070] |

N: 612
Log-likelihood: 779.823
LR test vs. linear model: chibar2(01) = 729.18 Prob ≥ chibar2 = 0.000.

* Significant at 10%, ** Significant at 5%, *** Significant at 1%.

Table A3
Regression results for modeling average hourly travel time of the taxi fleet

| Independent variable | Coefficient | Standard error | z-statistic | p > |z| |
|---------------------|-------------|----------------|-------------|-----|----|
| Newcase             | 0.005***    | 0.002          | 3.089       | 0.002 |
| Newcure             | -0.003      | 0.003          | -1.248      | 0.212 |
| Hospitalised        | 0.000       | 0.000          | -0.922      | 0.356 |
| Suncure             | 0.000       | 0.000          | -0.777      | 0.437 |
| Closedmanagement    | -0.024      | 0.020          | -1.197      | 0.231 |
| Normalorder         | 0.001       | 0.012          | 0.109       | 0.913 |
| Mastransit          | -0.020      | 0.034          | -0.582      | 0.560 |
| Highway             | -0.044      | 0.031          | -1.390      | 0.165 |
| Weekendornot        | -0.025**    | 0.010          | -2.415      | 0.016 |
| Trafficfee          | 0.000       | 0.000          | 0.782       | 0.434 |
| Population          | 0.000       | 0.000          | 0.914       | 0.361 |
| Density             | 0.000**     | 0.000          | -2.256      | 0.024 |
| Intercept (β₀)      | 0.238***    | 0.072          | 3.286       | 0.001 |

Random-effects parameters

| Estimate | Standard error |
|----------|----------------|
| Sd(_cons)| [0.005, 0.034] |
| Sd(residual)| [0.010, 0.118] |

N: 612
Log-likelihood: 469.00465
LR test vs. linear model: chibar2(01) = 2.69 Prob ≥ chibar2 = 0.050.

* Significant at 10%, ** Significant at 5%, *** Significant at 1%.

Table A4
Regression results for modeling average hourly travel time of the ride-sourcing fleet

| Independent variable | Coefficient | Standard error | z-statistic | p > |z| |
|---------------------|-------------|----------------|-------------|-----|----|
| Newcase             | -5.04e-04*  | 0.000          | -1.175      | 0.240 |
| Newcure             | -4.90e-04   | 0.000          | -1.157      | 0.240 |
| Hospitalised        | -2.86e-04***| 5.26e-05       | -0.589      | 0.560 |
| Suncure             | -8.96e-05***| 0.000          | -2.415      | 0.016 |
| Closedmanagement    | -3.09e-04   | 0.003          | -0.926      | 0.361 |
| Normalorder         | 0.023***    | 0.002          | 12.165      | 0.000 |
| Mastransit          | -0.030***   | 0.005          | -5.589      | 0.000 |
| Highway             | -0.004      | 0.005          | -0.796      | 0.426 |
| Weekendornot        | -0.026***   | 0.002          | -16.088     | 0.000 |
| Trafficfee          | 8.26e-06*** | 2.93e-06       | 2.817       | 0.005 |
| Population          | 4.56e-08*** | 8.90e-09       | 5.122       | 0.000 |
| Density             | -1.77e-05***| 6.17e-06       | -2.914      | 0.003 |
| Intercept (β₀)      | 0.128**     | 0.025          | 5.204       | 0.000 |

Random-effects parameters

| Estimate | Standard error |
|----------|----------------|
| Sd(_cons)| [0.005, 0.015] |
| Sd(residual)| [0.017, 0.019] |

N: 612
Log-likelihood: 1586.220

* Significant at 10%, ** Significant at 5%, *** Significant at 1%.
LR test vs. linear model: chibar2(01) = 95.03 Prob ≥ chibar2 = 0.000.

* Significant at 10%. ** Significant at 5%. *** Significant at 1%.

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