The influence of ride-hailing on travel frequency and mode choice

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Abstract: Using data derived from 597 face-to-face interviews with ride-hailing users in Chengdu, China, we examined the influence of ride-hailing on travel frequency and mode choice and further analyzed what the main determinants for these are. The results indicate that 16.8% of the respondents increase their frequency of trips because of the adoption of ride-hailing services, suggesting a complementary effect of ride-hailing on travel. Meanwhile, the use of traditional travel modes is considerably substituted by ride-hailing services. Particularly, around half of the respondents indicated a substitution of ride-hailing for sustainable modes (i.e., public transit, cycling, and walking), which may thus generate environmental problems (e.g., increasing greenhouse gas emissions). Additionally, regression outcomes show that higher accessibility to bus stations is negatively correlated with the shift from sustainable modes to ride-hailing. Therefore, optimizing the access to bus facilities may be effective to cope with potential transportation problems imposed by ride-hailing.

Keywords: ride-hailing services; travel behavior; mode choices; built environment; Chengdu (China)

1. Introduction

App-based ride-hailing (also named “ridesourcing”) is an emerging travel option that allows travelers to use an application on smartphones (such as Uber, Lyft, and Didi Chuxing) to request a car ride in real-time from potential suppliers (Rayle et al., 2016). Ride-hailing has unique advantages over traditional travel modes. When using ride-hailing services, for example, waiting time is usually shorter and more reliable than taxicab services, and travelers do not need to cruise for parking (Clewlow & Mishra, 2017; Rayle et al., 2016). Given these advantages, the use of ride-hailing services has increased substantially in recent years. In 2018, 516 million people were users of ride-hailing services around the world. The global revenue in the ride-hailing sector reached approximately US $ 66 billion. China has been the largest market, and its revenue was US $ 35 billion, amounting to 53% of the global revenue. The United States ranked in the second place with a revenue of US $ 18 billion (Haitou Academy, 2020).

It has been widely acknowledged that the great use of ride-hailing services can impact travel behavior, including trip frequency, travel mode choices, and vehicle miles traveled (e.g., Acheampong et al., 2020; Henao & Marshall, 2019; Tang et al., 2020; Wu & MacKenzie, 2021). However, previous empirical studies reveal inconsistent results regarding the influence of ride-hailing on travel (particularly on trip frequency and modal shifts). For example, some research indicates that ride-hailing is likely to increase trip frequency (e.g., Henao & Marshall, 2019; Jiao et al., 2020; Rayle et al., 2016). In contrast, some scholars argue that ride-hailing has a negligible effect on trip frequency (e.g., Kong et al., 2020a; Tang et al., 2020). With regard to modal shifts, some researchers find that public transit is most likely substituted by ride-hailing (e.g., Chen et al., 2018; Henao & Marshall, 2019). However, some studies suggest that the most substituted mode is taxi (e.g., Shen et al., 2020; Tang et al., 2020; Tirachini & Gomez-Lobo, 2020) or private car (e.g., Alemi et al., 2018a; Möller et al., 2019). These inconsistent findings make it hard for urban planners and policymakers to evaluate how and to what extent ride-hailing services have changed transportation systems and whether possible measures need to be implemented to cope with these changes.

In sum, researchers so far have not provided a clear answer on whether and how ride-hailing influences travel behavior. This could be attributed to the limitation of measurement methods. In previous studies, a stated preference design only regarding a specific trip (e.g., the most recent trip) is often used to measure the impacts of ride-hailing on trip frequency and mode choice. However, the design may generate measurement errors. Particularly, it may underestimate the extent to which ride-hailing influences trip frequency (more details will be discussed in the section of Literature Review). In addition, researchers argue that travel impacts of ride-hailing services may differ by geographical contexts (Alemi et al., 2018b; Hall et al., 2018). Most existing empirical attention has been paid to American contexts (e.g., Alemi et al., 2018a; Clewlow & Mishra, 2017; Henao & Marshall, 2019; Jiao et al., 2020; Möller et al., 2019; Rayle et al., 2016; Kong et al., 2020a). Compared to the United States, however, China – as the largest ride-hailing market – has not been fully investigated regarding this topic. Against this background, using data collected from Chengdu, China in 2019 and optimizing the measurement method used in previous studies, this paper aims to reexamine whether and how ride-hailing influences trip frequency and modal shifts, and analyze what the main determinants for these are. By doing so, the present study will help clarify how and to what extent ride-hailing services have changed transportation systems and shed light on the mechanism behind these changes, thus yielding policy recommendations. The remainder of this study is organized as follows. In Section 2, previous studies are reviewed. Data used in the present study are introduced in Section 3. In Section 4, the results are presented. We end this study with conclusions and discussion in Section 5.

2. Literature review

2.1 Effects of ride-hailing on travel

With the wide adoption of ride-hailing in recent years, an increasing body of research has explored how ride-hailing influences travel behavior. Nonetheless, this topic remains poorly understood, because results from previous studies are inconsistent and even conflicting in at least two aspects. The first debate is about whether and to what extent ride-hailing increases trip frequency. Compared to traditional travel modes, ride-hailing services are often considered more flexible, reliable, and convenient (Acheampong et al., 2020; Clewlow & Mishra, 2017; Rayle et al., 2016). Therefore, it can be reasonably assumed that the use of ride-hailing services can generate additional trips (i.e., complementary effect). However, not all previous studies support this assumption. Using a stated preference method, many researchers ask respondents whether they would have made a specific trip (e.g., the most recent ride-hailing trip or the ride-hailing trip made during the survey) if ride-hailing services had not been available (Alemi et al., 2018a; Gehrke et al., 2019; Henao & Marshall, 2019; Lavieri & Bhat, 2019; Rayle et al., 2016; Tang et al., 2020; Tirachini & Gomez-Lobo, 2020). The proportion of respondents who would not have traveled in the absence of ride-hailing services differs largely among these studies. For example, Henao and Marshall (2019) revealed that 12.2% of respondents would not have traveled, confirming the complementary effect. In contrast, Tang et al. (2020) indicated that only 0.4% of respondents would not have traveled, likely supporting the neutrality effect.

The study by Hampshire et al. (2017) pointed to another story. On May 7, 2016, Uber and Lyft – two ride-hailing companies – suspended their services in Austin, Texas. Using this "natural experiment", Hampshire and colleagues compared trip frequencies of 1080 residents pre- and post-suspension. They found that – of these residents – 696 (64.4%) indicated a decrease in trip frequency after the service suspension, while only 105 (9.7%) reported an increase in trip frequency. Meanwhile, the average monthly frequency of trips decreased from 5.65 pre-suspension to 2.01 post-suspension. The results suggested that ride-hailing has a substantially complementary effect on trip frequency. In particular, the share (64.4%) of respondents indicating an increase in trip frequency due to ride-hailing services is much higher than that in other studies (0.4%~12.2%).

In addition, another two studies explore the relationship between ride-hailing and personal trips in a different way. Using data derived from the 2017 National Household Travel Survey of the United States and applying negative binomial regression models, Jiao et al. (2020) found a significant and positive association between the use of ride-hailing services and trip frequency, which seems to support the complementary effect. Surprisingly, using the same data and estimating a structural equation model, Kong et al. (2020a) revealed that the association is statistically insignificant, thereby confirming the neutrality effect.

The second debate is about the traditional travel modes that are most substituted by ride-hailing services. Using a stated preference method, researchers measure the degree of the substitution of ride-hailing services for traditional modes by asking respondents to indicate which mode they would have taken for a specific trip if/when ride-hailing services had not been available. Results frequently suggest that taxi is the most substituted mode by ride-hailing services, because respondents who would have used a taxi in the absence of ride-hailing services account for the largest share (Alemi et al., 2018a; de Souza Silva et al., 2018; Rayle et al., 2016; Shen et al., 2020; Tang et al., 2020; Tirachini & Gomez-Lobo, 2020). However, other evidence shows that the most substituted mode is public transit (Chen et al., 2018; Gehrke et al., 2019; Henao & Marshall, 2019; Lewis & MacKenzie, 2017) or private car (Hampshire et al., 2017; Lavieri & Bhat, 2019; Möller et al., 2019). Furthermore, two studies measure the substitution effects of ride-hailing on other modes by asking respondents to directly report the changes in the use of other modes after they started using ride-hailing services. Alemi et al. (2018a) found that respondents are most likely to reduce the amount of driving after starting using ride-hailing services. Clewlow and Mishra (2017) revealed that public bus is the most reduced mode after using ride-hailing services.

The two debates may be partly attributed to the variation in the local contexts between the studied cities (Alemi et al., 2018b). Hall et al. (2018) confirmed the spatial heterogeneity of the effects of ride-hailing services on the use of public transit in the United States. They found that ride-hailing decreases the use of public transit by 5.9% in smaller cities. In larger cities, however, ride-hailing slightly increases the use of public transit by 0.8%. Therefore, providing evidence from various contexts can significantly contribute to a better understanding of the travel impacts of ride-hailing. However, most previous studies empirically analyze this issue in the context of the United States (e.g., Alemi et al., 2018a; Clewlow & Mishra, 2017; Gehrke et al., 2019; Hampshire et al., 2017; Henao & Marshall, 2019; Lavieri & Bhat, 2019; Lewis & MacKenzie, 2017; Möller et al., 2019; Rayle et al., 2016; Jiao et al., 2020; Kong et al., 2020a; Rayle et al., 2016). We can only be aware of a few empirical studies from China – the largest ride-hailing market in the world (e.g., Chen et al., 2018; Tang et al., 2020). Interestingly, as reviewed above, these China-based studies lead to inconsistent results regarding the most replaced mode by ride-hailing services. Therefore, there is a need to provide additional evidence from China to clarify the debatable issues.

Notably, most existing studies apply a stated preference (SP) method to design a question only regarding a specific trip (e.g., the most recent ride-hailing trip) to infer the influence of ride-hailing on travel, which may generate measurement errors. When measuring the impacts on trip frequency, the SP method can only assess whether this specific trip is additionally generated by ride-hailing. It can hardly indicate whether other trips made by the same person are generated by ride-hailing. In other words, the overall impacts on trip frequency cannot be fully pictured. Therefore, this method may underestimate the complementary effects of ride-hailing services on trip frequency. Compared to all studies adopting the SP method, the study by Hampshire et al. (2017) using a natural experiment in Austin, Texas showed a much stronger complementary effect on trip frequency, which confirms our assumption to some extent. When measuring the substitution effects on traditional modes, the SP method crudely assumes that – for a certain person – only one travel mode can be replaced by ride-hailing services. This violates the reality that an individual may shift away from multiple modes to ride-hailing, and the extent may differ by modes. For example, a person often shifts the travel mode from bus to ride-hailing but sometimes from private car to ride-hailing. Following the method, this person can only indicate bus as the substituted mode. The modal shift from private car to ride-hailing cannot be measured, although this shift actually exists for her/him. In other words, a traditional travel mode will be considered substituted in the method only when this mode is most likely replaced with ride-hailing. Consequently, the substitution degree for each traditional mode may be underestimated compared to real situations. Therefore, the current SP-based design regarding a specific trip needs to be improved.

2.2 Factors influencing changes in trip frequency and modal shifts

As reviewed above, quite a number of studies have empirically analyzed whether people increase their trip frequencies due to ride-hailing services and whether they shift away from traditional modes to ride-hailing. However, as a timely topic, the factors influencing the changes in trip frequency and modal shifts are rarely explored in these studies.

To the best of our knowledge, only three publications investigated the influential factors of changes in trip frequency due to the use of ride-hailing services. Tirachini and Gomez-Lobo (2020) revealed that low-income groups are more inclined to make additional trips because of ride-hailing, particularly after midnight (0:00 am-6:00 am). A possible reason is that transit services – a commonly-used mode by low-income people – are hardly available after midnight. In such a situation, ride-hailing services make it possible for them to engage in activities, thus inducing new trips. The study by Gehrke et al. (2019) indicated that people possessing a transit pass, using pooled ride-hailing services, or residing in areas with a high employment-population ratio tend to increase trip frequency due to ride-hailing. Additionally, passengers' latent travel demand is less likely generated when parking issues are their motivations for using ride-hailing services. Lavieri and Bhat (2019) found that young people, part-time employees, those who are self-employed, and those living in multi-worker households and urban neighborhoods are more likely to increase trip frequency due to ride-hailing. Additional trips are also more likely generated by ride-hailing during non-evening periods. However, possible explanations for the above-mentioned findings are absent in the work of both Gehrke et al. (2019) and Lavieri and Bhat (2019).

A few studies explore the factors influencing mode shifts from traditional transportation means to ride-hailing. These factors can be roughly classified into five categories, i.e. sociodemographics, built environment, trip attributes, motivations, and ride-hailing frequency. (1) *Sociodemographics*. A gender difference in mode shifts is found by Lavieri and Bhat (2019), indicating that women are more likely to shift their travel modes from walking, cycling, or transit to ride-hailing. It is widely acknowledged that low-income people are more likely to shift their travel modes from active modes (i.e., walking and cycling) or transit to ride-hailing, possibly because they prefer to make trips by walking, cycling, or public transit (Gehrke et al., 2019; Lavieri & Bhat, 2019; Tang et al., 2020; Tirachini & Gomez-Lobo, 2020). In contrast, high-income groups have a greater tendency to reduce the use of cars or taxis due to ride-hailing, mainly because they are more likely to be car or taxi users (Lavieri & Bhat, 2019; Tirachini & Gomez-Lobo, 2020). Age and educational background are also considered in previous studies. For example, Lavieri and Bhat (2019) found that young and well-educated people are more likely to shift their travel modes from walking, cycling, or transit to ride-hailing. Meanwhile, older adults and those who are better educated tend to replace taxi trips with ride-hailing. Furthermore, a high availability of a specific travel mode usually leads to a high likelihood of shifting from this mode to ride-hailing. The study by Gehrke et al. (2019) suggested that people who possess a transit pass are more likely to substitute ride-hailing services for public transit. Those who own a personal bicycle are more inclined to substitute ride-hailing services for active modes.

(2) *Built environment*. Residents in rural areas are found to have a greater tendency to replace taxi trips with ride-hailing (Lavieri & Bhat, 2019), while those in denser areas are more inclined to reduce the use of public transit due to ride-hailing (Kong et al., 2020b). This seems reasonable because normally rural residents are more likely to use taxis but less likely to use public transit compared to their counterparts in denser areas. Regarding accessibility to public transit facilities, previous studies yield mixed findings. Some researchers revealed that high accessibility to transit stations tends to result in a high

likelihood of shifting from public transit to ride-hailing (Gehrke et al., 2019; Kong et al., 2020b). This is a reasonable finding because passengers with high accessibility to transit services are more likely to be transit users, thus having a high probability of reducing transit trips due to ride-hailing. However, the work by Tang et al. (2020) pointed out that residents are less likely to use ride-hailing services rather than metros in cities with higher accessibility to metro services. They assumed that the advantages of metro services (e.g., high level of time reliability and low costs) are possible explanations for the result. In addition, other built environment elements such as housing price, land use diversity, and road density are also examined by Kong et al. (2020b), who found that these elements are positively associated with the mode shift from public transit to ride-hailing.

(3) *Trip attributes*. Trip distances/durations seem to influence mode shifts. For long trips, passengers are less likely to substitute ride-hailing for private cars and taxis, possibly because ride-hailing services are more expensive than the two traditional modes when trips are long (Tang et al., 2020). For short trips – as expected – people are more inclined to shift from walking and cycling to ride-hailing (Gehrke et al., 2019). Temporal characteristics are also considered in previous studies. It is found that public transit, walking, or cycling are more likely replaced by ride-hailing services when trips are made during peak hours (Gehrke et al., 2019; Tirachini & Gomez-Lobo, 2020). Additionally, people have a high tendency to shift from public transit to ride-hailing on weekdays (Tirachini & Gomez-Lobo, 2020).

(4) *Motivations*. Previous studies have consistently suggested that positive motivations

for using ride-hailing services encourage the shift from traditional modes to ride-hailing. For example, Tang et al. (2020) revealed that people who consider the costs of ride-hailing services lower are more likely to substitute ride-hailing services for buses. Those who feel encumbered by parking problems and driving restrictions are more likely to substitute ride-hailing services for private cars. Gehrke et al. (2019) indicated that public transit is more likely replaced by ride-hailing services when people adopt ride-hailing services because these services are quicker than public transit or transit services are unavailable. People have a greater tendency to shift from public transit and active modes to ride-hailing when they use ride-hailing services because of poor weather conditions.

(5) *Ride-hailing frequency*. The role of ride-hailing frequency in mode shifts was examined in the work by Lavieri and Bhat (2019). They found that infrequent ride-hailing users are more likely to shift their travel modes from walking, cycling, or transit to ride-hailing.

From these existing studies, some lessons can be learned. First, the issue of influential factors has not fully addressed. In particular, very little research explores the driving factors of the increase in trip frequency. Consequently, there is still a lack of an in-depth understanding of the mechanism behind the travel impacts of ride-hailing services. Second, as one of the usual influential factors of travel, the built environment is only considered in a few studies (e.g., Gehrke et al., 2019; Kong et al., 2020b; Lavieri & Bhat, 2019; Tang et al., 2020). There is a need to further explore the role of the built environment in whether individuals increase trip frequency due to ride-hailing and in whether they shift away from traditional modes to ride-hailing. Thus, it will help be clear whether built environment interventions are effective to make travel toward sustainable modes in the age of ride-hailing. Third, some potential factors such as ICT use and travel attitudes are missing in previous studies. It has been found that ICT use can positively contribute to the adoption of ride-hailing services (Alemi et al., 2018a, 2018b, 2019; Fu, 2020; Kong et al., 2020a). Therefore, it can be reasonably assumed that ICT use may influence changes in travel due to ride-hailing. In addition, attitudes toward travel modes are commonly considered as the factors impacting travel behavior (particularly travel mode choices) (De Vos et al., 2021; Guan et al., 2020; Lin et al., 2017). Therefore, attitudes may also play roles in changes in travel (e.g., modal shifts) due to ride-hailing. Importantly, the issue of self-selection can be largely addressed when travel attitudes are controlled for (Cao, 2015; Mokhtarian & Cao, 2008). Consequently, the actual influence of the built environment on changes in travel frequency and mode choices can be accurately measured.

In sum, there still exist some research limitations in previous studies. To address them, the present study will provide evidence from a Chinese context (i.e., Chengdu, China) to empirically reexamine the impacts of ride-hailing on trip frequency and travel modes and further investigate their determinants (particularly focusing on the roles of the built environment, ICT use, and travel attitudes).

3. Data

The data used in the present study are mainly derived from a face-to-face structured survey between June and August 2019 in Chengdu, China. A two-stage sampling approach was used to conduct the survey. At the first stage, the sampled units were selected. In Chengdu, there is a roughly continuous decrease in the urbanization level from the city center to the fringe. Given this situation, the main urban area of Chengdu was divided into five sub-areas by four ring roads in the survey (see Figure 1). The closer a sub-area is to the city center, the more highly urbanized it is. In each sub-area, 5-7 residential neighborhoods were geographically randomly selected as sampled units, thus leading to 29 sampled units in total. At the second stage, respondents were recruited at public spaces of these selected neighborhoods or/and by randomly knocking on doors at these neighborhoods.

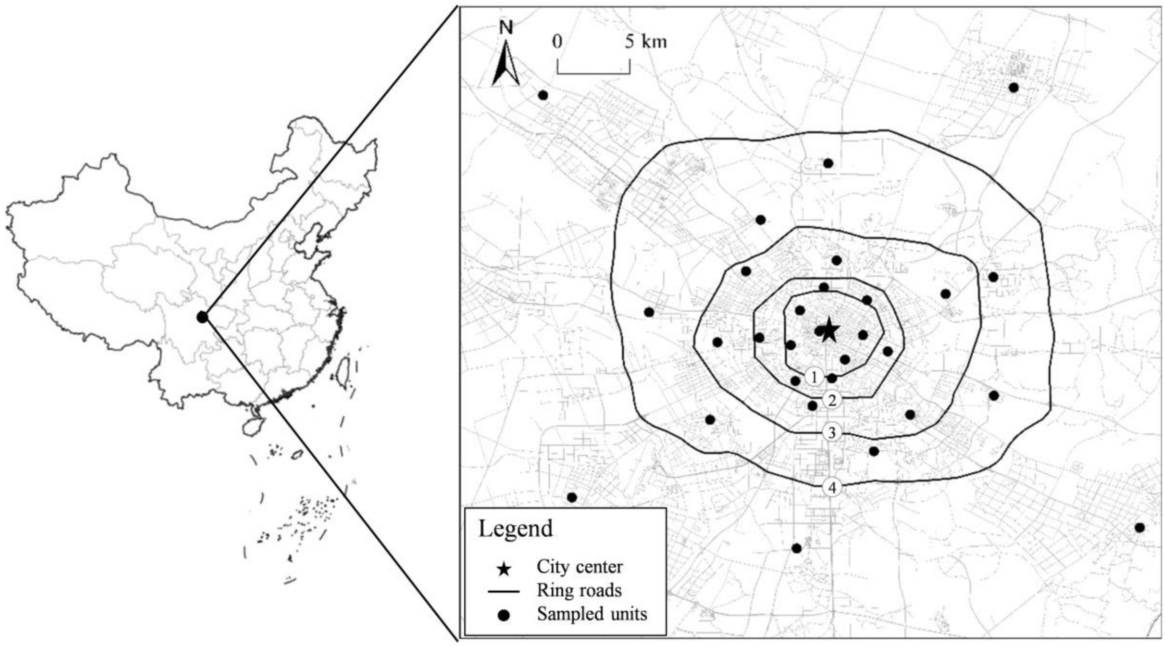

Figure 1 The location of Chengdu city and sampled units

In the end, a total of 1011 residents participated in this survey. Because we aim to explore the travel effects of ride-hailing, the users of ride-hailing services are the target population in the present study. Among these participants, 597 indicated that they had used ride-hailing services and completed this survey, thus being used as valid respondents in this study. Their characteristics are reported in Table 1. Notably, it has been widely acknowledged that young people and those with high educational levels and high incomes are more likely to be users of ride-hailing services (e.g., Acheampong et al., 2020; Alemi et al., 2018a, 2018b, 2019; Lewis & MacKenzie, 2017). This may be the main reason why the valid respondents in Table 1 are relatively young, better educated, and wealthy. Nevertheless, it is hard to assess the representativeness of these valid respondents because the characteristics of the population using ride-hailing services in Chengdu or China are unavailable.

Table 1 Sociodemographics of valid respondents

Variables	Descriptions	N	%
Gender	Male (Value=1)	276	46.2
	Female (Value=0)	321	53.8
Age (years)	20 or younger (Value=1)	93	15.6
	21-30 (Value=2)	337	56.4
	31-40 (Value=3)	113	18.9
	41 or more (Value=4)	54	9.0
Education	High school or less (Value=1)	88	14.8
	Colleges/technical school (Value=2)	201	33.7
	Undergraduate school (Value=3)	251	42.1
	Graduate school or more (Value=4)	56	9.4
Household annual	5 or less (Value=1)	56	9.4
income (10000 RMB)	6-10 (Value=2)	141	23.7
	11-15 (Value=3)	140	23.5
	16-20 (Value=4)	114	19.2
	21 or more (Value=5)	144	24.2
Having a driver's license	Yes (Value=1)	355	59.7
	No (Value=0)	240	40.3
Household car ownership	Yes (Value=1)	396	66.3
	No (Value=0)	201	33.7

Note: 1 RMB was around US $ 0.145 in 2019.

3.1 Measurement of the changes in trip frequency

Applying a stated preference method, previous studies usually measure the changes in trip frequency due to ride-hailing by asking respondents to indicate whether they would have made a specific trip (e.g., the last trip they had actually made by ride-hailing) in the absence of ride-hailing services. Following this method, we asked respondents to recall their experiences of the most recent trip by ride-hailing and to answer the question: “Would you have made this trip if ride-hailing services had been unavailable?”.

As we argued in Section 2.1, however, this method regarding a specific trip may underestimate the effects on trip frequency. To address this potential limitation, respondents were also asked: “How would your trip frequency change if ride-hailing services were unavailable?”. They could answer this question with “decrease”, “no change”, or “increase”.

By asking the two questions, we can analyze the impacts of ride-hailing services on trip frequency in greater detail.

3.2 Measurement of modal shifts

A stated preference method may also be problematic to measure the shift from other travel modes to ride-hailing services when the question is designed only for a specific trip. Therefore, we designed the following five questions to ask respondents in our survey:

- How would the frequency of trips by taxi change for you if ride-hailing services were unavailable?
- How would the frequency of trips by car change for you if ride-hailing services were unavailable?
- How would the frequency of trips by public transit (i.e., bus and metro) change for you if ride-hailing services were unavailable?
- How would the frequency of cycling trips change for you if ride-hailing services

were unavailable?

- How would the frequency of walking trips change for you if ride-hailing services were unavailable?

Respondents were asked to separately answer the five questions with “decrease”, “no change”, or “increase”. Modal shifts can thus be inferred from their answers.

3.3 Explanatory variables

According to previous studies and our assumptions in Section 2.2, five categories of variables are used in the present study to explain whether individuals change their trip frequency due to ride-hailing and whether they shift away from traditional travel modes to ride-hailing services.

The first category refers to sociodemographic factors, including gender, age, educational background, household income, possession of a driver’s license, and car ownership. Gender, possession of a driver’s license, and car ownership are measured using dummy variables. Other attributes are measured on ordinal scales. The values assigned to them are reported in Table 1.

The second category is the use of ICT, which is indicated by four dimensions: the number of years using the internet, the daily time spent using the internet on PCs, the number of years using smartphones, and the daily time spent using the internet on smartphones. The four dimensions are measured on ordinal scales, which are shown in Table 2.

Table 2 Measurement of ICT use

ICT use	Descriptions	N	%
Years of using the internet	2 or less (Value=1)	37	6.2
	3-5 (Value=2)	122	20.4
	6-8 (Value=3)	210	35.2
	9-11 (Value=4)	134	22.4
	12 or more (Value=5)	94	15.7
Daily time of using the internet on PCs (hours)	2 (Value=1)	224	37.5
	3-4 (Value=2)	141	23.6
	5-6 (Value=3)	111	18.6
	7 or more (Value=4)	121	20.3
Years of using the internet on smartphones	4 or less (Value=1)	80	13.4
	5-6 (Value=2)	171	28.6
	7-8 (Value=3)	201	33.7
	9 or more (Value=4)	145	24.3
Daily time of using the internet on smartphones (hours)	3 (Value=1)	178	29.8
	4-5 (Value=2)	201	33.7
	6-7 (Value=3)	109	18.3
	8 or more (Value=4)	109	18.3

The third category refers to the built environment. According to previous studies reviewed in Section 2.2, we assume that the built environment (accessibility to transportation infrastructures in particular) is likely to affect changes in trip frequency and mode choices due to ride-hailing. In addition, residential density (or population density) is often expected to relate to trip frequency and mode choices as well (Ewing & Cervero, 2010). In the end, a total of five built environment elements are selected as potentially explanatory factors (see Table 3). All built environment data were derived from Map.Baidu.com, which is one of the most used e-maps in China. Bus stations, metro stations, parking spaces, and residential locations were collected in November 2017, and the street networks in December 2019. It should be noted that – in Chinese large cities (e.g., Shanghai, Chengdu) – the maximum distance of access trips by walking is 800 meters for most residents (Pan et al., 2012). Therefore, an 800 m buffer was applied to extract these built environment elements.

Table 3 Measurement of built environment

Built environment elements	Descriptions	Mean	S.D.
Accessibility to bus stations	Number of bus stations within an 800 m buffer around residence	10.6	8.4
Accessibility to metro stations	Existence of metro stations within an 800 m buffer around residence (yes=1, no=0)	0.3	0.4
Accessibility to parking spaces	Number of parking spaces within an 800 m buffer around residence	19.6	20.5
Street density	Length of street within an 800 m buffer around residence (km)	22.2	7.6
Residential density	Number of residential locations within an 800 m buffer around residence	35.6	27.9

The fourth category is attitudes toward traditional travel modes. Corresponding to Section 3.2, we collected data regarding the attitudes toward five traditional modes in the survey by asking participants to separately respond to the following five statements:

- I like making trips by taxi (i.e., pro-taxi);
- I like making trips by car (i.e., pro-car);
- I like making trips by public transit (i.e., pro-transit);

- I like making cycling trips (i.e., pro-bicycle);
- I like making walking trips (i.e., pro-walk).

The answers were measured on a five-point scale ranging from “strongly disagree” (value=1) to “strongly agree” (value=5).

The fifth category is ride-hailing frequency, which is self-reported by respondents and measured on a monthly basis.

4. Results

4.1 Changes in trip frequency

In the section, using two methods, we examine whether people increase their trip frequencies due to ride-hailing services. First, respondents were asked to respond to the question regarding their most recent ride-hailing trip – “Would you have made this trip if ride-hailing services had been unavailable?”. A total of 590 respondents completed the question. Among them, 76 (12.9%) reported that they would not have traveled. This result is close to the finding (12.2%) by Henao and Marshall (2019) who measured the impacts using the same method in the Denver region (US). This result suggests that ride-hailing does increase trip frequency.

We assume that the above method may – to some extent – underestimate the impacts of ride-hailing services on trip frequency. Then, respondents were asked in another way, “How would your trip frequency change if ride-hailing services were unavailable?”. A total of 596 respondents completed this question. Their answers are reported in Figure 2.

Approximately 16.8% indicated a decrease in trip frequency in the absence of ride-hailing services, which is higher than the 12.9% that we measured with the former method. This result supports our assumption that the former method underestimates the impacts on trip frequency. It can therefore be concluded that ride-hailing services do result in an increase in trip frequency (i.e., complementary effect), which is in line with many previous studies. The complementary effect can largely be attributed to the unique advantages of ride-hailing services over traditional modes – i.e., in that they can be considered more convenient, reliable, and efficient (Clewlow & Mishra, 2017; Rayle et al., 2016).

Notably and interestingly, around 6.4% of respondents reported an increase in trip frequency in the absence of ride-hailing services. This result is roughly consistent with the study by Hampshire et al. (2017) who also observed a few people (9.7%) decreasing trip frequencies due to ride-hailing in Austin, Texas. The substitution of ride-hailing for trips could be mainly explained by travel costs. Normally, the costs of ride-hailing services are higher compared to some traditional modes like public transit and active modes. Using ride-hailing services may increase travel costs particularly for people who often use transit or active modes (e.g., non-car owners). In addition, the costs of running traditional taxis somewhat increase because of the fierce competition with ride-hailing in China. To compensate for extra running costs, taxi companies have raised the price of traditional taxi services in many Chinese cities, thus increasing the travel costs for taxi users. Therefore, travelers may reduce trip frequencies for saving money after starting to use ride-hailing services. The substitution of ride-hailing services for trips can offset the complementary effects of the services to some extent, thus somewhat alleviating the additional pressure on transportation systems imposed by the services.

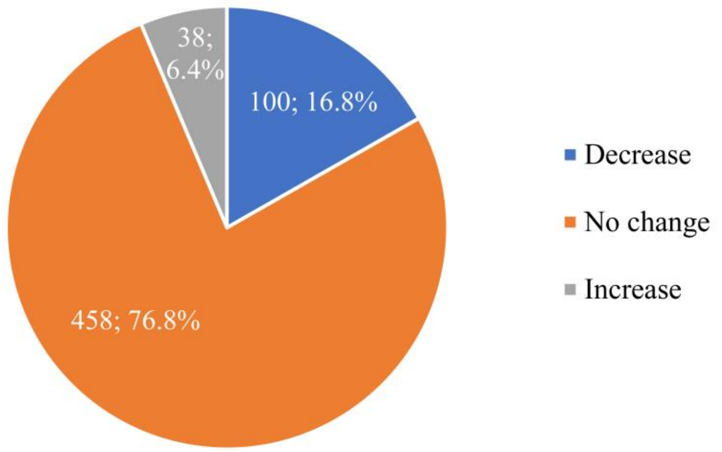

Figure 2 The changes in trip frequency if ride-hailing services were not available

A multinomial logistic (MNL) model is subsequently applied to investigate the determinants of changes in trip frequency due to ride-hailing. Based on Figure 2, respondents who indicated “increase”, “no change”, and “decrease” in trip frequency in the absence of ride-hailing services are categorized into three groups of “substitution” (N=38), “neutrality” (N=458), and “complementarity” (N=100), respectively. The three groups are considered as the dependent variables of the MNL model (the group of “neutrality” is used as the reference group). All explanatory factors in Section 3.3 are employed as the independent variables in the initial model. Meanwhile, to increase the efficiency of estimators, a backward stepwise approach is applied in the modeling process to remove insignificant independent variables from the model. According to Hosmer et al. (2013), a value ranging from 0.15 to 0.20 is highly recommended as the threshold of p-value to select valid explanatory variables in a stepwise regression. Nevertheless, we relax the threshold value to 0.30, in order to improve the goodness-of-fit of the model.

This means that insignificant independent variables are removed from the initial model step by step until all left variables have a significance level of $p<0.30$. In the end, nine variables are included in the final model (see Table 4). In a MNL model, the assumption of independence of irrelevant alternatives is required. A generalized Hausman test indicates that the final model does not violate this assumption.

Given the relatively low pseudo R^2, a prediction-success table (McFadden, 1997; Roorda et al., 2006) is further introduced to examine the validity of the MNL model. The prediction-success rates are calculated following a probability-weighted principle, which is often considered more appropriate than a traditional unit-weighted approach (Kim & Mokhtarian, 2018; Shi et al., 2020). The results in Table 5 show that the overall prediction success rate is highly acceptable (65.4%), although the prediction success rates for both substitution and complementarity are quite low (16.4% and 21.4%, respectively). This suggests that the MNL model is quite reliable.

As shown in Table 4, there is a significant gender difference in the decrease in trip frequency due to ride-hailing. Men – compared to women – are more likely to decrease their trip frequencies. Younger people have a higher likelihood to increase trip frequencies because of the use of ride-hailing services, which is in line with the finding of Lavieri and Bhat (2019). This may be because ride-hailing services – as an emerging travel mode – are more attractive for young groups, thus likely stimulating them to make additional trips. Expectedly, people in households not owning a car are more likely to reduce trips because of ride-hailing services. Compared to car owners, these non-car owners may use taxis, public transit, and active modes more frequently. In this situation, travel costs are more likely to increase for them after starting to use ride-hailing services. Therefore, they may be inclined to decrease trip frequencies to reduce travel costs. Not surprisingly, the greater use of ICT makes people more likely to increase trip frequencies due to ride-hailing.

People who have a positive attitude toward taxis are more likely to decrease trip frequencies due to ride-hailing. As mentioned above, ride-hailing services have raised the price of traditional taxi services due to the fierce competition between them in China. Consequently, people who prefer using traditional taxis need to pay more for traveling, thus possibly inhibiting their out-of-home activity participation. Another possible reason is that ride-hailing services are usually considered more convenient, reliable, and efficient than traditional taxi services (Clewlow & Mishra, 2017; Rayle et al., 2016). Traditional taxi users may become aware of these ride-hailing advantages over traditional taxi services after adopting ride-hailing services, thus reducing the use of traditional taxi services. In addition, frequent ride-hailing users are more likely to both increase and decrease trip frequencies due to ride-hailing services. The more frequently people use ride-hailing services, the more likely they increase trip frequency, which is in line with expectations. On the other hand, the frequent use of ride-hailing services may increase travel costs, which may make people reduce travel frequency for saving money. None of the built environment elements is significantly associated with changes in trip frequency.

Table 4 MNL outcomes regarding the changes in trip frequency due to ride-hailing (Neutrality=ref.)

Explanatory factors	Substitution		Complementarity	
	B	S.E.	B	S.E.
Sociodemographics				
Gender	1.09***	0.39	-0.00	0.24
Age	-0.24	0.23	-0.47**	0.18
Education	-0.32	0.23	0.14	0.15
Car ownership	-0.80**	0.37	0.00	0.25
ICT use				
Year of using the internet	-0.37**	0.18	0.08	0.12
Daily time of using the internet on PCs	0.20	0.18	0.21*	0.11
Daily time of using the internet on smartphones	-0.31	0.20	-0.09	0.12
Travel attitudes				
Pro-taxi	0.76***	0.21	0.12	0.12
Frequency of using ride-hailing services	0.05**	0.02	0.05***	0.02
Constant	-2.93**	1.17	-2.13***	0.74
McFadden's R^2	0.097			
Number of observations	565			

Note: ** p<0.05, ***p<0.01; Variables that are removed from the model because of insignificance (p>0.30) are omitted.

Table 5 Prediction success rates of the MNL model

Categories	Prediction success rates (%)
Substitution	16.4
No change	78.9
Complementarity	21.4
Total	65.4

4.2 Modal shifts

In this section, we aim to explore whether and how people shift away from traditional modes to ride-hailing (i.e., modal shifts). Figure 3 shows respondents' answers when they were asked to indicate how their trip frequencies by traditional modes would change if ride-hailing services were unavailable. Overall, a considerable share of respondents (35.2%-62.9%) reported an increase in frequencies. This implies that ride-hailing does reduce the use of traditional travel modes. In particular, people shifting away from public transit to ride-hailing account for the highest proportion (i.e., 62.9%), which means that public transit is the most substituted mode by ride-hailing. This result is consistent with previous studies (e.g., Chen et al., 2018; Clewlow & Mishra 2017; Gehrke et al., 2019; Henao & Marshall, 2019; Lewis & MacKenzie, 2017). The extent of the substitution for taxi (54.1%) is in the second place. This confirms fierce competition between ride-hailing services and traditional taxi services (Contreras & Paz, 2018; Rayle et al., 2016).

Cycling and walking are replaced by ride-hailing for 45.0% and 45.5% of respondents, respectively. This result seems counterintuitive but reasonable. In reality, people usually make trips by multiple modes (i.e., multimodal trips). Particularly for transit trips, travelers mostly make walking or/and cycling trips to/from transit stations (Guo et al., 2020, 2021). When multimodal trips are replaced by ride-hailing trips, the method in the present study allows respondents to report substitution for all modes used in these trips (Alemi et al., 2018a). This is the main reason why the substitution shares for cycling and walking seem quite higher than expectations. Notably, we assume that it is worthwhile to take feeder modes into account because feeder trips would have been made by travelers if ride-hailing services were unavailable.

In addition, respondents who shift away from cars to ride-hailing account for the least share (35.2%). This result is inconsistent with the findings by some studies from the United States showing that car trips are most replaced by ride-hailing services (e.g., Hampshire et al., 2017; Lavieri & Bhat, 2019; Möller et al., 2019). Specifically, Alemi et al. (2018a) applying a similar method revealed that 58.2% of the Generation X (born in 1981-1997) and 70.1% of the Millennials (born in 1965-1980) reported a decrease in car use in California. Both shares are much higher than that (35.2%) observed in the present study. It may be mainly attributed to the difference in the degree of car ownership between China and the United States. Compared to the United States, China has a much lower level of car ownership. According to data disclosed in 2015, the number of passenger vehicles per 1000 inhabitants was 380 in the United States, while the number was only 98 in China (Knoema, 2017). This means that non-car owners account for a much higher share in China. As a result, more people in China would not change rather than increase the frequency of car trips in the absence of ride-hailing services.

In sum, it can be expected that the modal shift from traditional modes to ride-hailing (in particular the shifts from sustainable modes, e.g., public transit, cycling, and walking) are generating additional pressure on transportation systems, e.g., an increase in road congestion, vehicle kilometers traveled, fuel consumptions, and carbon emissions.

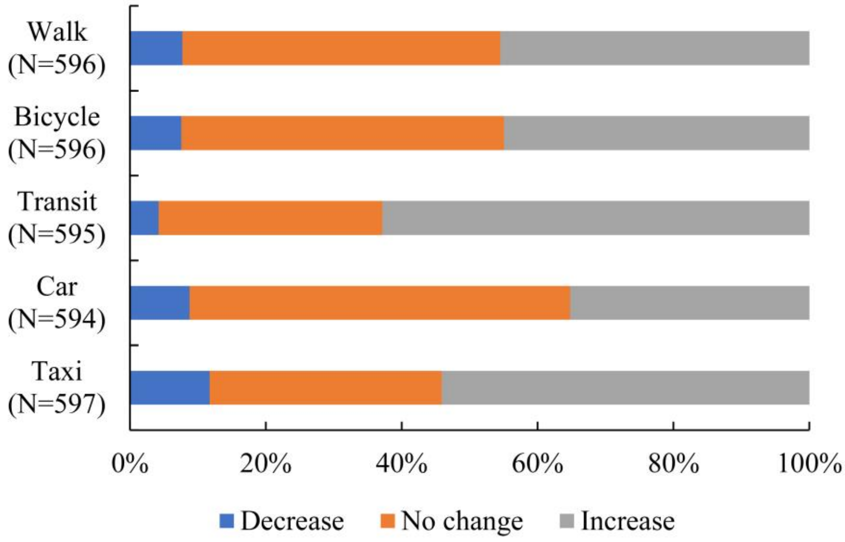

Figure 3 The changes in travel frequency by modes if ride-hailing services were not available

As observed above, quite a number of respondents shift away from traditional modes to ride-hailing. Therefore, a binary logistic method is applied to explore the determinants of these modal shifts in the following three steps. First, a set of binary variables is created for each traditional mode. A value of one is assigned when a respondent indicated an increase in the use of traditional modes in the absence of ride-hailing services, and otherwise a value of zero is given. Second, using the five sets of binary variables as the dependent variables and all explanatory factors in Section 3.3 as the independent variables, five initial binary logistic models are developed, respectively. Third, similarly, a backward stepwise approach (the threshold of p-value is set to 0.30) is also used to remove far insignificant independent variables from each model. The outcomes of all final models are reported in Table 6. Similarly, a prediction-success table (see Table 7) based on a probability-weighted principle is presented to assess the validity of these binary logistic models. The results indicate that the overall prediction success rates range from 53.6% to 62.4%, reaching an acceptable level.

Sociodemographic factors including gender, educational attainment, household income, possession of a driver's license, and car ownership are found to be significantly associated with the modal shifts. Compared to women, men are more likely to substitute ride-hailing for driving, possibly since in China men like driving more than women (Yang et al., 2013). Meanwhile, ride-hailing services have three major advantages over driving in China. First, people can avoid cruising for parking when using ride-hailing services. Second, ride-hailing is an option for car users after drinking alcohol (Clewlow & Mishra, 2017). Third, driving restriction policies are implemented in many Chinese large cities (e.g., Beijing, Shanghai, Chengdu). Car users tend to adopt ride-hailing services when their cars are not allowed to use (Tang et al., 2020). Consequently, men are more likely to substitute ride-hailing for driving. Older respondents are more likely to substitute ride-hailing for taxi and car trips, while younger respondents are more likely to substitute ride-hailing for cycling trips. This result is roughly consistent with the finding of Lavieri & Bhat (2019).

Better-educated respondents are more inclined to substitute ride-hailing services for all travel modes (it is insignificant only for bicycle). This result could be attributed to their more openness to emerging things, e.g., ride-hailing services. Therefore, they are more likely to abandon traditional modes when ride-hailing services are an option. High-income people have a higher likelihood to replace taxicab services with ride-hailing services, which is consistent with the result observed by Tirachini and Gomez-Lobo (2020). As mentioned before, some expensive ride-hailing services are of higher quality than traditional taxicab services (Tang et al., 2020). These services may be more attractive for high-income groups, and thus stimulate them to displace traditional taxicab services. People with higher access to car use (i.e., having a driver's license and owning a car) tend to be frequent car users and are thus more likely to shift away from cars to ride-hailing services. In contrast, those with lower access to car use usually make few car trips, therefore likely substituting ride-hailing for other modes (e.g., walking and cycling) rather than cars. This is in line with our expectations. Consequently, they have a higher likelihood to shift away from active modes to ride-hailing services.

ICT use also plays a significant role in modal shifts. Surprisingly, the greater use of the internet on PCs is negatively related to the shifts from taxi, transit, and walking to ride-hailing services. A possible reason is that more daily time spent on PCs – which usually requires a fixed in-door place – makes people travel less, thus leading to a lower likelihood of shifting away from traditional modes to ride-hailing services. As expected, people with more experience using smartphones are more likely to substitute ride-hailing trips for car and taxi trips. However, they are less inclined to shift from bicycles to ride-hailing services. In China, the widespread use of smartphones greatly encourages cycling trips dominated by app-based bike-sharing systems. People with frequent use of smartphones may tend to make trips by bicycle because of lower costs instead of the adoption of ride-hailing services. This result seems to indicate competition between bike-sharing and ride-hailing systems among frequent smartphone users.

In addition, the built environment influences modal shifts created by ride-hailing. The results show a negative association between higher accessibility to bus stations and the shift from transit to ride-hailing. This means that people are more likely to substitute ride-hailing for transit trips when it is inconvenient to access bus services, which is a reasonable finding. Correspondingly – as the most used feeder modes of bus trips – cycling and walking trips are less likely substituted. In contrast, there is a positive correlation between higher accessibility to metro stations and the shift from transit to ride-hailing, although the correlation is insignificant (p=0.131). This implies that people are somewhat more likely to replace transit trips with ride-hailing when they have higher accessibility to metro services. Normally, those with higher accessibility to metro services tend to be frequent metro users. Consequently, they may also have a higher likelihood of shifting away from metro to ride-hailing because of the advantages of ride-hailing services over metro services. Similarly, higher accessibility to metro stations tends to result in a shift from cycling and ride-hailing because cycling is usually used as a feeder mode of metro trips (Guo et al., 2020, 2021). The result regarding the accessibility to metro stations is roughly in line with the finding of Gehrke et al. (2019).

Higher accessibility to parking spaces has a positive association with shifts from the use of taxis and cars to ride-hailing. Parking spaces are also required for ride-hailing services because drivers often need to wait for passengers. In this circumstance, drivers may be more likely to accept orders from areas with sufficient provision of parking spaces. As a result, trips by traditional modes are more likely to be substituted by ride-hailing trips in these areas. A higher road density is positively correlated with the shift from cycling to ride-hailing. A possible explanation is that a higher road density usually means a cycling-friendly environment (Cervero et al., 2009). People in such an environment may be more likely to make cycling trips and therefore have a higher likelihood to replace cycling with ride-hailing. Moreover, a higher residential density is negatively associated with shifts from motorized modes (i.e., taxi, car, and transit) to ride-hailing. In general, daily life services are densely offered in areas with a high residential density. Residents living in these areas usually make short-distance trips by non-motorized modes (e.g., walking). Therefore, they have a lower likelihood to reduce motorized modes due to ride-hailing.

As expected, attitudes toward traditional modes are related to modal shifts. People with positive attitudes toward car, transit, and bicycle are more likely to substitute ride-hailing trips for car, transit, and cycling trips, respectively. This is a reasonable result. Normally, an individual uses a specific mode frequently when he/she has a positive attitude toward the mode. However, when ride-hailing services with marked advantages over the mode are available, he/she is also more likely to shift away from the mode to ride-hailing.

Moreover, frequent use of ride-hailing services is positively associated with the shift from cars to ride-hailing, which means that the more frequently people use ride-hailing services, the more likely they reduce driving.

Table 6 Regression outcomes regarding the substitution of ride-hailing for traditional travel modes

Explanatory factors	Taxi	Car	Transit	Bicycle	Walk
Sociodemographics					
Gender	0.22	0.41*	–	–	–
Age	0.20*	0.31**	-0.18	-0.23*	–
Education	0.29***	0.18	0.35***	0.18	0.23**
Household income	0.14**	–	–	–	–
Having a driver's license	–	0.76***	-0.24	-0.50**	-0.48**
Car ownership	–	0.58***	-0.29	–	-0.34*
ICT use					
Years of using the internet	-0.10	–	–	-0.13	–
Daily time of using the internet on PCs	-0.15*	–	-0.21**	–	-0.16*
Years of using smartphones	0.16	0.28**	–	–	–
Daily time of using the internet on smartphones	–	-0.10	0.15*	-0.28***	-0.13
Built environment					
Accessibility to bus stations	–	–	-0.02*	-0.03**	-0.04***
Accessibility to metro stations	–	–	0.32	0.62***	0.27
Accessibility to parking spaces	0.01**	0.01*	–	–	0.01
Road density	-0.02	-0.02	–	0.03*	0.02

Table 6 Continued

Residential density	-0.01**	-0.01*	-0.01**	–	-0.01
Travel attitudes					
Pro-taxi	–	–	-0.12	–	–
Pro-car	–	0.20*	-0.14	–	–
Pro-transit	–	-0.16	0.31***	–	0.11
Pro-bicycle	-0.10	-0.13	–	0.52***	–
Pro-walk	–	0.14	–	–	–
Frequency of using ride-hailing services	–	0.04***	–	0.01	0.01
Constant	-0.35	-3.22***	0.80	-1.17*	-0.18
McFadden's R^2	0.052	0.142	0.064	0.106	0.052
Number of observations	564	541	561	544	544

Note: * p<0.10, ** p<0.05, *** p<0.01; "–" Variables with a significance level of p>0.30 are removed from models.

Table 7 Prediction success rates (%) of binary logistic models

Substitution	Taxi	Car	Transit	Bicycle	Walk
Yes	58.2	46.7	66.9	53.0	50.7
No	48.6	70.9	41.2	60.7	56.2
Total	53.9	62.4	57.6	57.2	53.6

5. Discussion and conclusion

The increasing use of ride-hailing services is profoundly shaping travel behaviors, particularly in countries like the United States and China, where there are a huge number of ride-hailing users. In the present study, we provide empirical evidence from 597 valid face-to-face interviews in Chengdu, China to analyze whether and how ride-hailing influences trip frequency and travel modes. By doing so, the present study makes contributions to the body of literature in the following three aspects. First, most empirical studies are from the context of the United States and provide inconsistent and even conflicting results regarding the influence of ride-hailing on travel. The present study providing empirical evidence from a Chinese context can help clarify the debatable topic. Second, we argue that the often-used measurement method for the influence of ride-hailing on travel in prior research may lead to imprecise outcomes. The present study has attempted to improve the measurement method, which can be expected to correct the bias of the estimates in previous studies. Third, the factors driving the influence of ride-hailing on travel are not fully explored in previous studies. The present study has investigated the determinants of whether people change trip frequencies and mode choices due to ride-hailing. The results can help contribute to the understanding of the mechanism behind the implication of ride-hailing services for travel.

The major findings of the present study are as follows. First, around 16.8% of respondents increased their trip frequencies because of ride-hailing services, while only 6.4% decreased their trip frequencies. This means that – to some extent – new trips are generated by ride-hailing, suggesting a complementary effect of ride-hailing on travel. An MNL model reveals that the additional trips may be mainly contributed by young people, frequent ride-hailing users, and those who are experienced in using ICT. Second, the adoption of ride-hailing services has considerable substitution effects on the use of traditional travel modes (i.e., taxi, car, public transit, cycling, and walking). Specifically, public transit is the most substituted mode. It is worth noting that – because of the COVID-19 crisis – public transport is commonly considered unsafe compared to other motorized modes (e.g., private car, taxi, ride-hailing services) (De Vos, 2020; van Wee & Witlox, 2021). Additionally, people use the internet more frequently due to the pandemic (van Wee & Witlox, 2021), thus possibly accelerating the adoption of ride-hailing services. Therefore, it can be expected that the modal shift from public transit to ride-hailing has been facilitated to a large extent since the outbreak of the pandemic. Furthermore, binary logistic models indicate that various factors such as sociodemographics, ICT use, the built environment, attitudes toward traditional modes, and the frequency of ride-hailing are significantly associated with the substitution of ride-hailing services for traditional modes. Meanwhile, the associations between some influential factors and the substitution effect differ by traditional modes.

At least two policy implications can be learned from the present study. First, given the effects of ride-hailing on travel frequency and travel modes, it can be concluded that additional pressure is being generated by using ride-hailing services. In particular, we find that ride-hailing users have high likelihoods (45.0%-62.9%) to shift away from sustainable travel modes (i.e., public transit, cycling, and walking) to ride-hailing services, which may lead to an increase in road congestion, vehicle miles traveled, fuel consumptions, and greenhouse gas emissions. Therefore, ride-hailing may be an emerging barrier to the sustainable development of transportation systems. Second, we reveal that the built environment is significantly correlated with shifts from traditional modes to ride-hailing. Especially, higher accessibility to bus services can significantly reduce the likelihood of the substitution of ride-hailing for sustainable modes. Therefore, optimizing the access to bus services may be particularly effective to alleviate the transportation challenge caused by ride-hailing.

Although we have shed light on the travel effects of ride-hailing services, some limitations exist in the present study. First, we argue that the influence of ride-hailing services on travel may differ by various geographical contexts. In the present study, only empirical evidence from the city of Chengdu is provided, which may – to some extent – limit the generalization of the findings. Second, there is a two-year gap between data regarding the built environment and travel behavior. Consequently, the role of the built environment in regression models might be somewhat underestimated. Third, the values of McFadden's R^2 (ranging from 0.052 to 0.142) in regression models are relatively small. This implies that some potentially influential factors are not considered in the present study, such as the frequency of trips by traditional modes, the use of e-payment, and the built environment around workplaces. Notably, attitudes toward ride-hailing services are also absent in these regression models due to the limitation of data availability, although attitudes toward traditional travel modes are included. Consequently, the issue of residential self-selection may not be fully addressed. Fourth, we only confirm that the use of ride-hailing services does increase the frequency of total trips and has a substitution effect on the use of traditional modes. However, it remains unknown how many trips are exactly generated in total and how many trips by traditional modes are exactly replaced by ride-hailing. We encourage future studies to consider the above limitations in order to further deepen the knowledge on the impacts of ride-hailing on travel behavior.

Declaration of Competing Interest

None.

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