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Feature Identification and Fuel-Saving Estimation for Multimodal Travel of Online Car-Hailing Ride-Sharing and Subway

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Abstract: The combination of online car-hailing ride-sharing services and subway can not only achieve complementary advantages of two travel modes in terms of service functions but can also amplify the energy-saving and emission-reducing benefits of shared mobility. Based on the operational data of carpooling and hitchhiking services within the DiDi Chuxing ride-sharing platform in Beijing and the automatic fare collection (AFC) system of Beijing Subway, this paper conducts a comprehensive analysis of the competitive and cooperative relationship between ride-sharing services and the rail transit. Employing the non-negative matrix factorization algorithm, the paper identifies the extension commuting chain and develops a fuel-saving estimation model considering factors such as fuel economy index and vehicle operating conditions. Applying this method to Beijing, the paper reveals that most car-sharing orders involve competition and extension with subway. Conversely, ride-sharing orders primarily extend the reach of subway, with the extension commuting chain predominantly serving suburban commuters by offering subway connection services. Notably, hitchhiking proves to be more fuel-efficient than ride-sharing. The commuting chain that combines “online car-hailing ride-sharing + subway” primarily originates from suburban areas without subway coverage, with an average fuel-saving rate surpassing 50%. Furthermore, the travel chain of “hitchhiking + subway” demonstrates superior fuel-saving benefits compared to the travel chain combining “ridesharing + subway”. It is suggested that managers should adopt policy measures such as expense allowances and parking discounts to encourage the development of the “online car-hailing ride-sharing + subway” commuting travel mode. Such measures will enable more urban residents to benefit from green and efficient integrated mobility services. **DOI:** 10.13813/j.cn11-5141/u.2023.0010-en

Keywords: online car-hailing ride-sharing; rail transit; competition and cooperation relationship; trip chain; fuel saving estimation; big data

0 Introduction

As the mobile Internet and the sharing economy come to popularize, online ride-sharing services based on online taxi-hailing platforms have emerged, and have been accepted by an increasing number of travelers. The conventional carpooling between acquaintances is gradually changing to that between strangers who use the ride-sharing platform. Online car-hailing ride-sharing, as a new-style transportation mode, is gradually integrated into in the urban comprehensive transportation system and plays an increasingly important role in it. Ride-sharing platforms have developed various carpooling modes according to travel demands, the two most important of which are carpooling and hitchhiking. Carpooling mode means that a full-time ride-hailing driver carries two or more groups of passengers consecutively or simultaneously to complete a journey, while hitch-hiking mode refers to picking up passengers when a non-full-time driver travels by private car. Currently, research on online car-hailing ride-sharing mainly focuses on the matching mode, the competition and cooperation relationship with other modes of transportation, and the fuel-saving benefits. This paper mainly analyzes the relationship between online car-hailing ride-sharing and subway as well as the fuel-saving benefits it brings.

The rise of online taxi-hailing services poses some impacts on conventional public transportation. Existing studies have extensively discussed the interactions between online ride-hailing and public transportation services, especially the competitive and complementary relationship between online ride-hailing and subway. Some studies focus on the connection services of online ride-hailing and subways. Jin S. T. et al. [1] pointed out that online ride-hailing could solve the “last mile” problem faced by public transportation. Chen P. W. et al. [2] constructed a multimodal transport path optimization model based on the integrated operation of online car-hailing and public transportation and proved its validity. Other studies focus on the impacts of online ride-sharing services on choices of transportation modes or

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structures. Y. Babar et al. [3] argued that Uber had replaced road-based short-distance public transit and supplemented rail-based long-distance one. Shi X. Y. et al. [4] found that the emergence of online ride-sharing resulted in a decrease in passenger volume of bus and an increase in that of subway. Jiang S. X. et al. [5] classified the interactions between the taxi and subway into three categories, including competitive type, extended type and complementary type. In addition, the impacts of online car-hailing ride-sharing on the environment have also received great attention from researchers.

Energy consumption and emissions of online car-hailing ride-sharing was compared with driving alone or taking a taxi in many studies, and a conclusion that the carpooling travel was more environmentally-friendly was drew. Yin B. et al. [6] found that online car-hailing ride-sharing had a more obvious role in decreasing the emissions of CO_2 in the long-distance travel. Yu B. Y. et al. [7] analyzed the order data of the DIDI HITCH in Beijing, pointing out that hitchhiking services had contributed to annual energy consumption reduction by 26.6 million t, CO_2 emissions by 26.6 million t, and NO_X emissions by 235.7 t. Liu X. B. et al. [8] established a fuel consumption calculation model for hitchhiking that included fuel economy, passenger capacity, average weight, distance traveled on each section of the road of vehicles and other parameters. The fuel saving ratio was achieved after comparing the calculations of the model with the fuel consumption of driving a private car alone. In contrast, some researchers claimed that online car-hailing ride-sharing had a negative impact on the environment. D. N. Anderson [9] argued that online carpooling services for profit may not have the advantage of protecting the environment when compared with conventional taxies which were well-regulated and had a relatively clean energy source. Jin S. T. et al. [1] considered that online car-hailing ride-sharing replaced both traditional taxies and other modes of transportation, such as public transportation, walking, bicycling, etc, which may lead to more serious environmental pollution. Obviously, due to differences in investigation objectives and research methods, no consensus has been reached on the findings of interactions between online car-hailing ride-sharing and public transportation and the energy saving and emission reduction effects of online car-hailing ride-sharing.

The combination of online car-hailing ride-sharing services and subway can not only achieve complementary advantages of two travel modes in terms of service levels and social benefits but can also amplify the fuel-saving benefits of mobility, which is a multi-modal travel method that deserves popularization. However, there is a lack of quantitative research based on actual data on the identification of travel chain of online car-hailing ride-sharing connecting subway and its benefits of energy saving and emission reduction. In addition, carpooling and hitchhiking modes are significantly different in terms of operation modes and travel characteristics, so most studies do not make a clear distinction between them.

Therefore, this paper conducts a data-driven empirical study on carpooling and hitchhiking, the two major online car-hailing ride-sharing modes, to analyze the competition and cooperation relationship between online car-hailing ride-sharing and subway, to identify the extension commuting chain of subway and put forward a fuel-saving estimation model for online car-hailing ride-sharing that considers fuel economy indicator and vehicle operation status, so as to asses fuel-saving benefits of commuting trip chain. The above methodology is applied to the case of Beijing and policy recommendations for the differentiated development of carpooling and hitchhiking are proposed to promote the sustainable, coordinated and standardized development of shared mobility.

1 Data pretreatment

1.1 Data sources

The online taxi-hailing order data in this paper comes from the DiDi Chuxing ride-sharing platform, and data type includes carpooling and hitchhiking, of which the data of carpooling is extracted within the express order based on space-time relationship between two groups of orders. The time span of express order adopted in this paper was October 1–30, 2017 and the space span was in the whole area of Beijing, involving about 27.67 million user travel records. Each data contains passenger’s order ID, time of departure and arrival, GPS longitude and latitude of the origin and destination, GPS longitude and latitude of driver’s origin, distance of the driver from the passenger’s origin, navigation distance of the passenger’s travel, actual distance of the passenger’s travel, travel cost and other attribute fields. The spatial and temporal scope of the order data of hitchhiking is consistent with that of express, involving a total number of about 2.43 million records of user travels, which include data of passengers and drivers and fields are OD temporal and special information of passengers and drivers.

In addition, this paper adopts the data from the Automatic Fare Collection (AFC) system of Beijing Subway for a week from March 7 to March 13, 2016. The AFC can automatically record passenger’s IDs, names of entrance and exit stations and timestamps. This system has recorded more than 35 million passenger travels during this week. Between 2016 and 2017, there were few newly opened subway stations in Beijing, which had a negligible impact on the demand distribution of the subway network.

1.2 Data pretreatment

An exception may occur when the order data of ride-sharing platform was collected and stored. Therefore, data cleaning should be carried out first to eliminate abnormal data, including null values, duplicated data and one-sided order data. In addition, data of carpooling should be extracted from the data of express. The specific process is as follows. 1) Sort the order data of express according to the driver's ID to ensure that multiple orders of the same driver are adjacent, namely, to find out all the orders of each driver in a month and group them together; 2) sort all the orders of each driver by time from the morning to the evening; 3) retrieve the orders sequentially, with two adjacent orders each time; 4) if two adjacent orders belong to the same driver and the two orders overlap in time, namely, the start time of the latter order is earlier than the end time of the former order by more than 3 min, the two orders are considered to be a set of carpooling orders.

2 Identification method of multi-modal travel chain for online car-hailing ride-sharing and subway

2.1 Classification of competition and cooperation relationship between online car-hailing and subway

This paper explores the competition and cooperation relationship between online car-hailing and subway from the perspective of travel data mining. Relevant studies believe that taxi trips that could be completely replaced by the subway belong to the competition category while taxi trips in which one end of the trip is within the subway service range and the other end is beyond the range belong to the cooperation category [10]. Referring to the above classification methods, this paper conducts the following specific classification methods for the competition and cooperation relationship between online car-hailing and subway: if the origin and destination of a passenger are both within the walking radius of a subway station in the carpooling order, it is a subway-competing carpooling travel; if either the origin or destination of a passenger is within the walking radius of a subway station, it is a subway-extending carpooling travel; if neither the origin nor the destination of a passenger is within the walking radius of a subway, it is a subway-supplementary carpooling travel (Fig. 1). The subway-extending carpooling travels can be divided into two types according to the fact that the origin and the destination are within the radiation range of the subway station, namely, away from the station and close to the station. References [5, 11] set the walking radius of a subway station as 1 km.

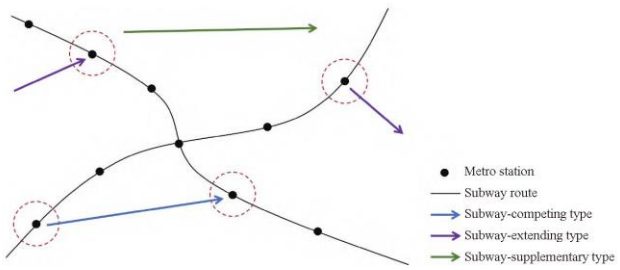


Fig.1 Illustration of the competition and cooperation relationship between online car-hailing ride-sharing and subway

It should be noted that if one section of the passenger's travel is within the metro service area, the passenger is actually considered to be a cooperative category. But in reality, the passenger may not necessarily use online car-hailing to connect with subway, and the area near the station may just be the origin or destination of the passenger's travel. However, according to the characteristics of passenger's travel, online car-hailing travel that connects to areas nearby the subway is more likely to belong to a passenger-cooperative category. In the subsequent identification of the commuting trip chain of "ride-sharing + subway", information like land use and travel purpose will be introduced to more accurately determine whether cooperative passengers are connected to the subway or not.

2.2 Non-negative matrix factorization algorithm-based extension commuting trip chain identification

To identify the commuting trip chain of "online ride-sharing + subway", the basic trip patterns of passenger groups who use online car-hailing should be found. As for high-dimensional spatial-temporal databases of trip, matrix decomposition can be applied to identify the basic trip patterns, such as principal component analysis, singular value decomposition and non-negative matrix factorization (NMF) [12]. NMF can make all decomposed components non-negative, while realizing the dimensionality reduction of non-linearity, which has become the main means to study trip patterns.

In this paper, NMF algorithm is applied to identify the basic trip patterns of passenger groups who use online car-hailing. First, a grid model is constructed for the range of study to generate a space-time matrix that considers trip time and volume. Each grid is numbered as (i, j), indicating that it is located in the i-th row and j-th column. The total number grid rows in the range of study is assumed to be p and the total number of columns is q, so $i \in [1, p]$ and $j \in [1, q]$ can be achieved. As for trip time issue, the time slice of the order is set to 24 slices and each slice is 1 h, which is represented by t, namely, $t \in [1, h]$, $h = 24$. According to the above method, the number of online car-hailing ride-sharing departure and arrival orders per hour per grid can be obtained, thus forming a transportation demand matrix:

$$V_{pq\times h} = \begin{bmatrix} v_{11,1} & \cdots & v_{11,h} \\ \vdots & \ddots & \vdots \\ v_{1q,1} & \cdots & v_{1q,h} \\ v_{21,1} & \cdots & v_{21,h} \\ \vdots & \ddots & \vdots \\ v_{pq,1} & \cdots & v_{pq,h} \end{bmatrix} = \begin{bmatrix} V_{11} \\ V_{12} \\ \vdots \\ V_{ij} \\ \vdots \\ V_{pq} \end{bmatrix},$$

The above matrix can reflect the basic trip pattern of spatial and temporal characteristics in each grid of the study area. The matrix is factorized using the NMF method, namely, $V_{pq\times h} = S_{pq\times h} B_{\lambda\times h}$.

In this paper, the coefficient matrix $S_{pq\times h}$ and basis matrix $B_{\lambda\times h}$are constructed from the perspectives of space and time, respectively, enabling the product of the two low-order matrices is close to the original transportation demand matrix. The basis matrix $B_{\lambda\times h}$ represents the basic trip pattern, and the coefficient matrix $S_{pq\times h}$ is used to describe the proportion of various basic trip patterns within a region. In this way, the trip pattern $V_{ij}$of any grid (i, j) can be regarded as a linear combination of multiple basic trip patterns, namely:

$$V_{ij} = S_{ij}\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ \vdots \\ B_\lambda \end{bmatrix}.$$

The NMF algorithm minimizes differences (Euclidean distance) between two matrices through continuous iterations. The application of non-negative matrix factorization to the order data of online car-hailing ride-sharing can not only extract several basic trip patterns of carpooling users, but also determine the land use of the grid through the proportion of different patterns in the total trip volume, so as to classify the commercial land or residential land. A key issue in the NMF algorithm solution and analysis is to determine the number of basic trip patterns λ. The value of λ is usually between 2–4 when analyzing transportation and land use problems in previous studies [11]. After finding the basic trip patterns of carpooling and hitchhiking, this paper filters out the residential grids with strong commuting demands according to the coefficient matrix, namely, the grids with a large proportion of residential land and a high degree of separation of residents' workplace and residence.

Subway AFC can reflect passenger's trip within the subway network and can assist in the study of competition and cooperation relationships. In this paper, the indicator passenger flow ratio of entrance and exit stations during morning peak is proposed to represent the functional characteristics of subway stations and to classify subway stations. The calculation formula is as follows:

$$r^k = \frac{P^k_{in}}{P^k_{out}},$$

where, r^k is the passenger flow ratio of entrance and exit station k in the morning peak; P^k_{in} is the passenger entry flow/(person·h^{-1}) at station k in the morning peak, and P^k_{out} is the passenger exit flow/(person·h^{-1}) at station k in the morning peak. Stations with $r^k > 2$ are defined as residential stations, with $0.5 \le r^k \le 2$ are as balanced stations and with $r^k < 0.5$ are as working stations. In this paper, online car-hailing orders that connect residential grids and residential subway stations are defined as extension commuting trip chains, thus realizing the identification of multi-modal commuting trip chains of online car-hailing ride-sharing and subway.

3 Fuel saving estimation model

3.1 Fuel saving estimation model for online car-hailing ride-sharing trip

In evaluating the fuel-saving level of ride-sharing services, the fuel consumption of cars is taken as a benchmark, and it is assumed that all passengers using ride-sharing services are potential users of car trips. Based on the above preconditions and assumptions, this paper proposes the concept of fuel saving ratio, namely, the ratio of the fuel consumption saved by ride-sharing trips compared to traveling alone in a carpooling process to the actual fuel consumption of the carpooling trips. The calculation formula is as follows:

$$F_{SR} = \frac{F^{Car}_C - F^R_C}{F^R_C},$$

where, $F^{Car}{}_C$ is the fuel consumption/L when the two groups of passengers are assumed to travel by car but do not share the ride; $F^R{}_C$ is the actual fuel consumption/L of the two groups of passengers who are carpooling.

The fuel-saving ability of ride-sharing is mainly achieved by increasing the passenger load factor of vehicles and reducing the total mileage of vehicles while meeting trip demands. A small vehicle providing ride-sharing transportation services may have driver-idle state, one-group-of-passenger carrying state and two-groups-of-passengers carrying state. Therefore, the travel distance and load capacity in each state need to be determined in a process of fuel-saving estimation. The calculation formula for the fuel consumption of online car-hailing ride-sharing trips is as follows:

$$F^R_C = \sum_n FE_n \times VK_n,$$

where, n is the number of passengers/person; FE_n is the fuel economy/(L·km^{-1}) of vehicles with n passengers; VK_n is the travel distance/km of vehicles with n passengers.

Due to the large randomness of passenger weights, the product of the number of passengers and the average weight of passengers is applied to roughly estimate the load capacity of vehicles. According to relevant data [13–15], the fuel economy FE of an empty passenger car is about 7.04 L·10^{-2} km^{-1} and the linear relationship between fuel economy and load capacity change is measured by the parameter R_{WF}= 0.3024 L·10^{-2} km^{-1}·person^{-1}. Therefore, the fuel economy of vehicles with n passengers is $FE_n = FE + nR_{WF}$.

After grasping the fuel economy indexes of vehicles with different number of passengers, the vehicle running status should be categorized and travel distance of both carpooling and hitchhiking in different statuses should be calculated to carry out the fuel-saving estimation for ride-sharing trips in terms of orders.

Similarly, the energy consumption of passengers taking the subway can be calculated:

$$F_C^{URT} = FE^{URT} \times \beta \times d^{Navigation} \times m \ ,$$

where $F^{URT}{}_C$ is the assumed energy consumption/L of passengers taking the subway; FE^{URT} is the fuel economy index that is converted into fuel consumption/(L·km^{-1}); β is the detouring index for the subway network compared to the road traffic network (cars); $d^{Navigation}$ is the navigation distance/km of passenger trips in online car-hailing order data; and m is the number of passengers within an order. By reviewing references, the path detour conversion index for Beijing Subway is 1.0 [8], and the fuel economy index for subway is about 0.4 L·person^{-1}·10^{-2}km^{-1} [16].

3.2 Fuel saving estimation model for extension commuting trip chains

As for two groups of passengers within a carpooling trip or drivers and passengers within a hitchhiking trip, the commuting trip chains may include the following combination forms: connection + connection, connection + nonstop, nonstop + connection, and nonstop + nonstop. To identify subway trips in the trip chain, which subway station to exit should be determined for carpooling passengers who need connection services to the next station. Based on the passenger transfer time information of AFC data, the connection stations that correspond to the exit station and flow distribution of all subway passengers should be first obtained, and then exit stations are assigned randomly for connection of online car-hailing ride-sharing passengers according to human traffic distribution of exit stations to ensure that the simulated trip chain is as close as possible to the actual commuting trip.

During a commuting ride-sharing trip with two groups of passengers, the sum of fuel consumption $F^R{}_C$ for carpooling services and that for taking the subway is defined as the fuel consumption of the commuting trip chain $F^{Chain}{}_C$. The calculation method of fuel consumption of commuting trip chains with different patterns is as follows:

1) Connection + connection

Both two groups of passengers share the car or hitch a ride to arrive in the area within the range of residential metro station and connect to the subway station. Subsequently, they enter the subway system and arrive at the assigned subway stations. The fuel consumption of this commuting trip chain is represented as

$$F_C^{Chain} = F_C^R + F_{C,Group1}^{URT} + F_{C,Group2}^{URT} \ ,$$

where $F^{URT}{}_{C,\ Group1}$ and $F^{URT}{}_{C,\ Group2}$ are the fuel consumption/L of two groups of passengers taking the subway in a carpooling trip, respectively.

2) Connection + nonstop

As for carpooling services, passenger group 1 share the car to arrive in the areas within the range of a residential subway station and connect to it; passenger group 2 carpool with others to get directly to their workplace without taking the subway. In the case of hitchhiking, the driver drives the car to reach the area within the range of a residential subway station and connects to it, and the passenger arrives at the workplace directly by hitching a ride without taking the subway. The fuel consumption for this type of commuting trip chain is represented as:

$$F_C^{Chain} = F_C^R + F_{C,Group1}^{URT}.$$

3) Nonstop + connection

As for carpooling, passenger group 1 carpool directly to the workplace without taking the subway; passenger group 2 carpool to reach the area within the range of a residential subway station and connect to it. As for hitchhiking, drivers drive the car directly to the workplace of passengers without taking the subway and passengers hitch a ride to reach the area within the range of a residential subway station and connect to it. The fuel consumption for this type of commuting trip chain is represented as:

$$F_C^{Chain} = F_C^R + F_{C,Group2}^{URT} \ 。$$

After calculating the fuel consumption $F^{Chain}{}_C$ of commuting trip chain for different patterns, the fuel saving ratio of extension commuting trip chain can be calculated:

$$F_{SR}^{Chain} = \frac{F_C^{Car} - F_C^{Chain}}{F_C^{Chain}} \ .$$

In terms of the fuel consumption $F^{Car}{}_C$ that is assumed in a scenario that all online car-hailing ride-sharing passengers travel alone by car, $F^{Car}{}_C$ can be calculated according to the navigation distance field of the carpooling trip if the trip of passengers is completed only by carpooling. If the trip of passengers is completed by a combination of online car-hailing ride-sharing and subway, the navigation distance between the origin of passenger and the exit station of subway is used as a distance index to estimate the fuel consumption.

4 Research results

4.1 Trip characteristics of “online car-hailing ride-sharing + subway”

The number of orders that involve competition and extension with subway is comparatively large in carpooling services, both of which exceed 40% of the total. The number of orders that extend the reach of subway is large in hitchhiking services, exceeding 50% of the total. This result is related to the spatial distribution of these two types of online car-hailing ride-sharing services. Carpooling orders are concentrated in the center of a city, while hitchhiking orders are scattered in the periphery of a city. As the metro network in Beijing has a “checkerboard + circular radial” layout, the net density of city center is much higher than that in the periphery of a city, which results in higher proportion of competition with subway carpooling orders than that of competition with subway hitchhiking orders. The proportion of competition with subway carpooling orders is much higher than that of competition with subway ride-hailing orders. From the perspective of average transportation distance, the average transportation distance of extension with subway orders is the longest. In carpooling orders, the average transportation distance of extension with subway is longer than competitive-type and supplementary-type and that of competitive-type is longer than that of supplementary-type. In hitchhiking orders, the average transportation distance of extended-type is longer than that of supplementary-type and that of supplementary-type is longer than that of competitive-type (see Table 1).

All trip stations within the range of a subway station are gathered to the nearest subway station, while all trip stations beyond the range of a subway station are gathered to the grid center where they are located. Based on this method, main service intervals of metro-extended carpooling and metro-extended hitchhiking are mapped in this paper, and the top 300 OD intervals with the largest order volumes are shown in Fig. 2. It can be seen that the ODs of metro-extended carpooling and hitchhiking orders represent the characteristic of dispersion from the peripheral metro stations to the urban outer areas, but the dispersion range of carpooling orders is smaller than that of hitchhiking orders, that is, the average transportation distance of carpooling is smaller than that of hitchhiking. Additionally, the subway stations connected by carpooling are closer to the city center than those connected by hitchhiking. For example, a large number of metro stations on the line 10 are connected by carpooling orders, but the subway stations connected by hitchhiking are mostly located in radial subway lines in the periphery of a city. Therefore, it is hypothesized that both carpooling and hitchhiking can provide connection services to subway stations for passengers in suburban areas without the coverage of subway. Compared with subway-competitive hitchhiking, subway-extended hitchhiking has a larger number of long-distance orders and longer average transportation distance, with an average transportation distance being about 23.65 km.

Departure time distribution of weekdays in subway-extending online car-hailing ride-sharing orders is shown in Fig. 3. Subway-extending type orders are categorized into near-station and far-from-station types according to corresponding directions, both of which have two different peaks in the morning and evening. The number of near-station orders peak mainly in the morning, while that of far-from-station orders peak mainly in the evening, which is determined by commuting characteristics of residents. During the morning rush hour, lots of people need to use online car-hailing ride-sharing services in the suburbs for connection to subway stations to work in the city, and vice versa in the evening peak.

Tab. 1 Statistical results of the classification according to interaction with subway and online car-hailing ride-sharing services

Competitive and cooperative relationship	Order share/%		Average transportation distance/km	
	Carpooling	Hitchhiking	Carpooling	Hitchhiking
Subway-competing type	43.7	26.2	9.18	20.93
Subway-extending type	45.2	52.3	9.39	23.65
Subway-supplementary type	11.1	21.5	8.79	23.58

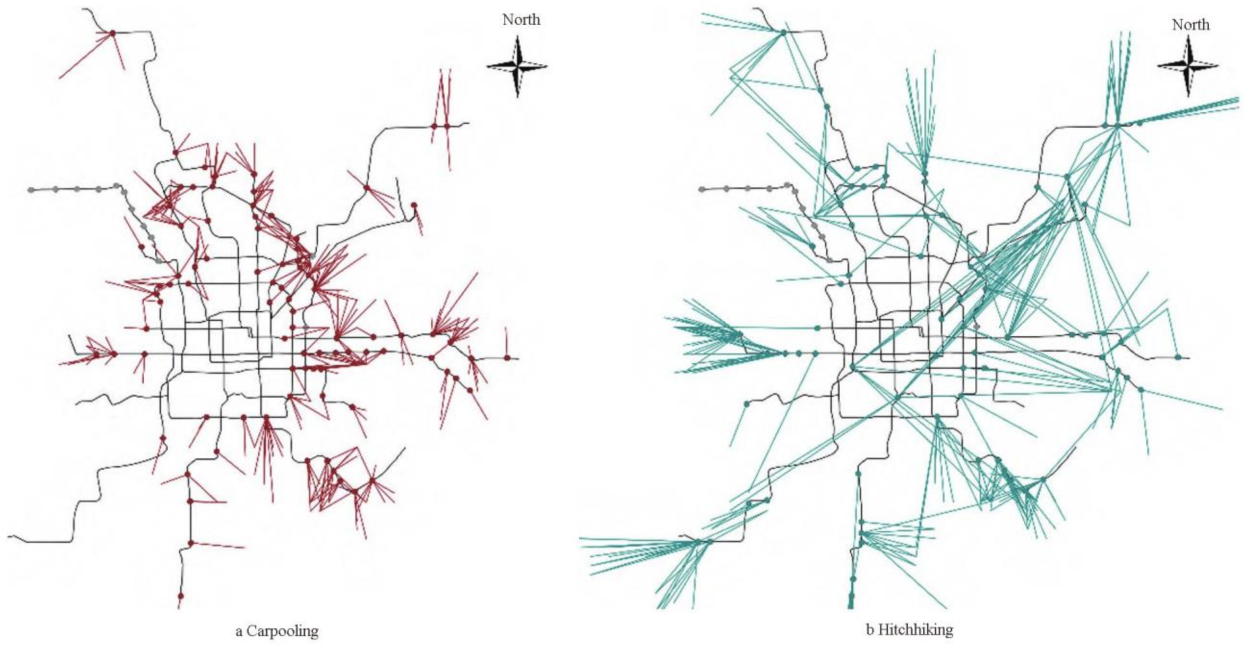


Fig. 2 Spatial distribution of subway-extending online car-hailing ride-sharing trips

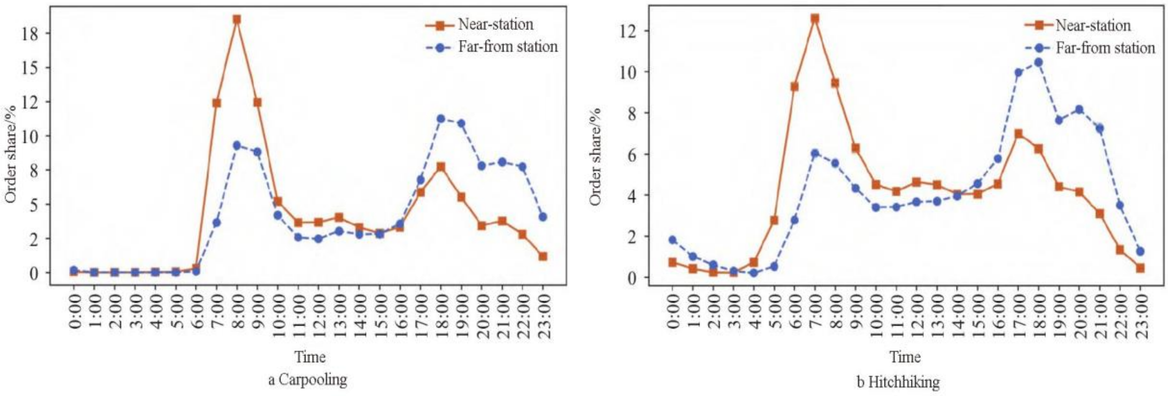


Fig. 3 Distribution of departure time of subway-extending online car-hailing ride-sharing order on weekdays

4.2 Result for identification of extension commuting trip chain

The distribution of basic trip patterns of carpooling and hitchhiking under different values of λ was plotted (Fig. 4 and Fig. 5). It can be seen that when the value of λ is taken as 3 for carpooling and 2 for hitchhiking, all basic trip patterns can be identified and repeated extraction of similar patterns can be avoided. The distribution of basic trip patterns is comparatively stable. The basic trip patterns of carpooling can be divided into three categories: morning peak, evening peak and nighttime, which correspond to pattern 1, pattern 2 and pattern 3 in Fig. 4b. The basic trip patterns of hitchhiking can be divided into two categories: morning peak and evening peak, which correspond to pattern 1 and pattern 2 in Fig. 5a, indicating that hitchhiking trips are mainly targeted for commuting services, while carpooling trips can serve for both commuting and nighttime trips.

After identifying the basic trip patterns of carpooling and hitchhiking, the residential grid is connected to the residential subway stations so that extension commuting trip chain can be identified. The proportional distribution of morning peak pattern trips of carpooling and hitchhiking to total trips is shown in Fig. 6, with the redder color representing the higher proportion of the morning peak pattern, namely, the stronger residential land attribute of the grid. In some major commercial or work areas in Beijing, such as Financial Street, Wangjing, Guomao, Xi’erqi, and Fengtai Science Park, people’s demands for online car-hailing trips are strong and the proportion of morning peak patterns are relatively low, which proves that the NMF method can classify residential land use as well as commercial and office land use.

A key feature of extension with subway commuting travel chains is that the subway station used for connection is located between the commuter’s place of residence and the place of work, and there are not a lot of job opportunities surrounding the subway station. As a result, the author argues that online car-hailing trips during morning rush hour from residential grids to residential subway stations are more likely to be a part of the commuting travel chain. As for carpooling trips, grids with over 50% of the morning peak pattern are defined as residential grids, with a total of 1 125 grids. As for hitchhiking trips, grids with more than 70% of the morning peak patterns are defined as residential grids, with a total of 2 270 grids. At the same time, online car-hailing ride-sharing orders in extension with subway in Section 4.1 are further filtered to retain the orders in which ODs are all within residential grids or stations and obtain the OD distribution of online car-hailing ride-sharing in commuting travel chain which is shown in Fig. 7. Notably, the vast majority of extension with subway online car-hailing ride-sharing during morning rush hour are concentrated between suburban subway stations and residential areas without subway coverage, which can better connect to the subway network and meet the diverse travel needs of commuters.

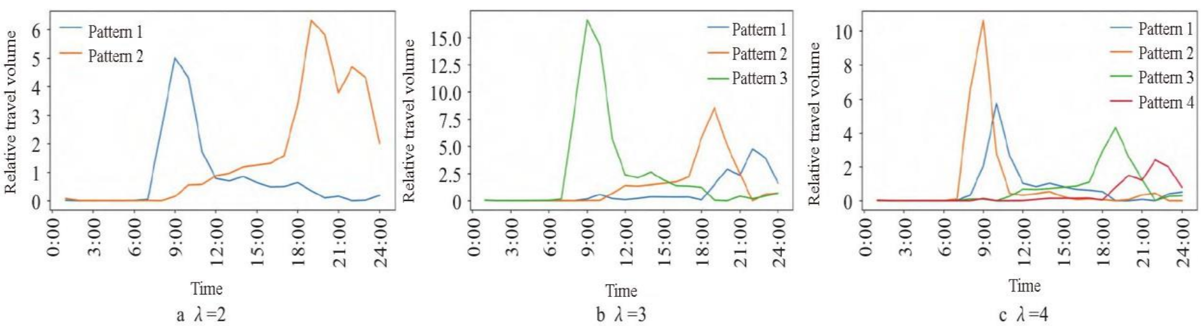
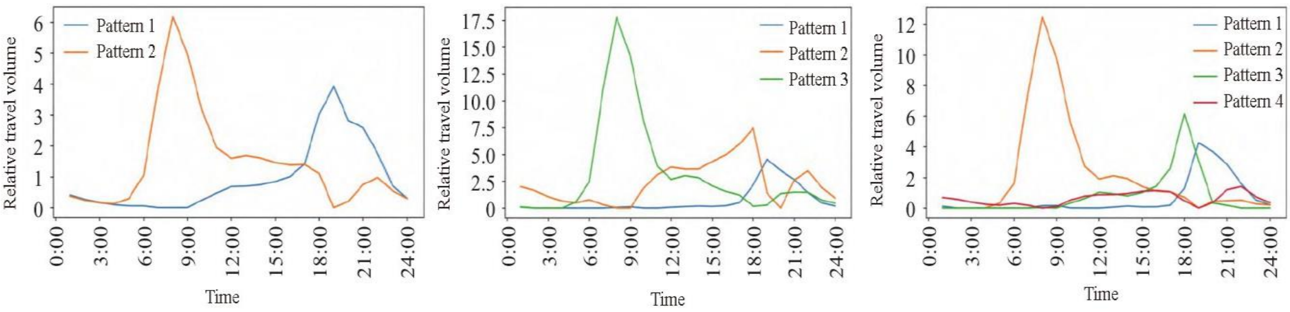
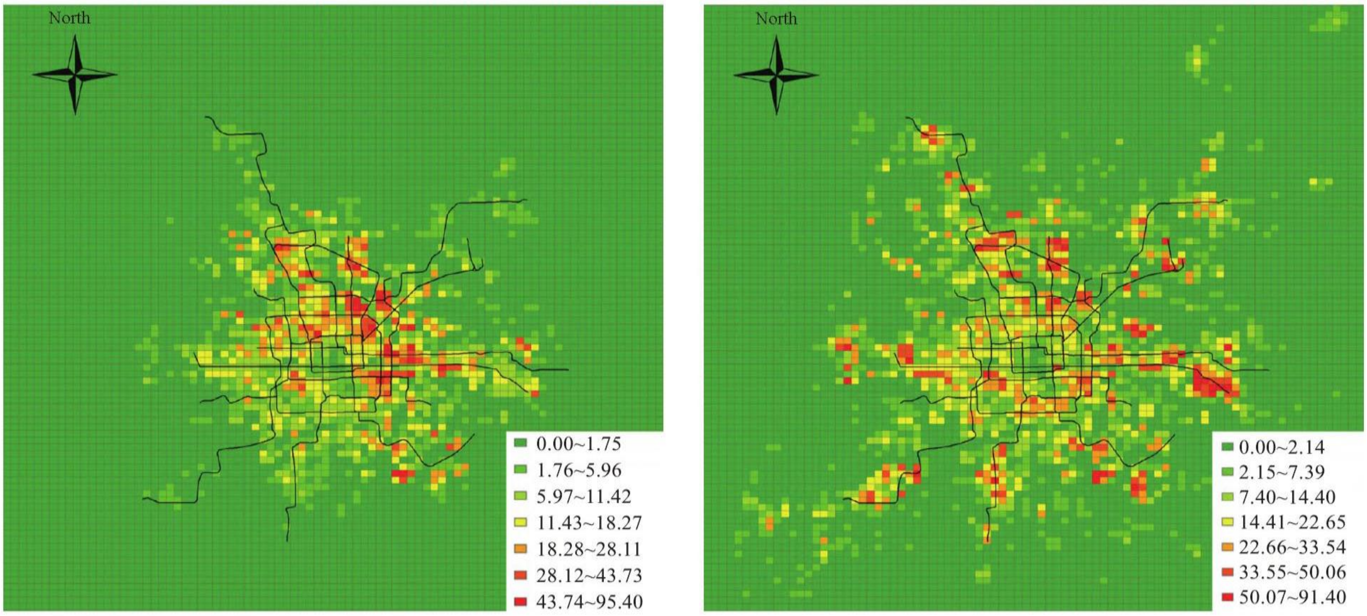


Fig. 4 The distribution of basis collective patterns for ride-sharing trips with different values of λ



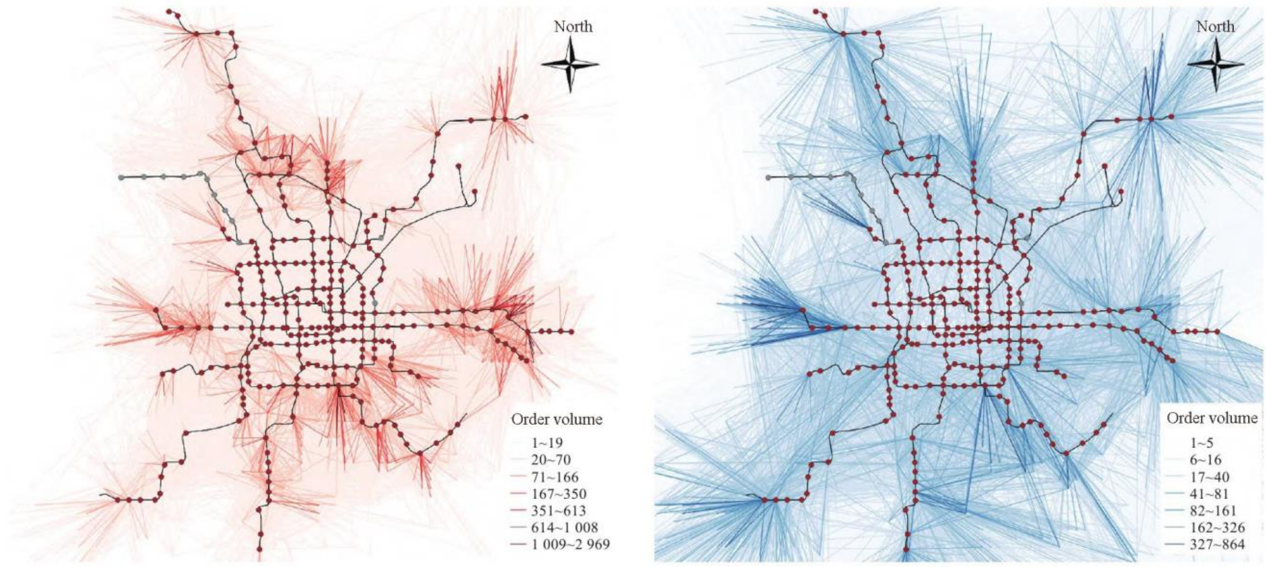
a λ=2 b λ=3 c λ=4

Fig. 5 The distribution of basis collective patterns for hitchhiking trips with different values of λ



a Carpooling b Hitchhiking

Fig. 6 Proportional distribution of travel volume during the morning peak mode as a percentage of total travel volume



a Carpooling b Hitchhiking

Fig. 7 Carpooling OD distributions of ride-sharing in commuting travel chains

4.3 Fuel-saving estimation for extension with subway commuting trip chain: taking Tiantongyuan for instance

Focusing on the commuting problem in suburban areas without subway coverage, Tiantongyuan area in Beijing is selected for the study. Tiantongyuan area is a large economically affordable housing project, which is located in the northern part of the city, about 20 km away from the city center. Tiantongyuan is well-known as a sleeping city with a serious problem of separation of workplace and residence. There is only one subway line in the area—Beijing Subway Route 5, which connects Tiantongyuan with central urban areas. Table 2 shows the passenger flow in subway stations during the morning rush hour at Tiantongyuan, which can be seen that four stations in this area are typical residential stations, and the number of passengers who enter subway station is much larger than that of passengers who exit subway station during the morning rush hour. To guarantee the accuracy of research results, the spatial range of Tiantongyuan (116.344–16.498°E, 40.042–40.253°N) is delimited and trips where the origin is within this area are the research objects.

After screening, the number of carpooling trips that connect to subway stations achieves 1 991 during morning rush hour of weekdays, namely, a total of 3 982 carpooling orders. Fig. 8 shows the number and proportion of travel chains of various basic trip patterns. In terms of connection to subway trips, carpooling plays a bigger role than hitchhiking. The proportion of “connection + connection” type travel chain is the highest in carpooling trips, reaching 42%, while the proportion of “nonstop + connection” type travel chain is the highest in hitchhiking trips, achieving 53%, indicating that carpooling plays the main role in helping two groups of passengers connect to subway stations in “carpooling + subway” commuting travel chain, while hitchhiking in “hitchhiking + subway” commuting travel chain mainly helps passengers connect to subway stations. Most of drivers will drive to the workplace after dropping off passengers without having to transfer to the subway.

First of all, fuel savings of online car-hailing ride-sharing trips are estimated. It is found that the average fuel saving ratio of carpooling is 18.25% and that of hitchhiking is 43.84%, which indicates that hitchhiking is more fuel-efficient than carpooling in general. By analyzing the relationship between the fuel saving ratio and the vehicle-miles of travel during the trip, it is found that the average fuel saving ratio of carpooling orders comes to decrease as the vehicle-miles of travel increases. Meanwhile, the fuel saving ratio of hitchhiking comes to increase as the vehicle-miles of travel increases. Second, fuel savings of commuting travel chain are estimated. The fuel saving ratio of extension travel chain for carpooling and hitchhiking in the three modes is shown in Fig. 9. The average fuel saving ratio of commuting connection trips with various patterns is able to reach over 50%. For carpooling, the average fuel saving ratio of “connection + connection” pattern is significantly higher than that of the other two patterns, which also indicates that the combination of carpooling and subway can effectively reduce the energy consumption of travel. For hitchhiking, the average fuel saving ratio of the “connection + connection” pattern also ranks the highest, but the difference with the other two patterns is smaller.

Tab. 2 Passenger flow at subway stations during the morning peak period in the Tiantongyuan area

Subway station	Subway route	Passenger entry flow /person time	Passenger exit flow/person times	Ratio of passenger entry flow to exit flow	Station type
Lishuiqiao	Subway route 5 and subway route 13	92 166	16 091	5.73	Residential-type
South of Tiantongyuan	Subway route 5	49 498	5 594	8.85	
Tiantongyuan	Subway route 5	144 088	8 951	16.10	
North of Tiantongyuan	Subway route 5	147 623	12 528	11.78	

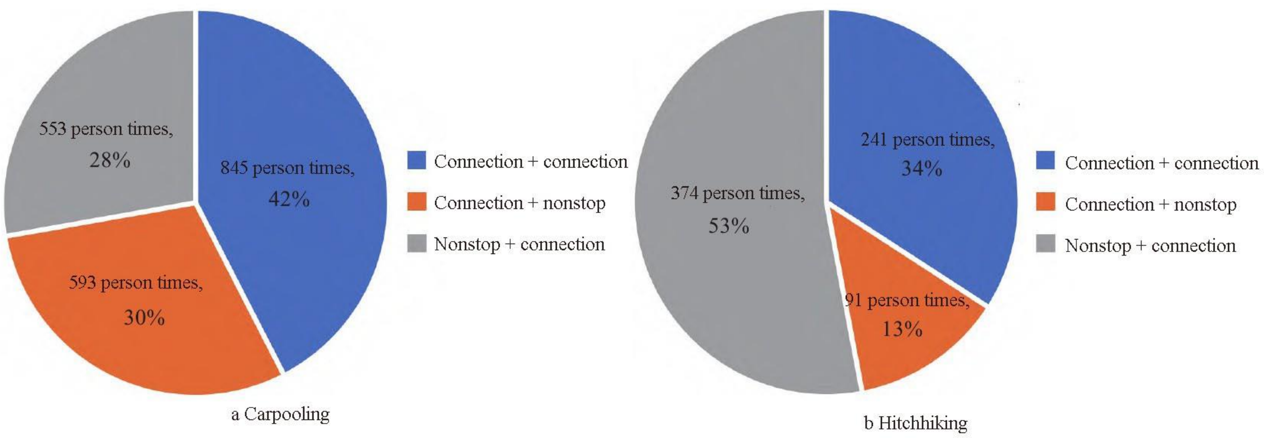


Fig. 8 Statistical analysis of extended commuting travel chain patterns during weekday morning peak hours

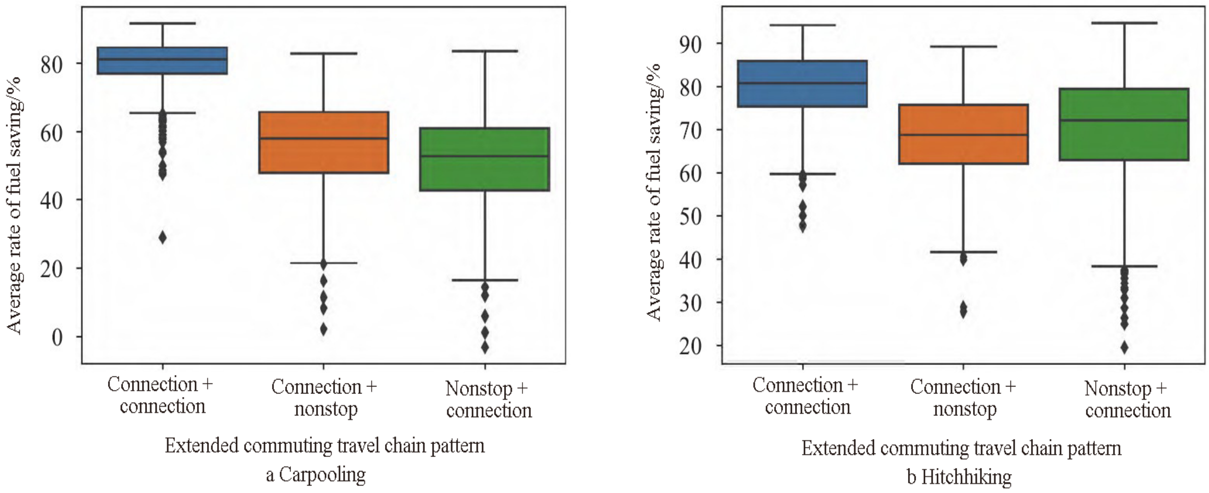


Fig. 9 Fuel-saving ratio of extended commuting travel chains

Although the average transportation distance of hitchhiking is longer than that of carpooling and the travel distance before connecting to the subway is much longer, the average fuel saving ratio of "hitchhiking + subway" travel chain is still higher than that of "carpooling + subway". The average fuel saving ratio of "connection + connection" pattern of hitchhiking ranks the top, which is consistent with carpooling pattern. The average fuel saving ratio for the "nonstop + connection" pattern is higher than that of "connection + nonstop" pattern, indicating that the fuel-saving benefits from connecting passengers to the metro network in hitchhiking are higher than that from connecting drivers to the metro network. In summary, both carpooling and hitchhiking can both help commuters to connect to the subway, and the commuting travel chain of "online car-hailing ride-sharing + subway" is able to save remarkable energy compared with driving a car all the way. Therefore, passengers should be encouraged to adopt this travel method.

5 Conclusions

Based on the actual operational data of carpooling and hitchhiking services and the AFC system of Beijing Subway, this paper analyzes the competition and cooperation relationship between online car-hailing ride-sharing and subway. NMF algorithm is utilized for identification of extended commuting travel chain, and then a set of fuel-saving estimation models for carpooling and hitchhiking is put forward that consider the fuel economy indexes and vehicle running status to estimate the fuel-saving benefits of extended commuting travel chain. Beijing is taken as a study case and the following conclusions are obtained:

1) Carpooling orders mostly involve competition and extension with subway, while hitchhiking orders primarily extend the reach of subway. Either carpooling or hitchhiking, extension with subway orders have the longest average transportation distance. Competition with subway in carpooling services mainly meets the travel demands in central city, while competition with subway in hitchhiking services mainly satisfy the travel demands in the suburbs. The vast majority of extended commuting travel chains are connections to subway stations in suburban areas where are not covered by subway stations, providing commuters with connection services to the subway.

2) There are certain differences of the fuel-saving level between carpooling and ride-sharing. The average fuel saving ratio of carpooling is lower than that of ride-sharing, and the fuel saving ratio of carpooling reduces with the growth of transportation distance. Conversely, the average fuel saving ratio of ride-sharing gradually increases as the transportation distance increases. The commuting travel chain of "online car-hailing ride-sharing + subway" can effectively reduce the energy consumption of commuters in suburban areas where has no subway coverage. The fuel-saving benefits of "ride-sharing + subway" travel chain is greater than that of "carpooling + subway", and ride-sharing reflects the travel characteristics of passengers connecting to subway stations and drivers going directly to destinations.

Both carpooling and ride-sharing have the advantages of flexibility and energy efficiency. They can serve suburban areas that lack subway coverage and provide suburban residents with access to the subway network as well as preventing traffic congestion caused by the influx of cars into a city. Therefore, administrators should adopt policy measures such as fare subsidies, parking discounts, etc. to promote the application of "online car-hailing ride-sharing + subway" commuting travel method to enhance the convenience of public transportation and give full play to the energy-saving advantages of online car-hailing ride-sharing, so that more urban residents can benefit from green and efficient integrated mobility services.

References

[1] JIN S T, KONG H, WU R, et al. Ridesourcing, the sharing economy, and the future of cities[J]. Cities, 2018, 76: 96–104.

[2] CHEN P W, NIE Y M. Connecting e-hailing to mass transit platform: analysis of relative spatial position[J]. Transportation research part C: emerging technologies, 2017, 77: 444–461.

[3] BABAR Y, BURTCH G. Examining the impact of ridehailing services on public transit use[J]. Information systems research, 2020, 31(3): 820–834.

[4] SHI X Y, XIA E J. The impact of online ridehailing on public transport: the moderating effect of the legitimacy[J]. Technology economics, 2020, 39(2): 79–86. (in Chinese)

[5] JIANG S X, GUAN W, HE Z B, et al. Exploring the intermodal relationship between taxi and subway in Beijing, China[J/OL]. Journal of advanced transportation, 2018, 2018: 1–14 (2022-04-18). https://www.hindawi.com/journals/jat/2018/3981845/.

[6] YIN B, LIU L, COULOMBEL N, et al. Appraising the environmental benefits of ridesharing: the Paris Region case study[J]. Journal of cleaner production, 2018, 177: 888–898.

[7] YU B Y, MA Y, XUE M M, et al. Environmental benefits from ridesharing: a case of Beijing[J]. Applied energy, 2017, 191: 141–152.

[8] LIU X B, YAN X D, LIU F, et al. A trip-specific model for fuel saving estimation and subsidy policy making of carpooling based on empirical data[J]. Applied energy, 2019, 240: 295–311.

[9] ANDERSON D N. “Not just a taxi”? For profit ridesharing, driver strategies, and VMT[J]. Transportation, 2014, 41(5): 1099–1117.

[10] WANG F R, ROSS C L. New potential for multimodal connection: exploring the relationship between taxi and transit in New York City (NYC) [J]. Transportation, 2019, 46(3): 1051–1072.

[11] WANG R, CHEN F, LIU X B, et al. Spatiotemporal analysis of competition between subways and taxis based on multi-source data[J]. IEEE access, 2020, 8: 225792–225804.

[12] LIU X B. Methods for Describing the Travel Characteristics and Optimizing the Operation of Carpooling under the Scale of Metropolitan Region [D]. Beijing: Beijing Jiaotong University, 2021. (in Chinese)

[13] Ministry of Industry and Information Technology of the People’s Republic of China. Five departments jointly issued the “Passenger Vehicle Enterprise Average Fuel Consumption Accounting Measures” [A/OL]. (2013-03-20) [2022-04-18]. https://www.miit.gov.cn/zwgk/zcwj/wjfb/gg/art/2020/art_f6c11f66b22c4064ada126c6899096e5.html. (in Chinese)

[14] US Environmental Protection Agency. Lightduty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975—2016[R/OL]. Washington, D.C.: US Environmental Protection Agency, 2016 [2022-04-18]. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100PKK8.pdf.

[15] Beijing Municipal Sports Bureau. Results bulletin of Beijing national physical fitness monitoring in 2014: children, adults and the elderly [EB/OL]. (2015-12-30) [2022-04-18]. http://tyj.beijing.gov.cn/bjsports/xxcx/tjxx/1168466/index.html. (in Chinese)

[16] YANG Y, WANG C, LIU W L, et al. Microsimulation of low carbon urban transport policies in Beijing[J]. Energy policy, 2017, 107: 561–572.