



## Research article

## Understanding the potential of taxi sharing: The case of Chengdu

Beibei Hu<sup>a</sup>, Xufeng Li<sup>a</sup>, Zixun Li<sup>b</sup>, Xianlei Dong<sup>a</sup>, Huijun Sun<sup>c</sup>, Minghe Sun<sup>d</sup>,  
Kexin Lin<sup>a</sup>, Jie Xue<sup>e,f,\*</sup><sup>a</sup> School of Business, Shandong Normal University, Jinan, China<sup>b</sup> School of Economics, Beijing Technology and Business University, Beijing, China<sup>c</sup> Key Laboratory of Transport Industry of Big Data Application Technologies for Comprehensive Transport, Ministry of Transport, Beijing Jiaotong University, Beijing, China<sup>d</sup> Carlos Alvarez College of Business, University of Texas at San Antonio, Texas, USA<sup>e</sup> National Science Library, Chinese Academy of Sciences, Beijing, China<sup>f</sup> Department of Information Resources Management, School of Economics and Management, University of Chinese Academy of Sciences, Beijing, China

## ARTICLE INFO

## Keywords:

GPS tracking data

Sharing conditions

Spatiotemporal distribution

The potential of taxi sharing

## ABSTRACT

The emergence of taxi sharing enhances urban transport efficiency and reduces carbon emissions. Using GPS tracking data from taxis in Chengdu, China, this study first outlines conditions for identifying shareable taxi orders based on their origins and destinations. We then develop a three-phase computational model to optimize matches among all potential shareable orders, calculating the shareable mileage and the proportion of original mileage that could be shared. Our comprehensive temporal and spatial analysis reveal a significant market for taxi sharing in Chengdu, with higher potential on workdays than non-workdays and four distinct demand peaks throughout the day. The morning peak on workdays and the night peak on non-workdays are particularly pronounced. Most shareable orders originate within major city districts. We find a positive correlation between the potential of taxi sharing and average traffic speed, and negative correlations with order volume, regional economic development, and population density. Functional zones related to Enterprises, Motorcycle Services, and Transportation Services exhibit significantly higher sharing potential. Compared to traditional taxi operations, taxi sharing significantly reduces total travel mileage. This quantitative analysis offers insights into the potential demand for taxi sharing among urban residents and may help government authorities optimize taxi resources for the sustainable development of urban transport.

## 1. Introduction

In recent years, there has been a significant surge in taxi demand, driven by urbanization and the increased need for transportation for social activities. This surge has resulted in intensified traffic congestion, particularly during peak hours, leading to severe jams [1]. Furthermore, escalating air pollution from carbon emissions has become a serious concern [2]. However, taxi sharing, an application of the sharing economy in public transportation [3], offers a promising solution. This involves matching at least two separate ride requests with similar spatiotemporal characteristics for a joint taxi trip [4]. It effectively enhances vehicle occupancy rates, optimizing

\* Corresponding author. No. 33, North 4th Ring West Road, Haidian District, Beijing, China.  
E-mail address: [xuejie@mail.las.ac.cn](mailto:xuejie@mail.las.ac.cn) (J. Xue).

<https://doi.org/10.1016/j.heliyon.2024.e29888>

Received 24 June 2023; Received in revised form 11 April 2024; Accepted 17 April 2024

Available online 26 April 2024

2405-8440/© 2024 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

resource allocation, and benefiting both passengers and drivers economically. For example, in Porto, a full deployment of the taxi sharing system could increase the average occupancy per kilometer travelled by 48 % compared to the traditional taxi operating mode [5]. Simultaneously, it reduces the number of vehicles needed, alleviating traffic congestion, lowering energy consumption, and reducing environmental pollution [6]. It is estimated that taxi sharing in New York could reduce the travel mileage by 2.89 million kilometers, save 231 kL of gas, and reduce CO<sub>2</sub> emissions by 532 tons per week [7]. Therefore, this approach can play a pivotal role in advancing the sustainable development of urban transportation.

Taxi sharing holds significant potential, defined as the maximum proportion of mileage that can be shared among all taxi trips [8]. Studies have found a high similarity in travel trajectories across various taxi trips [9,10], indicating a strong potential for taxi sharing. However, despite this promise, many cities currently impose limitations on taxi sharing implementation. For instance, during the 2020 Tokyo Olympics, the Japanese government temporarily allowed taxi sharing [11]. In New York, the ride-sharing platform Bandwagon primarily focuses on providing taxi sharing services for transportation hubs like JFK Airport [12]. The reasons why taxi sharing has not yet been widely applied include concerns about its impact on other modes of transportation. Additionally, the challenges of regulating pricing, which can often be unclear and disorderly, contribute to this situation [13,14]. Hence, it is crucial to devise a method for quantifying the potential for taxi sharing in a city. This can assist urban managers to recognize the latent demand for taxi sharing services and empower them to make well-informed decisions regarding the efficient management of the taxi sharing market. This, in turn, would facilitate an organized urban transportation network and promote environmentally friendly development.

The computation of the potential of taxi sharing involves solving the Dial-A-Ride Problem (DARP), entailing the design of vehicle routes and schedules for multiple users who specify pick-up and delivery requests between origins and destinations [15]. Studies on DARP have employed optimization techniques to formulate taxi sharing routes [9,16]. These methods aim to enhance the efficiency of taxi sharing by reducing search and travel times and achieving the best match between passengers and taxis [17]. Previous research has produced an abundance of results. However, there are still areas where improvements can be made. In comparison to prior research, our study introduces several significant developments:

- On the one hand, we abstain from imposing specific constraints on the timings or locations of taxi sharing, such as requiring passengers to be picked up and dropped off at designated meeting points. While this approach may yield higher sharing potential in the results, it might not align with real-world scenarios [4]. Instead, we rely on the actual GPS trajectories of taxi orders and conduct an analysis of their spatiotemporal overlaps to assess the possibility of sharing.
- On the other hand, the measurement of the potential of taxi sharing is frequently underemphasized. In contrast, our research delves into understanding the potential of taxi sharing within urban contexts and scrutinizing its spatiotemporal characteristics. The evaluation of the potential of taxi sharing from both temporal and geographical dimensions exposes evolving demand patterns. This discussion is instrumental for formulating more precise recommendations for urban management [18].

Based on taxis' GPS tracking data, this paper establishes conditions for identifying shareable taxi orders. We also present a comprehensive analytical model for calculating the potential shared mileage and the potential proportion of the original mileage that could be shared for each order. Additionally, we conduct an in-depth analysis of the spatial and temporal distribution characteristics of the potential of taxi sharing. The contribution of this paper is theoretically significant for the quantitative approach to identifying potentially shareable taxi orders and the model for calculating the potential of taxi sharing. These findings regarding the spatio-temporal distribution of potential taxi sharing demand also carry important practical implications. They contribute to achieving a balance between supply and demand in the urban taxi sharing market, optimizing its management, and facilitating the coordinated development of urban transport systems.

The rest of the paper is organized as follows: Section 2 presents the literature review, while Section 3 covers the data and pre-processing. In Section 4, we introduce the methodological design of this study and provide the approach used to identify potentially shareable taxi orders. Section 5 analyzes the characteristics of taxi sharing trips in both the spatial and temporal dimensions. Section 6 discusses the results of this study and compares them with other findings. Finally, in Section 7, we delve into a discussion and summary of the research presented in this article, as well as prospects for future research directions. The developed model algorithm is presented in the appendix. It is implemented using Python 3 and executed on a computer with 4 cores running at 2.7 GHz.

## 2. Literature review

Taxi sharing, also known as taxi ridesharing, combines the advantages of public transportation (low cost) with the flexibility of private cars [7]. In the contemporary landscape, taxi sharing is made possible by advanced information and communication technologies such as GPS, smartphones, and mobile apps [19]. By leveraging these technologies and considering travelers' preferences, including desired pick-up and drop-off times and locations, the taxi sharing system matches similar travel requests and consolidates multiple requests into one taxi trip [4]. In this section, we summarize previous relevant studies on taxi sharing, primarily focusing on two aspects: the factors influencing taxi sharing and DARP.

### 2.1. Influencing factors for taxi sharing

Taxi sharing is an emerging travel mode that requires further market expansion [20]. Understanding the factors that influence someone's choice to use taxi sharing is crucial for its continued growth and development. By considering these factors, stakeholders can make informed decisions to meet people's evolving demands for this emerging travel mode. Previous studies have discussed

influencing factors, including the passengers' individual attributes, travel characteristics, and environmental conditions.

To begin, individual attributes such as age, gender, and educational background influence the willingness to use taxi sharing services. Generally, younger travelers exhibit greater willingness to adopt taxi sharing, likely due to their higher receptivity to new technologies and greater concern for environmental benefits [21]. Similarly, individuals with higher educational backgrounds, who tend to be more accepting of new technologies, are also more likely to utilize taxi sharing services [22,23]. Gender is another significant factor influencing travel behavior. Compared to men, women are more accepting of longer waiting times and detours, making them more inclined to use taxi sharing services [24,25].

Next, travel characteristics primarily encompass factors such as travel period, distance, and purpose. In high-pressure car-hailing situations, individuals are more motivated to choose taxi sharing, leading to a higher willingness to share taxis on working days or during peak hours [26]. When individuals face long travel distances, they are more inclined to opt for taxi sharing, possibly to alleviate the monotony of extended journeys or to save on travel costs [27]. In addition, people going out for leisure, entertainment, or social purposes are more likely to engage in sharing [24,28].

Finally, environmental conditions, including climatic conditions, the population and regional economy, and building land attributes, play a significant role. People are less likely to opt for taxi sharing during cold weather conditions [29]. In comparison with other regions, people are more likely to share travel in intensely populated regions, because the distance between travelers is then likely to be lower [30]. A multi-factor regression model has been built to explore the effects of building land attributes [31]. It shows a high level of sharing in communities and areas related to transport and communication, but a low level in areas around universities, postal offices, public transport companies, and other places. The building land attributes of sport and leisure services, bus stations, train stations, airports, and parking lots have been shown to have positive effects on ridesharing, while government and social organizations seem to have the opposite effect [32].

## 2.2. Dial-A-Ride Problem

Originally designed to provide door-to-door transportation for elderly or disabled individuals, DARP has evolved significantly over time [33]. In the context of taxi sharing, DARP involves the design of routes that consider time and routing constraints to accommodate the cost considerations of both passengers and drivers. Time constraints encompass factors such as the earliest acceptable pick-up and latest acceptable drop-off times, as well as the maximum ride duration, all of which reflect passengers' tolerance for time spent sharing [34]. Furthermore, routing constraints can lead to more direct routes by allowing users to be picked up or dropped off at intermediate locations, which are referred to as meeting points [4].

Efficiency in taxi sharing is often indicated by relatively short search and travel times, contributing to a better travel experience. Research has shown that the methods used to match drivers and sharing passengers significantly affect the search time drivers require to find passengers or passengers to find drivers [35,36]. Enhancing the search algorithm for the swift retrieval of user queries can effectively reduce the matching time between taxis and passengers. For instance, heuristic and approximate algorithms for building a taxi sharing system have been considered, utilizing taxi trajectory data from San Francisco and Porto to test the algorithms' efficiency [17]. Additionally, a Lagrange decomposition algorithm [16] and linear allocation algorithm [37] have been proposed to facilitate passenger-to-taxi assignments. Through rapid screening of taxis and potential fellow passengers for suitable matches, and efficient route planning so that the destination is reached promptly, a matching optimization method can also effectively reduce the total travel time [38,39]. Moreover, the overall travel time is primarily influenced by the choice of travel path and the level of congestion along the route [40].

Conversely, some studies focus on optimizing the dynamic taxi sharing model to meet routing constraints. This includes methods such as the taxi searching algorithm and path-planning strategy, which have been proposed to reduce the total travel mileage. For example, two innovative real-time optimal routing algorithms have been introduced with the goal of maximizing ride requests and minimizing travel distances for taxis [41]. Following route planning, research utilizing models and urban data has quantified the mileage saved and the reduction in taxi trips. In New York, it was discovered that 48.34 % of taxi orders could be shared, resulting in a saving of 2,892,036 km in travel distance [7]. Additionally, the total number of taxi trips could be decreased by approximately 30 % [17]. These findings emphasize the significant impact that an efficient taxi sharing model could have on improving urban transportation efficiency and sustainability.

**Table 1**  
Fields and numerical values of an example taxi GPS tracking record.

Fields	Example numerical values
Taxi ID	1253
Latitude	30.6625
Longitude	104.0078
Loading status	0 (1 for occupied, and 0 for non-occupied)
Time	08/03 15:01:12

### 3. Data

#### 3.1. Data source

The taxi GPS tracking data for Chengdu spans from August 3 to August 16, 2014, except for August 7 and 13, when data collection did not occur. The dataset includes 672,047,131 valid taxi GPS tracking records of 14,336 taxis in eight workdays and four non-workdays. Each tracking record contains five fields, including Taxi ID with desensitization, Latitude, Longitude, Loading status and Time. An example of such records is shown in Table 1.

#### 3.2. Data preprocessing

**Isolation of taxi orders.** The change of loading status of a taxi, i.e., 1 for occupied and 0 for non-occupied, is the time point for transition from one order to the next as shown in Fig. 1. The taxi is “seeking passengers” when its loading status is 0, and is “carrying passengers” when its loading status is 1.

From Fig. 1, a complete taxi service cycle includes “seeking passengers”, i.e., with a loading status 0, and “carrying passengers”, i.e., with a loading status 1. A taxi order is defined by the process of “carrying passengers” once. All the taxi orders are then isolated by using the taxi tracking data. After sorting the tracking data according to its operating time and its searching time, all the orders of each taxi can be obtained. Table 2 shows the daily number of taxi orders for the 14,336 taxis in Chengdu in the dataset. It can be seen from Table 2 that the daily taxi demands in Chengdu are relatively stable, basically in the interval between 450,000 and 530,000.

**Data cleaning.** Abnormal tracking records are deleted from the dataset. Weak signals, e.g., caused by building blocking, might result in positioning errors. An adjacent tracking record is regarded as abnormal if its average speed is too high, e.g., over 200 km per hour. A total of 584,236 abnormal tracking records are deleted from the dataset, which comprise less than one-thousandth of the total tracking records. Furthermore, the following four types of unreasonable orders are deleted. (1) Orders only having entry in one field, i.e., only having a single tracking record, are deleted. As a result, a total of 67,490 orders are deleted. (2) Orders with too short or too long travel time or distance are deleted. According to the travel time and distance distributions of taxi orders in Table 3, orders with travel time shorter than 52 s, i.e., the bottom 1 %, or longer than 20,355 s, i.e., the top 0.1 %, and orders with travel distance shorter than 0.47 km, i.e., the bottom 1 %, or longer than 60.48 km, i.e., the top 0.1 %, are deleted. (3) Orders with unclear destinations are deleted. The orders that have more than five consecutive following abnormal tracking records are deleted, because their destinations cannot be determined accurately. A total of 1016 such orders are deleted. (4) 397 orders that are geographically outside of the study area are removed. Consequently, a total of 258,266 unreasonable orders are deleted, accounting for approximately 4 % of the total number of orders in the dataset. Finally, 5,708,604 taxi orders are kept in the dataset for further analyses, of which 67.92 % are on workdays and 32.08 % are on non-workdays.

**Matching between the addresses of the administrative districts and the functional zones.** The origin of an order can intuitively reveal the initial location of passenger travel demands. Consequently, this study uses the origin of each order to determine the administrative districts and functional zones to which it belongs. The origin is matched with its specific address (i.e., the longitude and latitude) and Point of Interest (POI) using Amap’s reverse geocoding function [42]. Functional zones are then categorized according to Amap’s POI classification standard [43]. All orders are classified into the 20 administrative districts and the 19 functional zones of Chengdu. The administrative districts include Wuhou, Jinjiang, Qingyang, Jianyang and so on. The functional zones are Auto Service, Auto Dealers, Auto Repair and so on, as shown in Table 4.

Using POI as the classification criterion for functional zones is deemed appropriate in this study. This is primarily because the geographic scale defined by POIs aligns well with the grid, which acts as the fundamental unit of functional zones in our analysis. Specifically, there are six types of basic units for functional zones: grids, blocks, traffic analysis zones, cluster units, landscapes, and building units [44–46]. The division of functional zones is based on five main criteria: POI, geographical clustering, deep learning recognition, land attributes, and survey interviews, with the selection of criteria influenced by the type of the basic unit [47]. Land

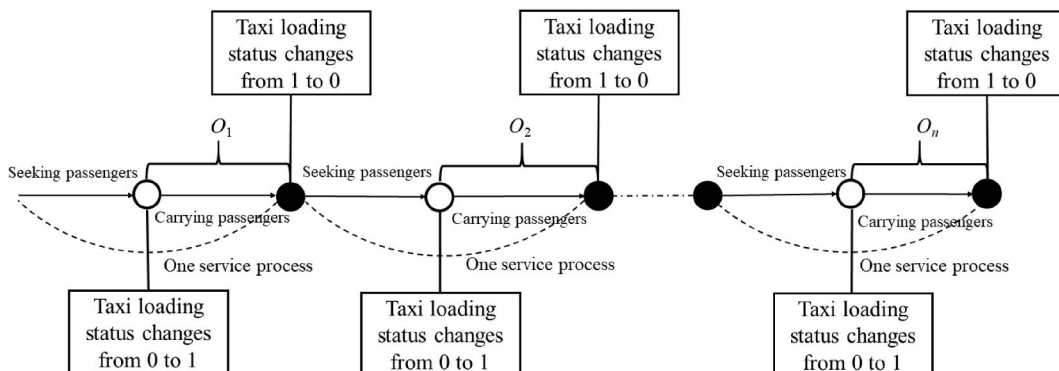


Fig. 1. The changing process of taxi loading status.

**Table 2**  
Daily number of taxi orders in Chengdu in the dataset.

Date	Order counts	Date	Order counts
08/03 (Sunday)	458764	08/10 (Sunday)	465394
08/04 (Monday)	496895	08/11 (Monday)	514666
08/05 (Tuesday)	497250	08/12 (Tuesday)	527115
08/06 (Wednesday)	486875	08/14 (Thursday)	517940
08/08 (Friday)	479031	08/15 (Friday)	534824
08/09 (Saturday)	482346	08/16 (Saturday)	505770

**Table 3**  
Percentiles and their corresponding times (seconds) and distances (kilometers).

Percentile	Time	Percentile	Time	Percentile	Distance	Percentile	Distance
1 %	52	90 %	1679	1 %	0.47	90 %	12.71
5 %	174	95 %	2118	5 %	1.13	95 %	16.78
10 %	254	99 %	4089	10 %	1.61	99 %	26.65
25 %	438	99.5 %	6034	25 %	2.76	99.5 %	32.48
50 %	741	99.9 %	20355	50 %	4.86	99.9 %	60.48
75 %	1162			75 %	8.09		

**Table 4**  
Functional zones.

No.	Classification	POI
1	Auto Service	Filling stations, charging stations, other energy stations, etc.
2	Auto Dealers	Volkswagen franchised sales, Honda franchised sales, etc.
3	Auto Repair	Volkswagen franchised repair, Honda franchised repair, etc.
4	Motorcycle Service	Motorcycle sales, motorcycle repair.
5	Food and Beverages	Chinese food restaurants, foreign food restaurants, fast food restaurants, coffee houses, tea houses, bakeries, etc.
6	Shopping	Shopping plazas, convenience stores, home electronics hypermarkets, supermarkets, comprehensive markets, etc.
7	Sport and Recreation	Sports stadiums, recreation centers, theatres, cinemas, etc.
8	Medical Service	Hospitals, clinics, emergency centers, disease prevention institutions, pharmacies.
9	Accommodation Service	Hotels, motels.
10	Tourist Attraction	Parks and squares, scenery spots.
11	Commercial House	Industrial parks, buildings, residential areas.
12	Governmental Organization and Social Group	Government organizations, foreign organizations, social groups, public security organizations, industrial and commercial taxation institutions, etc.
13	Science, Culture and Education Service	Museums, exhibition halls, art galleries, libraries, planetariums, media organizations, schools, etc.
14	Transportation Service	Airport related, railway stations, bus stations, etc.
15	Finance and Insurance Service	Banks, ATMs, insurance companies, securities companies, finance companies.
16	Enterprises	Farming, forestry, animal husbandry and fishery bases, mining companies, construction companies, etc.
17	Road Signs	Warning signs, toll gates, service areas, traffic lights, signposts.
18	Place Name and Address	Normal place names, natural place names, etc.
19	Pass Facilities	Gates of buildings, gates of street house, virtual gates, special corridors.

Note: The first column (No.) is used to represent the functional zones in the figures below.

attributes and survey interviews are typically used for larger-scale functional units, such as blocks, while cluster units often utilize geographical clustering for division. Both POI and deep learning recognition are suitable for dividing smaller-scale basic units, such as grids and building units. However, deep learning frequently relies on remote sensing data, which may not capture socio-economic information as effectively as POI [48]. For instance, a deep learning model might only identify basic geographical features, such as buildings and roads, without accurately distinguishing specific information further subdivided based on different functions like commercial areas, residential areas, and public service facilities. Therefore, POI represent the most suitable standard for dividing functional zones in this study. Moreover, POI have been widely used as a classification criterion in functional zone research, with over 70 % of studies related to functional zones indexed in the Web of Science from 2000 to 2021 utilizing POI as a classification criterion [46].

In the following, let  $L_m$  represent the distance between the origin of the order to the  $m$ -th POI. Let  $P_m$  represent the probability that the order belongs to the  $m$ -th POI. A short distance  $L_m$  usually indicates a relatively high probability that the order belongs to the  $m$ -th POI. Therefore, the probability  $P_m$  can be calculated using (1) below:

$$P_m = \frac{1/L_m}{\sum_{m=1} 1/L_m} (m = 1, 2, 3, \dots). \tag{1}$$

The cumulative probabilities of all orders associated with a specific POI are utilized to ascertain the total number of orders within that POI. The values of  $m$  are 1, 2 and 3 in actual computation, meaning that only the three POIs with the closest distance  $L_m$  are retained. Fig. 2 shows the distributions of taxi orders in different administrative districts and functional zones in Chengdu. As can be seen from the left side of Fig. 2, taxi demands are mainly distributed in the main urban areas, including the districts of Wuhou, Jinniu, Qingyang, Jinjiang and Chenghua. The right side of Fig. 2 shows that there is a high demand for taxis in some functional zones such as Commercial House, Science, Culture and Education Service and Finance and Insurance Service.

#### 4. Methodology

This paper builds on the work of Tachet et al. [49], introducing conditions for shareable taxi orders and presenting a general analytical model. This model is designed to calculate the potential shared mileage and the proportion of original mileage that could be shared for each order, serving as a vital tool in assessing the potential of taxi sharing. The higher the proportion that could be shared for each order, the greater is the potential for taxis to participate in sharing activities, and vice versa.

##### 4.1. Shareable conditions for two taxi orders

All orders are sorted by their starting times in ascending order, i.e., with the latest order to start listed last. Let  $N = \{1, 2, \dots, n\}$  denote the set of taxi orders under consideration. The set of orders that occurred before order  $j$  ( $j \in N$ ) is represented by  $I = \{1, 2, \dots, j - 1\}$ . An order has at least one passenger and a ride so that an index  $i$  or  $j$  may refer to the order, the passenger, or the ride.

Two orders  $i$  and  $j$  are considered one at a time. The search process starts from the first, i.e., the earliest, order in the dataset. The orders are not flagged before the process begins. A taxi driver always picks up passenger  $i$  first and then looks forward for passenger  $j$ . In the following, route  $i$  represents the shortest path from the origin to the destination of ride  $i$ , and route  $j$  represents the shortest path from the origin to the destination of ride  $j$ . After picking up passenger  $j$ , the taxi driver will not go back to where he left route  $i$ , but will plan and select a path from the current location to the destination of passenger  $i$  or  $j$ . Rides  $i$  and  $j$  are shareable if they satisfy the following conditions:

- 1) Neither ride  $i$  nor ride  $j$  is flagged.
- 2) Ride  $j$  originates later than ride  $i$  but within a certain time limit.
- 3) The origin of ride  $j$  is in the vicinity of a point on route  $i$  (which can be any point) and passenger  $j$  is ready for the ride when the taxi reaches that point.
- 4) The destination of ride  $j$  is in the vicinity of a point on route  $i$  (which can be any point), or the destination of ride  $i$  is in the vicinity of a point on route  $j$  (again this can be any point on route  $j$ ).

Each order, after being placed, may be shared with any previous one that has not yet been completed. Orders  $i$  and  $j$  will be flagged after this search process if they are shareable.

##### 4.2. The computation process of the model

Given the shareable conditions, we propose the following assumptions in our model:

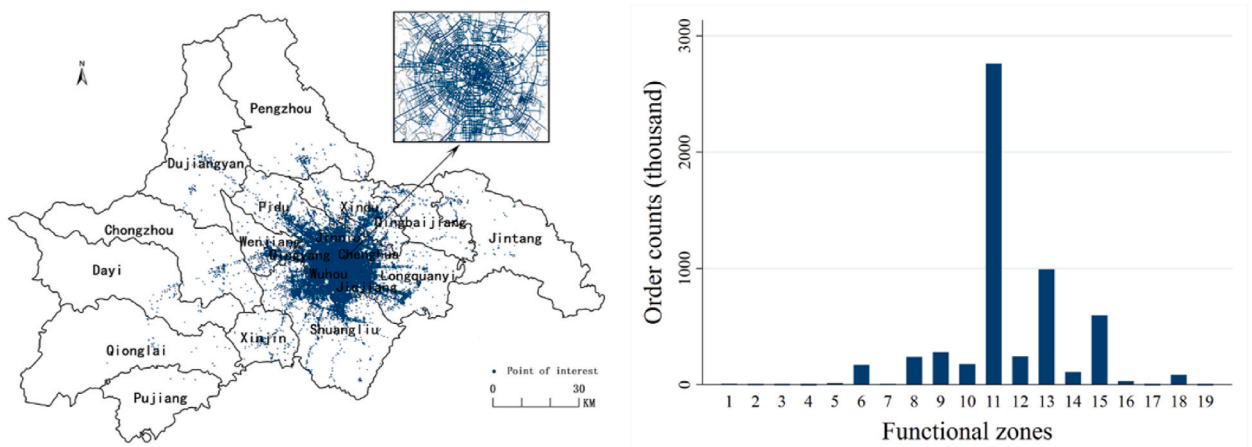


Fig. 2. The distribution of taxi orders in administrative districts and functional zones.

- 1) Each order is assumed to be shareable at most once. This assumption is based on practicality and efficiency. Although it recognizes that orders could, albeit rarely, be shared multiple times, this simplification helps streamline the modeling process without notably compromising realism [19,49].
- 2) Vicinity is defined by driving time. This assumption is grounded in the practicality of defining vicinity for sharing purposes [7,16]. While distance is a common metric, using driving time offers a more realistic measure as it reflects the actual travel experience and considerations of traffic congestion and road conditions.
- 3) Passengers have the same tolerance for the extra time taken for shared travel. This assumption is made to simplify the model and maintain consistency in passenger behavior [37]. While this may not be entirely accurate in reality, it provides a standardized basis for modeling passenger behavior.
- 4) The drivers always choose the shortest route, delivering the passenger with the closer destination after picking up passenger  $j$ . This assumption is rooted in efficiency and simplicity, aiming to minimize travel time for all passengers involved in the sharing process. By prioritizing the shortest route, the model ensures optimal resource utilization and passenger satisfaction [50,51].
- 5) The average speed on the sharing part of the ride, is approximately the same as the average speed on route  $i$ . This assumption facilitates the estimation of travel times and allows for straightforward modeling of taxi sharing scenarios [52].

The model aims to find the optimal match among all possible shareable order pairs that satisfy the shareable conditions. As shown in Fig. 3, the computation process can be divided into three phases. In Phase I, any order  $i \in I$  is checked to determine whether it meets the origin condition for sharing with order  $j$  at the starting time point. Consequently, an order set  $I'$  is obtained which represents the set of orders shareable with order  $j$  at the starting time. In Phase II, any order  $i \in I'$  is tested to determine whether it meets the destination condition for sharing with order  $j$  at the ending time point. In this phase, an order set  $I''$ , in which each order can be shared with order  $j$  at both their starting and ending times is obtained. In Phase III, the potential shared travel mileage and proportion of the original mileage that could be shared, for any order  $i \in I''$  and  $j$  are calculated, and the order  $i_{\max}$  with the maximum shared mileage with respect to order  $j$  is determined.

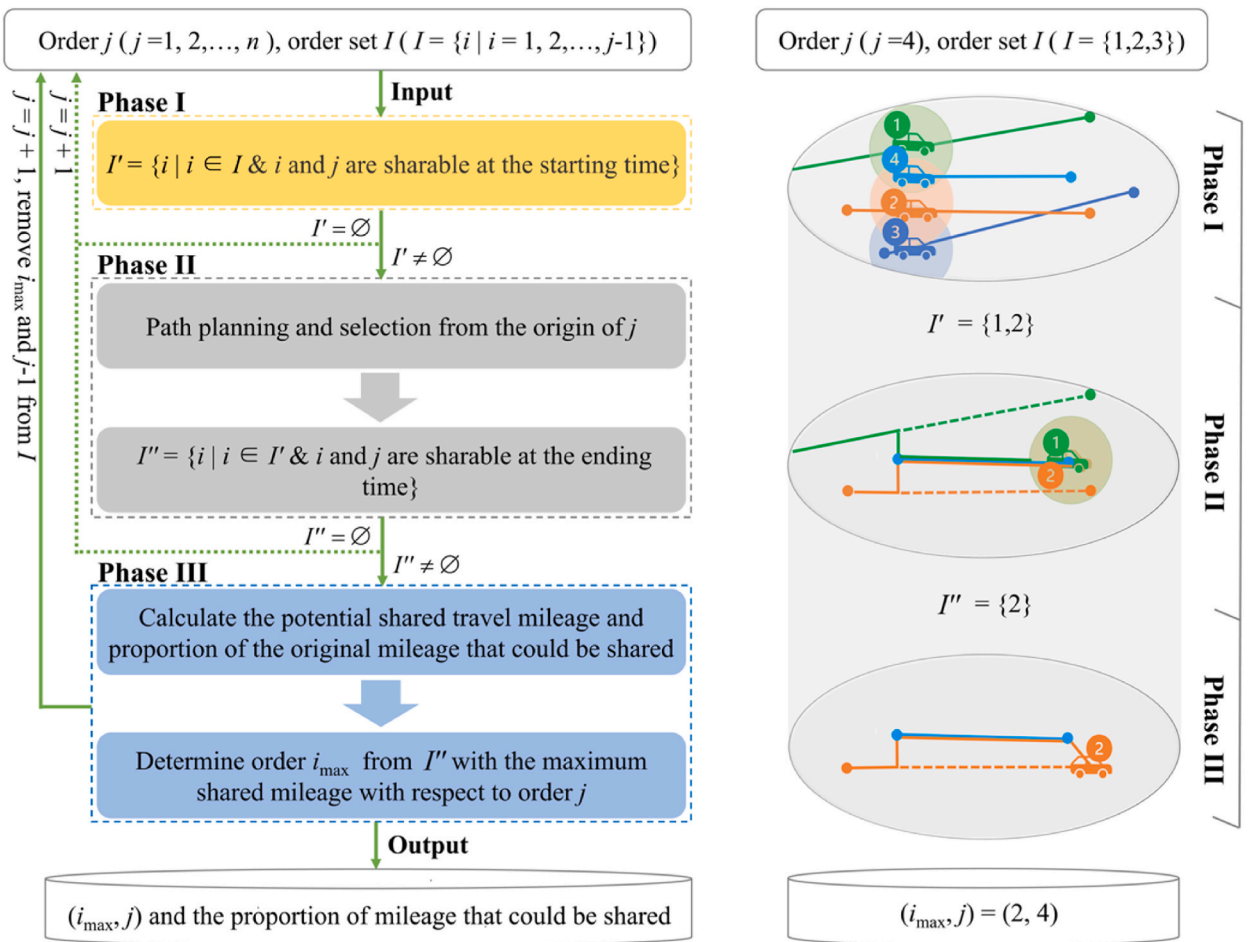


Fig. 3. The computation process for the proportion of mileage that could be shared.

Through the computation process, an optimal matching order  $i_{\max} \in I$  is found for order  $j$ . An example is shown on the right side of Fig. 3. In this example, order  $j = 4$  is the order concerned and the orders in the set  $I = \{1, 2, 3\}$  will be checked. In Phase I, orders 1 and 2 are determined to be shareable with order 4 at the start of order 4's trip. In Phase II, only order 2 is determined to be shareable with order 4. In Phase III, the potential sharing travel mileage and proportion are calculated for the pair of shareable orders 2 and 4.

4.2.1. Phase I: the shareability of orders  $i$  and  $j$  at the starting time of order  $j$

In this subsection, the shareable condition at the origin is described. The shareability of each order  $i$  in  $I$  with order  $j$  at its start time is checked, as shown in Phase I in Fig. 3. Without loss of generality, the taxi driver picks up passenger  $i$  first. Order  $i$  with passenger  $i$  has its route from origin  $O_i$  to  $D_i$ . Similarly, order  $j$  with passenger  $j$  has its route from origin  $O_j$  to destination  $D_j$ . Let  $S_i$  and  $S_j$  represent the distances of orders  $i$  and  $j$ , respectively. Let  $t_{i1}$  and  $t_{i2}$  denote the starting and ending times of taxi order  $i$ , and let  $t_{j1}$  and  $t_{j2}$  denote the starting and ending times of taxi order  $j$ , respectively. Hence, the average speed of the route  $i$  is estimated to be  $v_i = \frac{S_i}{t_{i2} - t_{i1}}$ .

The two orders are considered, to determine if they meet the shareable conditions at time point  $t_{j1}$ , i.e., the starting time of order  $j$ . The taxi is assumed to be at point  $P$  on route  $i$  at time  $t_{j1}$  when passenger  $j$  issues his/her order. Let  $r'$  represent an acceptable distance for a taxi driver to make a detour so as to pick up the second passenger, and  $S'$  represent the shortest distance from  $P$  to  $O_j$ , as shown in Fig. 4. Let  $\delta'$  represents the maximum time that the second passenger is willing to wait for the taxi to come. The time it takes the taxi to reach  $O_j$  from point  $P$ , i.e., traveling a distance  $S'$ , must be less than or equal to a tolerance  $\delta'$ . The timing condition at the origin is then given by (2):

$$\frac{S'}{v_i} \leq \delta', \tag{2}$$

where  $\frac{S'}{v_i}$  is the time taken for the taxi to detour from route  $i$  to travel to  $O_j$ . Consequently, each order  $i \in I$  that can be shared with order  $j$  at the starting time is added to the set  $\hat{I}$ . If  $\hat{I} \neq \emptyset$ , then each order  $i \in \hat{I}$  is tested with order  $j$  to determine if they meet the shareable conditions at their ending times.

4.2.2. Phase II: the shareability of orders  $i$  and  $j$  at their ending times

In this subsection, the shareable condition at the destination is described. The shareability of each order  $i$  in  $\hat{I}$  with order  $j$  at their ending times is tested, i.e., Phase II in Fig. 3. Two orders that are shareable at the starting time of order  $j$  may not be shareable for the whole trip. Let  $r''$  represent the maximum extra distance that the taxi driver and passenger  $i$  are willing to detour to drop off passenger  $j$  and let  $S''$  represent the extra distance that the taxi has to travel to drop off passenger  $j$ , as shown on Fig. 4(a). Likewise, let  $r''$  also represent the maximum extra distance that the taxi driver and passenger  $j$  are willing to detour to drop off passenger  $i$  and let  $S''$  also represent the extra distance that the taxi has to travel to drop off passenger  $i$ , as shown on Fig. 4(b). From Fig. 4, it can be clearly seen that the two orders can be shared at their origins if  $S' \leq r'$  and destinations if  $S'' \leq r''$ , thus they are a pair of potential sharing travel

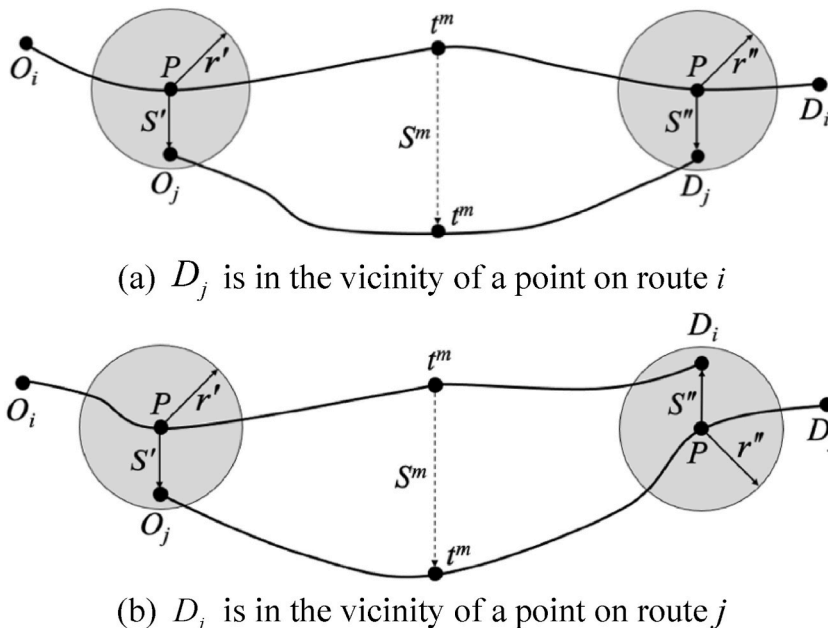


Fig. 4. Shareable taxi orders.



orders. However, the two orders cannot be shared at the time point marked as  $t^m$ , for the distance  $S^m$  between the two locations of orders  $i$  and  $j$  to be too long.

In the first case as shown in Fig. 5(a),  $D_j$  is closer to  $O_j$ , thus passenger  $j$  will be dropped off first and then  $D_j$  should be in the vicinity of a point on route  $i$ . Let  $\delta^s$  be the maximum time delay that all passengers onboard are willing to wait over their whole shared trip. Let  $S_i^s$  represent the extra distance that the taxi has to travel to drop off passenger  $j$ , i.e., the driving distance from  $D_j$  to  $D_i$ , and let  $S_i^m$  represent the driving distance from  $O_j$  to  $D_i$ . In this case,  $S_i^m \geq S_j$ , the timing condition at the destination is then given by (3):

$$\frac{S' + S_j + S_i^s}{v_i} - (t_{i2} - t_{j1}) \leq \delta^s, \tag{3}$$

where  $\frac{S+S_j+S_i^s}{v_i}$  is the time when the travel sharing occurs, and  $t_{i2} - t_{j1}$  is the time without sharing, for passenger  $i$  to travel from the location of  $P$  to  $D_i$ . Hence, the left hand side of (3) is the time delay for passenger  $i$  resulting from the travel sharing. Meanwhile, since the driver would drop off passenger  $j$  first, passenger  $j$  will not have delay in this case.

In the second case as shown in Fig. 5(b),  $D_i$  is closer to  $O_j$ , and thus passenger  $i$  will be dropped off first and then  $D_i$  should be in the vicinity of a point on route  $j$ . Let  $S_j^s$  represent the extra distance that the taxi has to travel to drop off passenger  $i$ , i.e., the driving distance from  $D_i$  to  $D_j$ . In this case,  $S_i^m < S_j$ , and the timing condition at the destination is then given by (4) and (5):

$$\frac{S' + S_i^m}{v_i} - (t_{i2} - t_{j1}) \leq \delta^s, \tag{4}$$

$$\frac{S' + S_i^m + S_j^s}{v_i} - (t_{j2} - t_{j1}) \leq \delta^s, \tag{5}$$

where the left hand side of (4) and (5) denote the time delays for passengers  $i$  and  $j$ , respectively, resulting from the travel sharing. In (4),  $\frac{S+S_i^m}{v_i}$  is the time taken when travel sharing occurs. Similarly in (5),  $\frac{S+S_i^m+S_j^s}{v_i}$  is the time when travel sharing occurs, and  $t_{j2} - t_{j1}$  is the time taken without sharing, for passenger  $j$  to travel from  $O_j$  to  $D_j$ .

Consequently, all orders in the set  $I$  that can be shared with order  $j$  up until one of the orders' ending times are put into set  $I'$ , i.e., each order in set  $I'$  is shareable with order  $j$ , meeting the conditions at both origin and destination. If  $I' = \emptyset$ ,  $j$  cannot be shared with any previous orders. However, it is still possible for  $j$  to be shared with orders that occur later.

4.2.3. Phase III: the potential shared travel mileage and proportion of original mileage that could be shared between orders  $i$  and  $j$

In this subsection, the potential shared travel mileage and its proportion of the original mileage, for every order  $i \in I'$  is computed, and order  $i_{max}$  is found for order  $j$ , as shown in Phase III in Fig. 3. Without sharing, the total mileage travelled for the two orders is  $S_i + S_j$ . With sharing, the calculation of the total mileage and shared mileage differs for the two cases mentioned in Section 4.2.2, as described below.

In the first case, if  $D_j$  is closer to  $O_j$  than  $D_i$  is, the taxi driver will drop passenger  $j$  first and then proceed from  $D_j$  to  $D_i$ . Let  $S_i^s$  denote the driving distance from  $O_i$  to  $P$ . With sharing, the total mileage actually travelled for the two orders is given by (6):

$$S_i^a = S_i^s + S' + S_j + S_i^s, \tag{6}$$

and the shared mileage is given by (7):

$$S_i^s = S_j, \tag{7}$$

as shown in Fig. 5(a). The mileage saved for orders  $i$  and  $j$  by sharing is then given by (8):

$$\Delta_i = (S_i + S_j) - (S_i^s + S' + S_j + S_i^s) = S_i - S_i^s - S'. \tag{8}$$

Hence, the proportion of the shared mileage for orders  $i$  and  $j$  based on the total distance without sharing is given by (9):

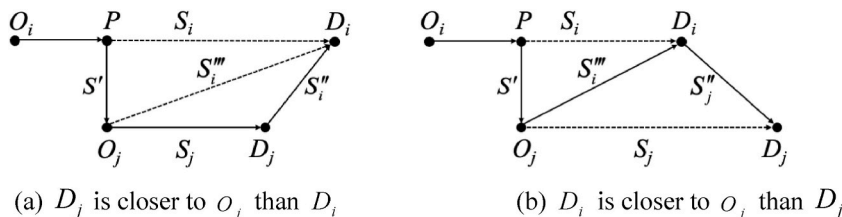


Fig. 5. Computation of performance measures.

$$P_i^{s1} = \frac{S_j}{S_i + S_j}, \tag{9}$$

and the proportion of shared mileage for orders  $i$  and  $j$  based on the total distance with sharing is given by (10):

$$P_i^{s2} = \frac{S_j}{S_i^a} = \frac{S_j}{S_i + S' + S_j + S_i^a}. \tag{10}$$

In the second case, if  $D_i$  is closer to  $O_j$  than  $D_j$  is, the taxi driver will drop passenger  $i$  first and then proceed from  $D_i$  to  $D_j$ . With sharing, the total mileage actually travelled for the two orders is given by (11):

$$S_i^a = S_i + S' + S_i^m + S_j^a, \tag{11}$$

and the shared mileage is given by (12):

$$S_i^s = S_i^m, \tag{12}$$

as shown in Fig. 5(b). The mileage saved for orders  $i$  and  $j$  by sharing is given by (13):

$$\Delta_i = (S_i + S_j) - (S_i + S' + S_i^m + S_j^a). \tag{13}$$

Hence, the proportion of the shared mileage for orders  $i$  and  $j$  based on the total distance without sharing is given by (14):

$$P_i^{s1} = \frac{S_j^m}{S_i + S_j}, \tag{14}$$

and the proportion of shared mileage for orders  $i$  and  $j$  based on the total distance with sharing is given by (15):

$$P_i^{s2} = \frac{S_j^m}{S_i^a} = \frac{S_j^m}{S_i + S' + S_j + S_i^a}. \tag{15}$$

Consequently, by comparing the  $S_i^s$  of all orders in  $I^r$ , we can determine the order  $i_{max}$  that has the maximum shared mileage with order  $j$ . Therefore, orders  $i_{max}$  and  $j$  are the optimal orders to be shared. Furthermore, we can obtain the proportion that could be shared, based on the total distance without sharing (i.e.,  $P_i^{s1}$ ) and with sharing (i.e.,  $P_i^{s2}$ ).

### 5. Results

This experiment uses the average of all taxi orders'  $P_i^{s2}$  to measure the potential of taxi sharing of Chengdu. It is found that, when  $\delta$

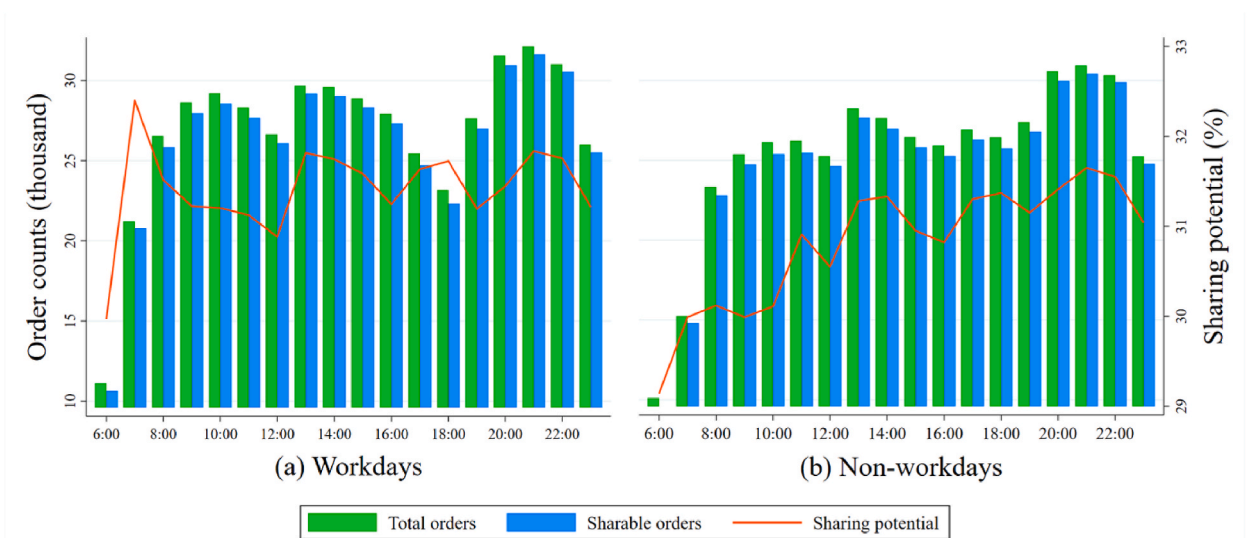


Fig. 6. The daily changing patterns of the numbers of taxi orders and the potential of taxi sharing.

= 5 min, taxi trips exhibit over 95 % shareability [19]. Therefore, we set  $\delta'$  as 5 min and  $\delta^*$  as 10 min in the case study.

5.1. Overall analysis on the potential of taxi sharing

The analysis of Chengdu’s taxi orders reveals that 97.77 % of these orders are potentially shareable, indicating a robust potential for the taxi sharing market. Furthermore, the possibility to share approximately 31.28 % of total travel mileage underscores the feasibility of shared transportation in the region. A significant majority, 67.96 % of shareable orders, occur on workdays, highlighting the heightened demand for sharing services during these times.

The daily changing patterns of taxi order counts and their sharing potential on both workdays and non-workdays from 6:00 to 24:00 is shown in Fig. 6. The order counts on the vertical axis refer to the average number of taxi orders per day. Notably, the total orders and shareable orders exhibit similar daily patterns across workdays and non-workdays. Specifically, taxis tend to have more shareable orders on workdays compared to non-workdays, with the sharing potential being 0.56 % higher during workdays. The peaks in the potential of taxi sharing occur at four distinct intervals throughout the day: morning, noon, evening, and night. The highest peak appears in the time period 7:00–8:00 on workdays. After this time period, the sharing potential drops sharply from 32.4 % to 31.21 %, primarily due to morning rush-hour traffic congestion. Unlike workdays, the highest peak on non-workdays appears in the time period 21:00–22:00, coinciding with the highest number of taxi orders.

Generally, the potential of taxi sharing is intricately linked with traffic conditions and the volume of taxi orders. Under favorable traffic conditions, there is a positive correlation between the number of taxi orders and the potential of taxi sharing. This relationship, however, inversely flips under congested traffic conditions, adversely affecting the potential of taxi sharing during peak hours on workdays. As shown in Fig. 6, from 6:00–7:00 on workdays, a gradual increase in taxi orders coincides with a sharp rise in sharing potential. The number of taxi orders continues to increase during the morning peak 7:00–10:00, but the potential of taxi sharing declines due to the impact of traffic congestion. A similar pattern is observed in the evening. The reduction in taxi orders before the peak period (16:00–18:00) leads to an increased sharing potential, which subsequently falls during the peak hours of 18:00–20:00 as orders surge. This analysis indicates that while the potential of taxi sharing positively correlates with an increase in taxi orders, it is negatively impacted by vehicular speed reduction during congestion. Therefore, ensuring a balanced increase in taxi orders to avoid reaching congestion thresholds is essential for optimizing the potential of taxi sharing. This highlights the vital role of strategic traffic and demand management in promoting the advancement of shared mobility solutions.

5.2. A spatial dimension analysis on the potential of taxi sharing

In the spatial dimension analysis, the study reveals significant insights into the variation of the potential of taxi sharing across different administrative districts and functional zones. As shown in Fig. 7, the administrative districts of Wuhou, Jinniu, Qingyang, Jinjiang and Chenghua, which constitute the core urban areas of Chengdu, dominate the taxi order landscape, collectively accounting for 97.42 % of total orders. These districts exhibit the potential of taxi sharing at approximately 30.75 %, showing a positive correlation between the volume of taxi orders and shareable orders. This relationship suggests that higher taxi orders within a district generally lead to an increased number of potential shareable orders, thereby elevating the district’s potential of taxi sharing. Furthermore, the study uncovers that an administrative district’s economic development level and population density significantly influence its potential of taxi sharing. For instance, Shuangliu and Longquanyi, with higher economic development, showcase sharing

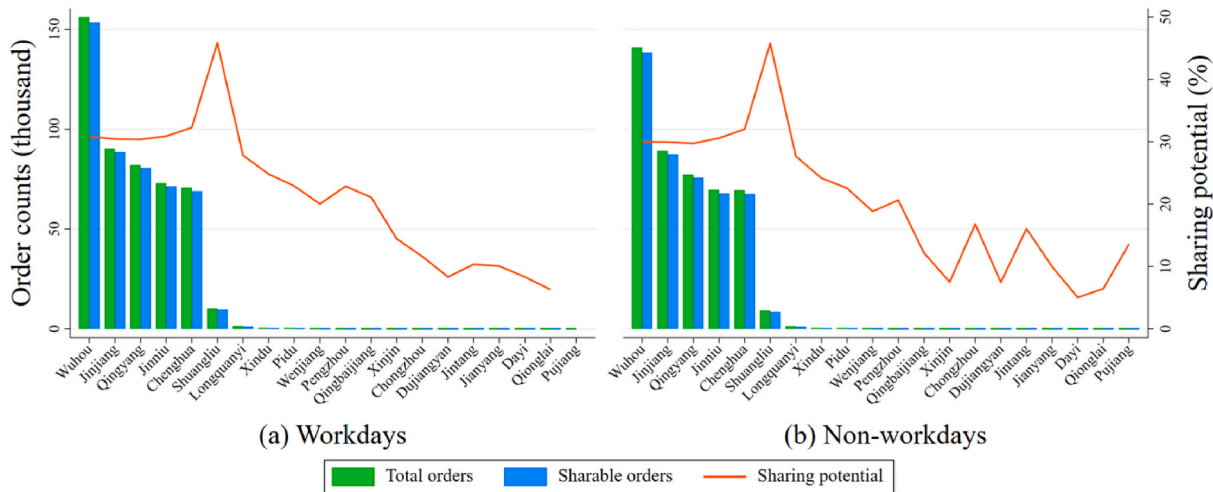


Fig. 7. The distributions of the numbers of taxi orders and the potential of taxi sharing in different administrative districts.

potentials markedly above the city average, while less developed districts such as Dujiangyan and Chongzhou display considerably lower potentials.

Shifting the focus to functional zones, the study reveals a consistent positive correlation between the total number of taxi orders and shareable orders, as illustrated in Fig. 8. Notably, taxi orders are predominantly concentrated in functional zones associated with Commercial House, Science, Culture, and Education Service, Finance and Insurance Service, Accommodation Service, and Governmental Organization and Social Group, collectively accounting for 85.34 % of total orders. In contrast, zones such as Motorcycle Service and Auto Repair exhibit minimal taxi orders. The potential of taxi sharing varies distinctly across these functional zones, with specific areas such as Enterprises, Transportation Service, and Tourist Attractions showcasing high potentials. Interestingly, the variation in the potential of taxi sharing between workdays and non-workdays is minimal across most zones, indicating a consistent demand for taxi sharing services regardless of the day of the week. However, exceptions exist, as demonstrated by the Motorcycle Service zones, which experience significant fluctuations in sharing potential between workdays and non-workdays.

### 5.3. A temporal dimension analysis on the potential of taxi sharing

The temporal dimension analysis of the potential of taxi sharing across administrative districts and functional zones in Chengdu reveals significant insights into the temporal and spatial dynamics of urban mobility. In the administrative districts of Wuhou, Jinniu, Qingyang, Jinjiang, and Chenghua, an overwhelming majority of taxi orders are found to be shareable, with little variation between workdays and non-workdays, as shown in Fig. 9. This high shareability underscores the constant demand for efficient transportation options within these densely populated areas. Notably, the potential of taxi sharing exhibits a pronounced peak during the morning rush hours on workdays, indicating a surge in commuting activity that temporarily enhances the feasibility of sharing rides. However, this potential sharply declines as traffic congestion worsens, underscoring the detrimental impact of heavy traffic on the efficiency of taxi sharing systems.

Furthermore, the analysis extends to five functional zones characterized by high volumes of taxi orders, including Commercial House zones, Science, Culture and Education Service zones, Finance and Insurance Service zones, Accommodation Service zones, and Governmental Organization and Social Group zones. Similar to the administrative districts, these zones show a high proportion of shareable orders, with negligible fluctuations between different days of the week, as shown in Fig. 10. The morning peak in the potential of taxi sharing is also evident in these zones, further highlighting the influence of commuting patterns on sharing opportunities. After this peak, the potential stabilizes, reflecting a balance between supply and demand for shared rides outside of peak commuting times.

### 5.4. The analysis of mileage reduction through taxi sharing

Taxi sharing has the potential to significantly reduce the total mileage of taxis in the city, averaging approximately 170,660.97 km per hour and 1.1 km per taxi trip. However, it is important to note that not all shareable orders will result in a reduction in total mileage. In fact, some may even lead to increased mileage. Statistics indicate that about 54.12 % of shareable orders could result in a decrease in total mileage after sharing.

The daily patterns of taxi order numbers and travel distances, considering different sharing scenarios (one resulting in reduced mileage and the other in increased mileage), reveal a notable disparity between workdays and non-workdays, as illustrated in Fig. 11.

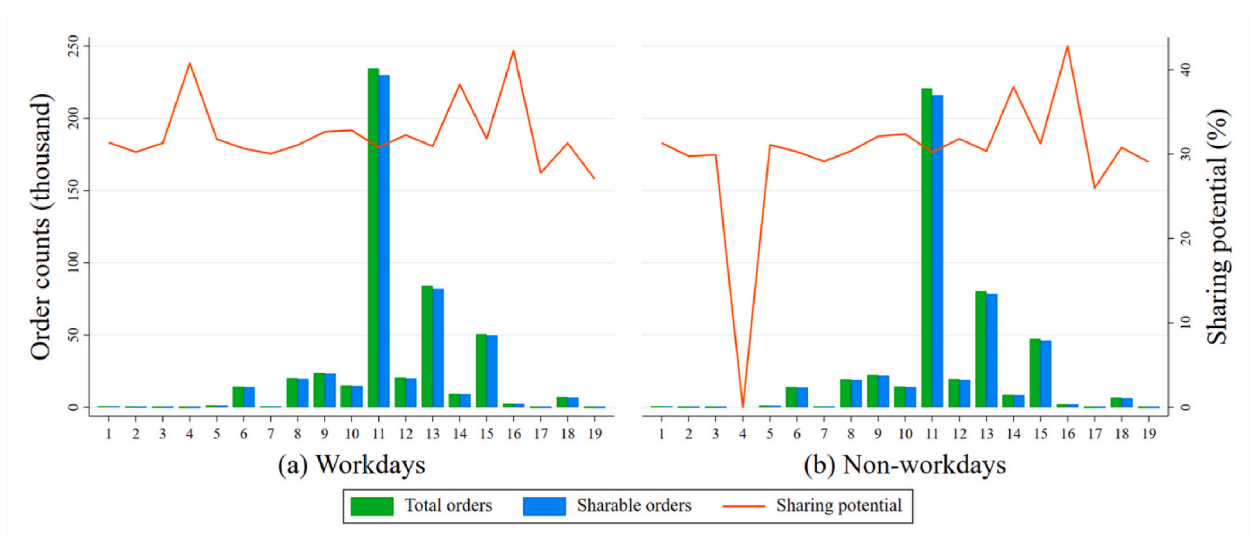
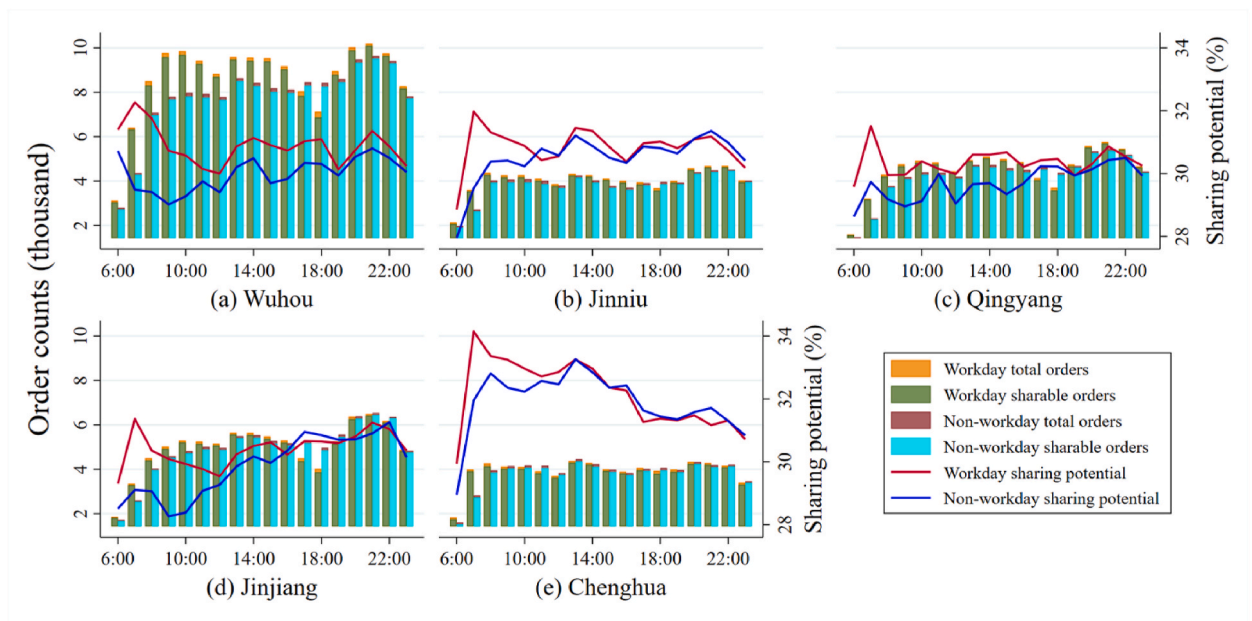
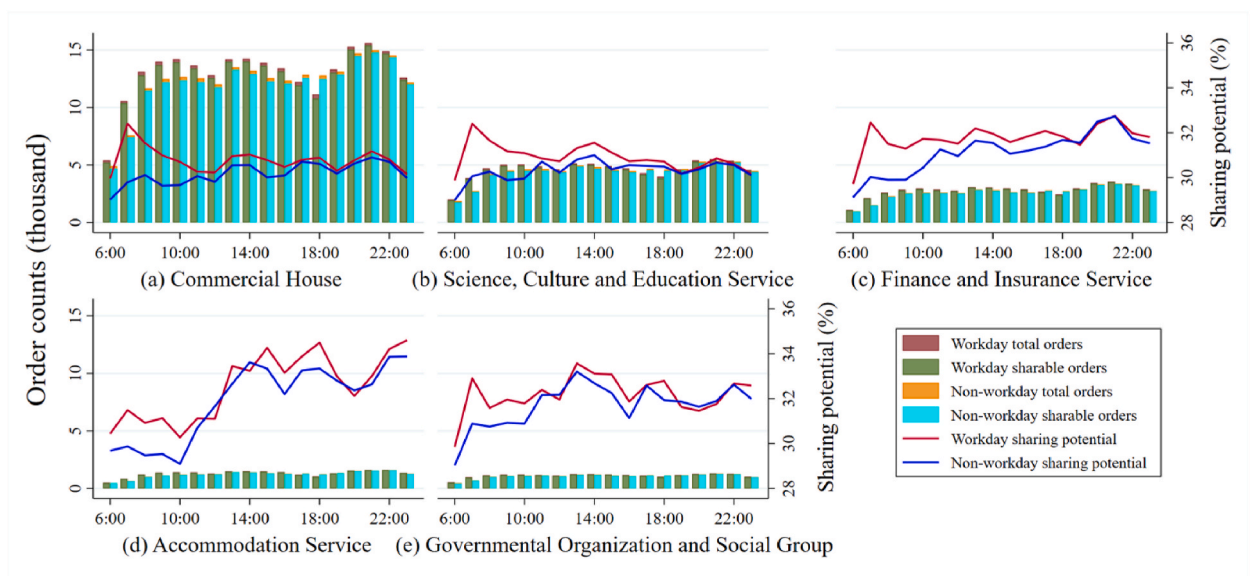


Fig. 8. The distributions of the numbers of taxi orders and the potential of taxi sharing in different functional zones.



**Fig. 9.** The daily changing patterns of the numbers of taxi orders and the potential of taxi sharing on workdays and non-workdays in the five administrative districts.



**Fig. 10.** The daily changing patterns of the numbers of taxi orders and the potential of taxi sharing on workdays and non-workdays in the five functional zones.

Specifically, between 7:00 and 19:00 on workdays, there is a significant prevalence of orders leading to a reduction in mileage compared to those causing an increase. After 19:00, the order trends for both workdays and non-workdays remain relatively consistent across the two sharing scenarios. However, after 21:00, it is observed that the number of orders leading to an increase in mileage might surpass those causing a decrease.

From Fig. 12, it is evident that the mileage change caused by taxi sharing in different time periods is relatively balanced across workdays and non-workdays, but there is a significant difference in the amount of mileage saved. On workdays, the saved mileage ranges from 15,000 km to 30,000 km in different time periods, while on non-workdays, the saved mileage mostly falls between 15,000 km and 25,000 km. Moreover, whether on workdays or non-workdays, except for the time period from 23:00 to 24:00, the mileage reduction caused by taxi sharing is much greater than the mileage increase.

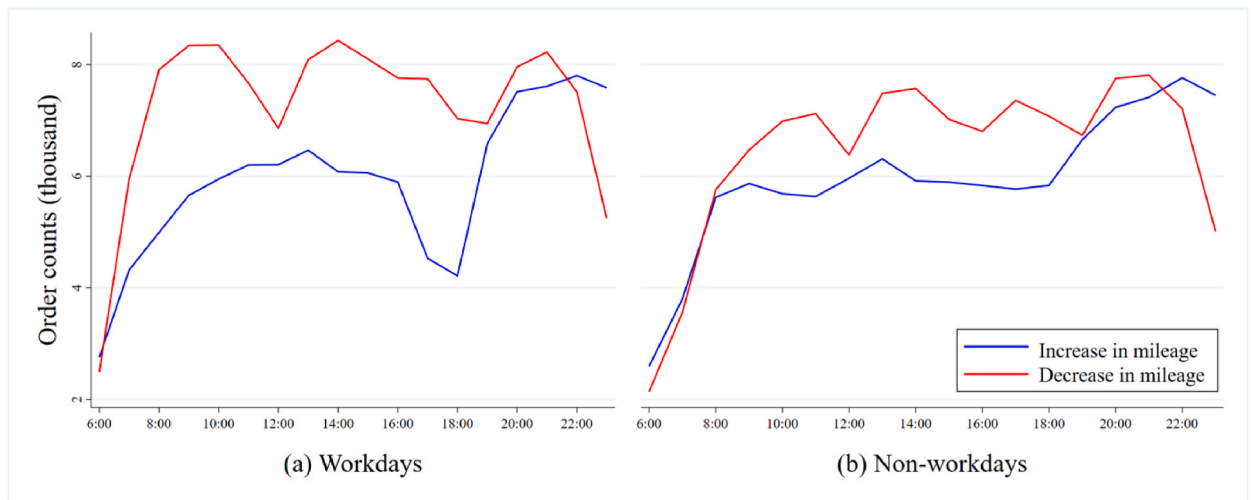


Fig. 11. The daily changing patterns of the numbers of taxi orders on workdays and non-workdays across different sharing scenarios.

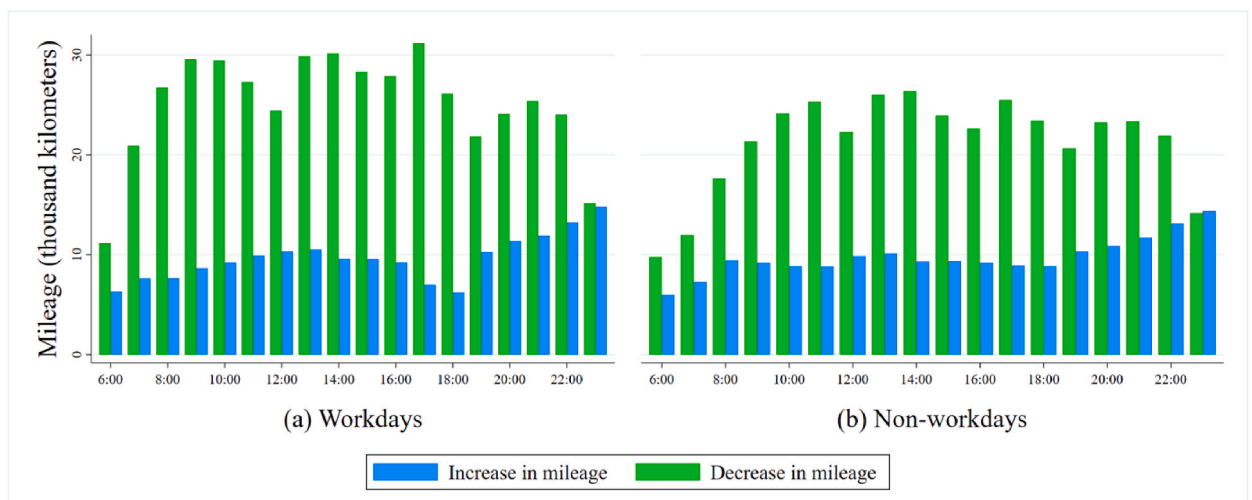


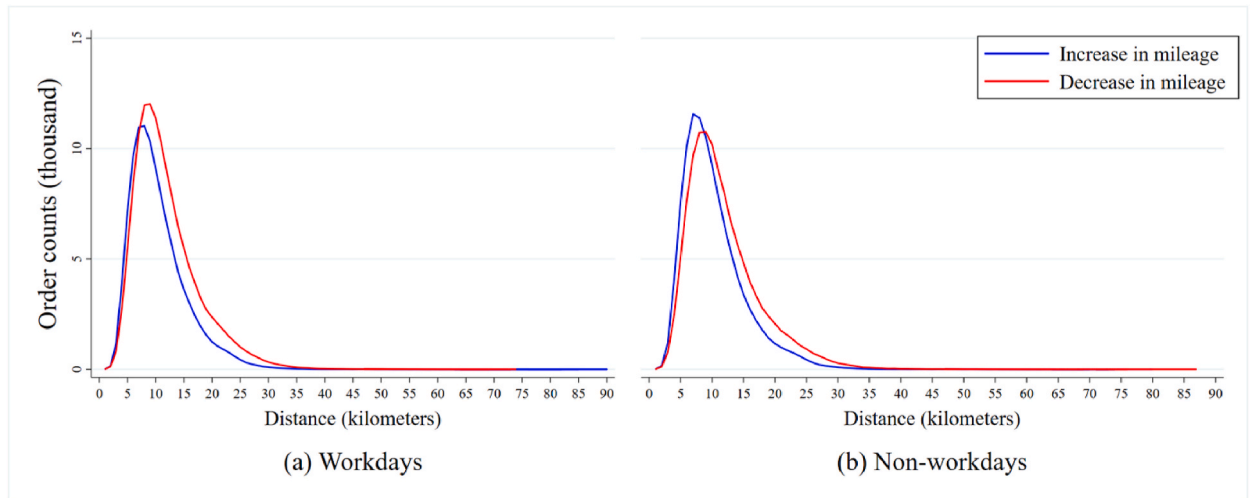
Fig. 12. The daily patterns of mileage change for taxi orders on workdays and non-workdays across different sharing scenarios.

Additionally, our study reveals no significant difference in the distribution of travel mileage changes for taxi orders across sharing scenarios, whether they resulted in increased or decreased mileage. Fig. 13 demonstrates that regardless of whether it is a workday or not, the modifications in mileage resulting from sharing primarily fall within the range of 5–20 km, suggesting that taxi sharing primarily impacts travel distances within this range. Furthermore, a comparison between workdays and non-workdays indicates that, on workdays, orders resulting in reduced mileage due to sharing generally cover greater distances compared to those resulting in an increase in mileage.

## 6. Discussion

This paper comprehensively studies the calculation model of the potential of taxi sharing, considering both the spatial and temporal distribution of taxi sharing demand to gain a thorough understanding of taxi sharing. Conducting a comprehensive analysis of the potential of taxi sharing provides valuable insights for enabling strategic planning and organizing of taxi sharing services. Moreover, our analysis reveals that taxi sharing significantly reduces the original distance to be travelled, resulting in overall traffic and environmental improvements. This study was conducted in Chengdu, and the spatial and temporal distribution characteristics of the potential of taxi sharing may be different in other regions. However, the research methodology we have proposed is applicable universally, and this model framework can be used to study similar issues in different geographical areas.

We used Chengdu as a research case mainly for the following two reasons. On the one hand, this article aims to present a calculation model for the potential of taxi sharing and to understand its changing patterns in both temporal and spatial dimensions. It has been



**Fig. 13.** The distribution of mileage change for taxi orders on workdays and non-workdays across different sharing scenarios.

demonstrated that Chengdu's shared market has enormous potential but has not been fully explored [53]. Hence, we chose Chengdu as our research subject and provide well-founded suggestions for the development of taxi sharing based on the research findings. This study holds significant importance for enabling government departments to regulate the taxi market accurately and to plan shared taxi operations according to local conditions. On the other hand, Chengdu holds a vital position in the development of transportation in China. As a comprehensive transportation hub city, Chengdu plays a crucial role in regional coordination and convenient transportation. There are ambitions to develop it into an international comprehensive transportation hub city. Therefore, many scholars tend to choose Chengdu as their research subject when studying issues related to urban transportation [32,54].

The choice to utilize data from traditional taxi services in August 2014 was strategically made, despite its limitations. This decision leveraged the superior availability and reliability of traditional taxi data compared to emerging ride-hailing platforms at the time of research, providing a comprehensive dataset for in-depth analysis. By focusing on this period, our research captures a crucial moment in China's urban mobility landscape—just before the rapid expansion of ride-hailing platforms like Didi and Uber—offering critical insights into passenger travel behaviors and the dynamics of taxi sharing during the platforms' nascent stage. Moreover, selecting August, a peak tourist season in Chengdu characterized by high passenger flow, allowed us to explore the full potential of taxi sharing and its role in addressing urban transport challenges during periods of high demand. This dual focus not only reflects the strategic considerations behind our data selection but also aligns with our goal to provide targeted insights and recommendations for enhancing shared mobility services. Consequently, our study contributes to the broader discourse on optimizing urban transport solutions amidst evolving mobility trends.

The purpose of this paper is to examine the potential demand for taxi sharing, which refers to the maximum proportion of taxis that could be shared if all parties were willing to participate. Recent statistics indicate that China's shared mobility market reached 201.2 billion RMB in transactions in 2022, with a growth rate 3.9% higher than the national economic growth rate [55]. Fluctuo found that shared mobility generated 3.1 billion euros in revenue in 2022 and has become increasingly popular on European streets [56]. These findings highlight that shared transportation has gradually become one of the primary modes of commuting for urban residents. It is reasonable to believe that a substantial portion of individuals would be open to sharing a taxi with fellow passengers. Moreover, relevant governmental bodies and platforms could implement incentivizing measures to further encourage people to engage in taxi sharing. This would contribute to realizing the maximum potential of taxi sharing and thereby advancing a sustainable urban transportation system.

### 6.1. Model comparison

Taxi sharing algorithms can be categorized into two main types. The first type relies on fixed collection points, where carpool passengers gather before being taken to another predetermined drop-off point nearby [4]. This differs from the model in our study, where taxis offer door-to-door service, prioritizing passenger convenience and aligning closely with practical taxi sharing. The second type focuses on logistical optimization through heuristic algorithms, aiming to reduce fleet size or minimize mileage [37,39]. While this involves picking up and dropping off multiple passengers along the route, neglecting the cumulative impact on travel time may reduce passenger comfort and satisfaction. Our model assumes each ride can only be shared once and sets a limit on additional travel time, aiming to enhance passenger satisfaction. This ensures comfort and makes taxi sharing more appealing for commuters by balancing efficiency and user experience. In conclusion, our algorithm represents a significant advancement in taxi sharing. By addressing the critical balance between operational efficiency and user satisfaction, it prioritizes convenience, reduces environmental impact, and ensures passenger comfort. This innovative approach sets a new standard for urban mobility solutions, offering more sustainable and passenger-friendly transportation options.

We now compare our findings with prior studies. Our research shows that the potential of taxi sharing is inversely correlated with average traffic speed, which is similar to some earlier research results [30,57]. On the contrary, regional economic development and population density may exert a considerable influence on the potential of taxi sharing across different administrative districts. This corresponds to previous findings [58]. Notably, functional zones like those for Transportation Services and Tourist Attractions exhibit high sharing potential, consistent with the conclusions of Cheng et al. [32]. They argue that bus stations, train stations, airports, and recreational areas positively impact demand.

## 6.2. Countermeasures

Currently, the domestic taxi sharing industry faces several challenges to its development. Exploring effective measures for boosting demand for taxi sharing could significantly contribute to the sustainable growth of the urban economy and transportation. Based on the results acquired in this study, a range of valuable insights can be derived.

It is evident that there is a notable difference between the percentage of shareable orders (97.77 %) and the percentage of shareable mileage (31.28 %). This is primarily due to the fact that approximately 45.88 % of shareable orders result in an increase in the total travel distance, leading to a smaller sharing portion and some inefficient sharing trips. To achieve the economic and environmental benefits of taxi sharing, government authorities should implement measures to promote shared trips that contribute to a reduction in total travel distance. This could include policies such as encouraging taxi sharing operations between 7:00 and 19:00 on workdays and discontinuing the service between 23:00 and 24:00 on both workdays and non-workdays. Furthermore, in central urban areas like Wuhou, Jinniu, and Qingyang, there is untapped potential demand for commuting via taxi sharing. Government authorities could further encourage travelers to utilize taxi sharing through increased education and awareness campaigns, fully capitalizing on the potential sharing market.

Taxi sharing enhances service availability in the transportation market, catering to diverse travel demands. This paper offers valuable information that can assist taxi sharing platforms in making informed decisions. Firstly, platforms should prioritize efficient passenger-to-taxi matching and route planning to establish standardized and orderly sharing strategies. This would minimize wait times for passengers and provide financial and time gains for drivers. Secondly, operating platforms should recognize the high potential demand for taxi sharing in specific functional areas. They should allocate vehicles accordingly. For instance, areas where there are enterprises, motorcycle services, and transportation services, with a high sharing potential, should be equipped with more vehicles and drivers. Finally, platforms could introduce dynamic pricing models to incentivize passengers during peak demand hours and in busy regions, such as 7:00–9:00 on workdays and 21:00–23:00 on non-workdays in Jinjiang.

Taxi drivers and the general public could also glean meaningful perspectives from our study. For drivers, strategically positioning themselves near busy transportation hubs, like bus stops or subway stations, during peak times of passenger flow, could greatly enhance the likelihood of picking up shared rides, due to the greater convenience and timeliness. Moreover, aligning work and rest schedules with the spatiotemporal patterns of the potential of taxi sharing could provide a competitive edge. For instance, drivers could proactively operate during peak hours from 7:00–9:00 and 13:00–15:00 on workdays, while scheduling breaks during periods of lower sharing potential, such as 6:00–7:00 and 12:00–13:00 on workdays. As for the public, it is essential to understand that participating in taxi sharing not only reduces travel expenses but also carries positive environmental implications, by ultimately shortening overall travel distances. This awareness could motivate passengers to actively engage in taxi sharing.

Through the implementation of these recommendations, governments, drivers, platforms, and the public could collectively optimize taxi sharing services. This collaborative effort would not only enhance economic efficiency but also contribute to a more sustainable and environmentally conscious urban transportation system. Ultimately, these measures would pave the way for a greener, more efficient, and socially responsible urban economy.

## 7. Conclusions

To gain insights into the potential demand for taxi sharing, we first proposed conditions for identifying shareable taxi orders based on the origin and destination, using GPS tracking data from taxis operating in Chengdu, Sichuan Province. Then, we presented a three-phase computational model to find the optimal match among all possible shareable orders that meet the defined sharing conditions. This model aims to calculate the potential shared mileage and the proportion of original mileage that could be shared. Furthermore, our analysis explored the temporal and spatial dynamics of taxi sharing demand, revealing its fluctuating patterns within an urban context.

Our findings indicate a significant potential for taxi sharing in Chengdu, albeit with an uneven distribution across different times and areas. Notably, the demand for taxi sharing is higher on workdays, with distinct peak periods, and is concentrated primarily within the urban core. The study also reveals a complex interplay between the potential of taxi sharing and factors such as traffic speed, order volume, economic development, and population density. Furthermore, we discovered that certain areas, specifically those related to business and transportation services, have a pronounced positive effect on the viability of taxi sharing.

Compared to the traditional taxi operating mode, we have confirmed that taxi sharing brings about a reduction in total travel mileage. In addition to reducing total travel mileage, taxi sharing could play a pivotal role in carbon emission reduction. By optimizing travel routes and minimizing unnecessary mileage, taxi sharing not only enhances transportation efficiency but also contributes significantly to urban sustainability efforts. The adoption of taxi sharing could serve as a key strategy in the broader context of reducing vehicular emissions, aligning with global objectives to combat climate change.

Though our study offers valuable insights, it also faces several limitations. These include the reliance on a heuristic matching



algorithm that may not always yield the optimal solution and the oversight of taxi sharing's impact on other transportation modes. Additionally, the use of data from 2014 may not fully reflect the recent shifts in urban mobility trends. Future research will refine the matching algorithm and explore the interplay between taxi sharing and alternative transportation, incorporating the latest data available. This effort aims to deepen our understanding of urban residents' potential demand for taxi sharing. Ultimately, we seek to provide actionable recommendations to government authorities for optimizing taxi services and promoting the sustainable development of urban transportation systems.

### Data availability statement

The data has not been deposited into a publicly accessible repository, but will be made available on request.

### CRediT authorship contribution statement

**Beibei Hu:** Writing – review & editing, Funding acquisition, Conceptualization. **Xufeng Li:** Visualization, Methodology, Data curation. **Zixun Li:** Investigation, Conceptualization. **Xianlei Dong:** Writing – original draft, Project administration, Methodology. **Huijun Sun:** Supervision, Conceptualization. **Minghe Sun:** Writing – review & editing. **Kexin Lin:** Software, Data curation. **Jie Xue:** Writing – original draft, Methodology, Formal analysis.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Acknowledgments

This work was partially supported by the National Social Science Fund of China (Grant No. 20BGL302).

### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.heliyon.2024.e29888>.

### References

- [1] Z. Peng, W. Shan, X. Zhu, B. Yu, Many-to-one stable matching for taxi sharing service with selfish players, *Transp. Res. Part A Policy Pract* 160 (2022) 255–279, <https://doi.org/10.1016/j.tra.2022.04.012>.
- [2] S. Ma, Y. Zheng, O. Wolfson, Real-time city-scale taxi ridesharing, *IEEE Trans. Knowl. Data Eng.* 27 (2015) 1782–1795, <https://doi.org/10.1109/TKDE.2014.2334313>.
- [3] Y. Wang, R. Kutadinata, S. Winter, The evolutionary interaction between taxi sharing behaviours and social networks, *Transp. Res. Part A Policy Pract* 119 (2019) 170–180, <https://doi.org/10.1016/j.tra.2018.10.043>.
- [4] P. Dieter, M. Stumpe, M.W. Ulmer, G. Schryen, Anticipatory assignment of passengers to meeting points for taxi-ridesharing, *Transp Res D Transp Environ* 121 (2023) 103832, <https://doi.org/10.1016/j.trd.2023.103832>.
- [5] P.M. d'Orey, R. Fernandes, M. Ferreira, Empirical evaluation of a dynamic and distributed taxi sharing system, in: 2012 15th International IEEE Conference on Intelligent Transportation Systems, IEEE, 2012, pp. 140–146, <https://doi.org/10.1109/ITSC.2012.6338703>.
- [6] K.M. Gurumurthy, K.M. Kockelman, Dynamic ride-sharing impacts of greater trip demand and aggregation at stops in shared autonomous vehicle systems, *Transp. Res. Part A Policy Pract* 160 (2022) 114–125, <https://doi.org/10.1016/j.tra.2022.03.032>.
- [7] B. Barann, D. Beverungen, O. Müller, An open-data approach for quantifying the potential of taxi ridesharing, *Decis. Support Syst.* 99 (2017) 86–95, <https://doi.org/10.1016/j.dss.2017.05.008>.
- [8] Y. Wang, B. Zheng, E.-P. Lim, Understanding the Effects of Taxi Ride-Sharing — A Case Study of Singapore, vol. 69, *Comput Environ Urban Syst*, 2018, pp. 124–132, <https://doi.org/10.1016/j.compenvurbsys.2018.01.006>.
- [9] J. Choi, Y. Kim, M. Kwak, M. Park, D. Lee, Measuring taxi ridesharing effects and its spatiotemporal pattern in Seoul, Korea, *Travel Behav Soc.* 30 (2023) 148–162, <https://doi.org/10.1016/j.tbs.2022.09.001>.
- [10] M.M. Vazifeh, P. Santi, G. Resta, S.H. Strogatz, C. Ratti, Addressing the minimum fleet problem in on-demand urban mobility, *Nature* 557 (2018) 534–538, <https://doi.org/10.1038/s41586-018-0095-1>.
- [11] Hideki Kitami. Ride-share taxis get green light to meet demand during Olympics. <https://www.asahi.com/ajw/articles/13067117>. Accessed October 31, 2023.
- [12] Bandwagon. And we're equally proud of our flagship NYC Taxishare Hubs. <http://www.bandwagon.io/about-1>. Accessed October 31, 2023.
- [13] J.-W. Hu, F. Creutzig, A systematic review on shared mobility in China, *Int J Sustain Transp* 16 (2022) 374–389, <https://doi.org/10.1080/15568318.2021.1879974>.
- [14] A. Witt, N. Suzor, P. Wikström, Regulating ride-sharing in the peer economy, *Commun. Res. Pract.* 1 (2015) 174–190, <https://doi.org/10.1080/22041451.2015.1048041>.
- [15] J.-F. Cordeau, G. Laporte, The dial-a-ride problem: models and algorithms, *Ann. Oper. Res.* 153 (2007) 29–46, <https://doi.org/10.1007/s10479-007-0170-8>.
- [16] H. Hosni, J. Naoum-Sawaya, H. Artail, The shared-taxi problem: formulation and solution methods, *Transp. Res. Part B Methodol.* 70 (2014) 303–318, <https://doi.org/10.1016/j.trb.2014.09.011>.
- [17] Y. Wang, M. Li, Optimization algorithm design for the taxi sharing problem and application, *Math. Probl Eng.* 2021 (2021) 1–10, <https://doi.org/10.1155/2021/5572200>.
- [18] Y. Wang, Y. Zhang, Y. Zhang, J. Ma, Dynamic real-time high-capacity ride-sharing model with subsequent information, *IET Intell. Transp. Syst.* 14 (2020) 742–752, <https://doi.org/10.1049/iet-its.2019.0641>.

- [19] P. Santi, G. Resta, M. Szell, S. Sobolevsky, S.H. Strogatz, C. Ratti, Quantifying the benefits of vehicle pooling with shareability networks, *Proc. Natl. Acad. Sci. USA* 111 (2014) 13290–13294, <https://doi.org/10.1073/pnas.1403657111>.
- [20] X. Dong, Y. Wang, X. Li, Z. Zhong, X. Shen, H. Sun, B. Hu, Understanding the influencing factors of taxi ride-sharing: a case study of Chengdu, China, *Transp. Res. Part A Policy Pract* 176 (2023) 103819, <https://doi.org/10.1016/j.tra.2023.103819>.
- [21] P. Delhomme, A. Gheorghiu, Comparing French carpoolers and non-carpoolers: which factors contribute the most to carpooling? *Transp Res D Transp Environ.* 42 (2016) 1–15, <https://doi.org/10.1016/j.trd.2015.10.014>.
- [22] A. Misra, M. Shirgaokar, A. Weinstein Agrawal, B. Dobbs, M. Wachs, How older adults use Ride-hailing booking technology in California, *Transp. Res. Part A Policy Pract* 155 (2022) 11–30, <https://doi.org/10.1016/j.tra.2021.10.022>.
- [23] S.A. Shaheen, N.D. Chan, T. Gaynor, Casual carpooling in the San Francisco Bay Area: understanding user characteristics, behaviors, and motivations, *Transport Pol.* 51 (2016) 165–173, <https://doi.org/10.1016/j.tranpol.2016.01.003>.
- [24] Á. Aguilera-García, J. Gomez, G. Velázquez, J.M. Vassallo, Ridesourcing vs. traditional taxi services: understanding users' choices and preferences in Spain, *Transp. Res. Part A Policy Pract* 155 (2022) 161–178, <https://doi.org/10.1016/j.tra.2021.11.002>.
- [25] R.N. Buliung, K. Soltys, R. Bui, C. Habel, R. Lanyon, Catching a ride on the information super-highway: toward an understanding of internet-based carpool formation and use, *Transportation* 37 (2010) 849–873, <https://doi.org/10.1007/s11116-010-9266-0>.
- [26] A. Manjunath, V. Raychoudhury, S. Saha, S. Kar, A. Kamath, CARE-Share: a cooperative and adaptive strategy for distributed taxi ride sharing, *IEEE Trans. Intell. Transport. Syst.* 23 (2022) 7028–7044, <https://doi.org/10.1109/TITS.2021.3066439>.
- [27] R. Cervero, B. Griesenbeck, Factors influencing commuting choices in suburban labor markets: a case analysis of Pleasanton, California, *Transport. Res. Gen.* 22 (1988) 151–161, [https://doi.org/10.1016/0191-2607\(88\)90033-7](https://doi.org/10.1016/0191-2607(88)90033-7).
- [28] K.N. Habib, Mode choice modelling for hailable rides: an investigation of the competition of Uber with other modes by using an integrated non-compensatory choice model with probabilistic choice set formation, *Transp. Res. Part A Policy Pract* 129 (2019) 205–216, <https://doi.org/10.1016/j.tra.2019.08.014>.
- [29] T. Yoon, C.R. Cherry, L.R. Jones, One-way and round-trip carsharing: a stated preference experiment in Beijing, *Transp Res D Transp Environ* 53 (2017) 102–114, <https://doi.org/10.1016/j.trd.2017.04.009>.
- [30] D. Yao, S. He, Z. Wang, A new ride-sharing model incorporating the passengers' efforts, *Nav. Res. Logist.* 68 (2021) 397–411, <https://doi.org/10.1002/nav.21965>.
- [31] T. Vanoutrive, E. Van De Vijver, L. Van Malderen, B. Jourquin, I. Thomas, A. Verhetsel, F. Witlox, What determines carpooling to workplaces in Belgium: location, organisation, or promotion? *J. Transport Geogr.* 22 (2012) 77–86, <https://doi.org/10.1016/j.jtrangeo.2011.11.006>.
- [32] Y. Cheng, X. Chen, X. Ding, L. Zeng, Optimizing location of car-sharing stations based on potential travel demand and present operation characteristics: the case of Chengdu, *J. Adv. Transport.* 2019 (2019) 1–13, <https://doi.org/10.1155/2019/7546303>.
- [33] O.B.G. Madsen, H.F. Ravn, J.M. Rygaard, A heuristic algorithm for a dial-a-ride problem with time windows, multiple capacities, and multiple objectives, *Ann. Oper. Res.* 60 (1995) 193–208, <https://doi.org/10.1007/BF02031946>.
- [34] M. Stiglic, N. Agatz, M. Savelsbergh, M. Gradisar, Enhancing urban mobility: integrating ride-sharing and public transit, *Comput. Oper. Res.* 90 (2018) 12–21, <https://doi.org/10.1016/j.cor.2017.08.016>.
- [35] Z. Liu, T. Miwa, W. Zeng, M.G.H. Bell, T. Morikawa, Dynamic shared autonomous taxi system considering on-time arrival reliability, *Transport. Res. C Emerg. Technol.* 103 (2019) 281–297, <https://doi.org/10.1016/j.trc.2019.04.018>.
- [36] J. Jung, R. Jayakrishnan, J.Y. Park, Dynamic shared-taxi dispatch algorithm with hybrid-simulated annealing, *Comput. Aided Civ. Infrastruct. Eng.* 31 (2016) 275–291, <https://doi.org/10.1111/micc.12157>.
- [37] J. Monteil Simonetto, C. Gambella, Real-time city-scale ridesharing via linear assignment problems, *Transp Res Part C Emerg. Technol.* 101 (2019) 208–232, <https://doi.org/10.1016/j.trc.2019.01.019>.
- [38] Z. Liu, Z. Gong, J. Li, K. Wu, mT-Share: a mobility-aware dynamic taxi ridesharing system, *IEEE Internet Things J.* 9 (2022) 182–198, <https://doi.org/10.1109/JIOT.2021.3102638>.
- [39] M. Zhu, X.-Y. Liu, X. Wang, An online ride-sharing path-planning strategy for public vehicle systems, *IEEE Trans. Intell. Transport. Syst.* 20 (2019) 616–627, <https://doi.org/10.1109/TITS.2018.2821003>.
- [40] C.-Y. Chen, S. Yan, Y.-S. Wu, A model for taxi pooling with stochastic vehicle travel times, *Int J Sustain Transp* 13 (2019) 582–596, <https://doi.org/10.1080/15568318.2018.1490468>.
- [41] S. Nguyen Van, N. Vu Thi Hong, D. Pham Quang, H. Nguyen Xuan, B. Babaki, A. Dries, Novel online routing algorithms for smart people-parcel taxi sharing services, *ETRI J.* 44 (2022) 220–231, <https://doi.org/10.4218/etrij.2021-0406>.
- [42] Geocoding/Reverse Geocoding. <https://lbs.amap.com/api/webservice/guide/api/georegeo>. Accessed October 31, 2023.
- [43] POI classification coding. <https://lbs.amap.com/api/webservice/download>. Accessed October 31, 2023.
- [44] D. Zhang, J. Wan, Z. He, S. Zhao, K. Fan, S.O. Park, Z. Jiang, Identifying region-wide functions using urban taxicab trajectories, *ACM Trans. Embed. Comput. Syst.* 15 (2016) 1–19, <https://doi.org/10.1145/2821507>.
- [45] Y. Yao, X. Li, X. Liu, P. Liu, Z. Liang, J. Zhang, K. Mai, Sensing spatial distribution of urban land use by integrating points-of-interest and Google Word2Vec model, *Int. J. Geogr. Inf. Sci.* 31 (2017) 825–848, <https://doi.org/10.1080/13658816.2016.1244608>.
- [46] B. Liu, Y. Deng, M. Li, J. Yang, T. Liu, Classification schemes and identification methods for urban functional zone: a review of recent papers, *Appl. Sci.* 11 (2021) 9968, <https://doi.org/10.3390/app11219968>.
- [47] G. Li, C. Fang, B. Pang, Quantitative measuring and influencing mechanism of urban and rural land intensive use in China, *J. Geogr. Sci.* 24 (2014) 858–874, <https://doi.org/10.1007/s11442-014-1125-z>.
- [48] X. Huang, J. Yang, J. Li, D. Wen, Urban functional zone mapping by integrating high spatial resolution nighttime light and daytime multi-view imagery, *ISPRS J. Photogrammetry Remote Sens.* 175 (2021) 403–415, <https://doi.org/10.1016/j.isprsjprs.2021.03.019>.
- [49] R. Tachet, O. Sagarra, P. Santi, G. Resta, M. Szell, S.H. Strogatz, C. Ratti, Scaling law of urban ride sharing, *Sci. Rep.* 7 (2017) 42868, <https://doi.org/10.1038/srep42868>.
- [50] Cui, F. Liu, D. Janssens, S. An, G. Wets, M. Cools, Detecting urban road network accessibility problems using taxi GPS data, *J. Transport Geogr.* 51 (2016) 147–157, <https://doi.org/10.1016/j.jtrangeo.2015.12.007>.
- [51] N. Agatz, A.L. Erera, M.W.P. Savelsbergh, X. Wang, Dynamic ride-sharing: a simulation study in Metro Atlanta, *Procedia Soc. Behav. Sci.* 17 (2011) 532–550, <https://doi.org/10.1016/j.sbspro.2011.04.530>.
- [52] Y. Lin, W. Li, F. Qiu, H. Xu, Research on optimization of vehicle routing problem for ride-sharing taxi, *Procedia Soc. Behav. Sci.* 43 (2012) 494–502, <https://doi.org/10.1016/j.sbspro.2012.04.122>.
- [53] The 14th Five-Year Plan for Transportation and Logistics in Chengdu. [http://jtys.chengdu.gov.cn/cdjtys/c148589/2022-06/30/content\\_18d1dc94eb324f42be42eccc2fff72ef.shtml](http://jtys.chengdu.gov.cn/cdjtys/c148589/2022-06/30/content_18d1dc94eb324f42be42eccc2fff72ef.shtml). Accessed October 31, 2023.
- [54] X. Liu, Y. Tian, X. Zhang, Z. Wan, Identification of Urban Functional Regions in Chengdu Based on Taxi Trajectory Time Series Data, vol. 9, *ISPRS Int J Geoinf.* 2020, p. 158, <https://doi.org/10.3390/ijgi9030158>.
- [55] 2022, The Sharing Economy White Paper: China's Shared Mobility Development Report, 2023, <https://baijiaohao.baidu.com/s?id=1764383429683161538&wfr=spider&for=pc>. (Accessed 31 October 2023).
- [56] European Shared Mobility Index. <https://european-index.fluctuo.com/>. Accessed October 31, 2023.
- [57] A. Tirachini, Ride-hailing, travel behaviour and sustainable mobility: an international review, *Transportation* 47 (2020) 2011–2047, <https://doi.org/10.1007/s11116-019-10070-2>.
- [58] F. Alemi, G. Circella, S. Handy, P. Mokhtarian, What influences travelers to use Uber? Exploring the factors affecting the adoption of on-demand ride services in California, *Travel Behav Soc* 13 (2018) 88–104, <https://doi.org/10.1016/j.tbs.2018.06.002>.