Journal of Transport Geography 117 (2024) 103897

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Carsharing in China: Impact of system and urban factors on usage and efficiency

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ARTICLE INFO

Keywords:
Carsharing
Vehicle utilization rate
System characteristics
Urban factors

ABSTRACT

The carsharing service has experienced significant growth over the past few years in China, yet few studies have scrutinized the multi-city variations of this service. Using carsharing data from 61 cities in China, we analyzed the usage and efficiency of each city and investigated the impact of system and urban factors on the service performance. The study reveals vast differences in carsharing supply and demand across Chinese cities. Our results show the parking station density and the parking lot to vehicle ratio of the carsharing system are positively related to the usage. Urban factors such as public transportation availability, educational attainment levels, and vehicle restriction policies, are found to have significantly positive associations with the carsharing usage. However, no urban factors demonstrate significant associations with the efficiency measured by vehicle utilization rate. Moreover, the presence of other competing carsharing services within a city exhibits a positive impact on the performance of carsharing systems. This study also examined nonlinear effects of the factors. It provides valuable insights into the management of carsharing services in China, which can inform policy-making and operational strategies for sustainable development of carsharing.

1. Introduction

The growing number of private cars in cities has exacerbated the energy crisis, contributed to environmental degradation, and worsened traffic congestion (Shaheen and Cohen, 2007). As a potential solution, carsharing has emerged as a sustainable transportation strategy for city governments to promote environmental sustainability. Carsharing service enables individuals to access vehicles without the associated costs and responsibilities of ownership, providing greater flexibility in long-distance travel, billing options, and rental locations (Jorge and Correia, 2013). Previous studies point out that carsharing can help to address the increasing demand for personal transportation, promoting vehicle utilization (Litman, 2000), and reducing vehicle miles traveled (Lane, 2005) and greenhouse gas emissions (Martin and Shaheen, 2011b). Moreover, the use of electric vehicles in carsharing can reduce fuel consumption and operating costs, further enhancing the environmental advantages of carsharing services (Baptista et al., 2014). These benefits provide a compelling argument for carsharing and may encourage more cities to adopt them as a sustainable transportation option.

Carsharing has experienced significant growth in Chinese cities, coinciding with the rapid development of electric vehicles in China since its introduction in 2010. This growth can be attributed to several factors, including policies limiting private car ownership and usage in response to rapid motorization and heavy traffic congestion. Carsharing offers an option for non-car owners to travel by car, particularly in areas with inadequate public transportation. As of 2019, the carsharing service covers more than eighty cities in China, with more than three million monthly active users on the platform (Song, 2019; Aurora Mobile, 2020; Foresight Industry Research Institute, 2020; Yin et al., 2020). However, it is noteworthy that despite the rapid expansion of carsharing, its success may vary among cities. Different development stages and policy agendas have led to varying degrees of carsharing adoption in China, and the performance of carsharing systems across different cities has yet to be systematically evaluated. Hence, it is needed to investigate the factors influencing the usage and efficiency of carsharing systems in different cities in China.

The widespread adoption of carsharing across cities has prompted

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https://doi.org/10.1016/j.jtrangeo.2024.103897
Received 12 September 2023; Received in revised form 6 May 2024; Accepted 7 May 2024
Available online 11 May 2024

researchers to investigate associated challenges. However, the success of carsharing has been inconsistent due to the potential variability in demand across districts, cities, and countries (Goddeke et al., 2021; Munzel et al., 2019). Previous studies have primarily focused on evaluating factors that influence carsharing in a single city (De Lorimier and El-Geneidy, 2013; Sioui et al., 2013), with limited attention given to multiple-city comparison, potentially constrained by data availability. Generalizing findings from a single city study to other cities may not be appropriate due to variations in urban forms and socio-demographic characteristics. For instance, an early study found significant differences in carsharing supply across cities and countries in Western Europe (Munzel et al., 2019). Moreover, companies previously lacked effective tools for decision-making involving service expansion to new areas or cities. Understanding the differences in usage and efficiency of carsharing systems among cities and urban factors that drive these differences is critical in making strategic decisions on service expansion and configuration in the long run.

Previous studies have identified the country context as an important factor influencing differences in carsharing across countries, as reflected in market history, operators, and policies (Munzel et al., 2019; Shaheen et al., 2019; Tuominen et al., 2019). Additionally, city-level factors such as built environmental attitudes (Costain et al., 2012), education levels (Juschten et al., 2019; Zhou and Kockelman, 2011), urban transit, and city types (Goddeke et al., 2021) have been found to have a potential relationship with carsharing supply and demand. Most related studies to date have focused on market research, and there is a lack of quantitative comparisons on factors that influence carsharing usage across cities, especially in China, which limits the generalizability of findings across different contexts. Therefore, there is a need for further research to investigate the influence of urban characteristics on carsharing demand and adoption across different cities and regions in China.

Despite the growing popularity of carsharing in China, few studies have summarized the carsharing developments in China and investigated the city characteristics that influence carsharing trip numbers across multiple cities. Analyzing city characteristics that are closely related to carsharing use can help carsharing companies to rationalize their operational strategies. It is critical to understand the differences in carsharing usage among Chinese cities, as the context and development of carsharing in China differ significantly from those of Western countries.

To address the gaps, this study investigates the influence of system and urban characteristics on carsharing in multiple Chinese cities. It collects carsharing data from one leading carsharing operator in China and analyzes carsharing usage and efficiency in 61 Chinese cities. To the best of our knowledge, this study is the first to provide a comprehensive analysis of carsharing supply and demand across multiple Chinese cities. The study further employs regression analysis to examine the linear and non-linear relationship between city-level characteristics of carsharing trips and shared vehicle efficiency. By analyzing these results, this study sheds light on the key factors that influence carsharing adoption in China, which can inform policy-making as well as operational strategies for carsharing companies.

2. Literature review

The utilization of carsharing services may be influenced by a multitude of factors, including system features, social culture, transportation characteristics, and individual preferences. To analyze the factors related to mobility on demand, Shaheen et al. (2017) utilized five dimensions, namely spatial, temporal, economic, physiological, and social. Furthermore, Munzel et al. (2019) drew on theories from transportation studies, urban geography, and innovation studies to develop multiple factors for carsharing demand. As synthesized by previous research, these factors can be broadly categorized into four groups: urban form and design, socio-demographic factors, innovation adoption, and urban transit features. It is important to note that the effects of these factors on carsharing demand may vary across different scales of study units, such as city and neighborhood levels. The forthcoming subsection will present a summary of previous research and findings concerning the aforementioned factors.

2.1. Urban socio-demographic factors

The adoption and utilization of carsharing services may vary significantly across different cities, as a result of various social and economic demographic factors. These factors can greatly impact the demand for and availability of shared mobility services in urban areas (Martin and Shaheen, 2016). Several studies have demonstrated that carsharing tends to be more prevalent in urban areas that are densely populated and highly mixed-use, as these factors provide a larger potential customer base for carsharing services (Becker et al., 2017a; Stillwater et al., 2009). Researchers have noted a strong correlation between low-density urban areas and high levels of car dependence, as well as between high-density urban areas and low levels of car dependence, since the 1990s (Newman and Kenworthy, 1989, 1999). Centrally located urban areas with high population densities offer a range of travel options, such as walking, cycling, and public transport, which are particularly attractive to active individuals. The trend towards sustainable travel preferences will impact demand, markets, and policies for sustainable transport, including carsharing, which will expand the availability of these resources.

Carsharing demand may also be influenced by various socio-demographic factors, such as gender, age, education, household size, and private car usage (Millard-Ball et al., 2005; Prieto et al., 2017). These factors are particularly relevant to carsharing as they can greatly impact an individual's mobility patterns and travel habits (Prieto et al., 2017). Previous research has suggested that men are more likely to use carsharing services, potentially due to differences in the perceived attractiveness of mobile technology platforms (Alonso-Almeida, 2019; Nansubuga and Kowalkowski, 2021). The relationship between income and carsharing use is more complex. While some studies have indicated that carsharing users are predominately students and from low-income households (Correia and Viegas, 2011a; Shaheen et al., 2004), other research has suggested that moderate or upper-income groups are more likely to use carsharing (Goddeke et al., 2021; Le Vine et al., 2014). In addition, studies have found that carsharing is more prevalent among single-person or small households without children, while larger households are associated with lower rates of carsharing use (Kortum et al., 2016; Le Vine et al., 2014; Schmoller et al., 2015). By considering the various socio-demographic factors that impact carsharing use, policymakers and practitioners can develop more effective strategies to promote and expand the availability of shared mobility services.

2.2. Urban transit features

The impact of public transportation proximity on carsharing demand is controversial. Some research has found that cities with robust public transportation systems show decreased demand for shared vehicles (Munzel et al., 2019). However, there are potential synergies between public transportation and carsharing (Tyndall, 2019). Shaheen et al. (2004) noted that carsharing could potentially improve transit infrastructures by creating a new transportation option for routes with limited public transit. De Luca and Di Pace (2015) found that interurban carsharing services could be a substitute for car transportation and a complementary option to public transport. Several studies have also shown that the relationship between public transit and carsharing is heterogeneous across different users, carsharing programs, and cities (Martin and Shaheen, 2011a, 2016). The proportion of private car trips in commuting patterns also significantly impacts carsharing usage. A higher percentage of private cars and the number of cars per household negatively influence the willingness to use shared vehicles (Heilig et al., 2018; Stillwater et al., 2009). In comparison, the mode share of public transit and pedestrians shows a positive relationship with carsharing demand (Celsor and Millard-Ball, 2007; Hu et al., 2018a).

2.3. Innovation acceptance

Early adopters of new technology or innovation are typically young or middle-aged individuals, particularly students, who possess higher levels of education (Burkhardt and Millard-Ball, 2006; Efthymiou et al., 2013; Prieto et al., 2017). In developed countries such as those in Europe and North America, studies have shown that carsharing is primarily used by individuals with higher levels of education (Boldrini et al., 2019; Coll et al., 2014; Munzel et al., 2019; Nansubuga and Kowalkowski, 2021). However, in developing economies, highly educated individuals may be more likely to own a car rather than rent one (Chun et al., 2019). University students, in particular, are considered more open to alternative transportation services, including carsharing, than the general public (Konstantinos et al., 2013). The prevalence of young carsharing customers can be attributed to their familiarity with new devices, particularly smartphones, and their willingness to try innovative technologies (Burlando et al., 2019; Guglielmetti Mugion et al., 2019). Interestingly, participation in other shared trips may also impact carsharing, as individuals who have already utilized other shared mobility models may be more likely to try carsharing, a phenomenon known as the spillover effect among innovations (Munzel et al., 2019; Jaffe et al., 2000).

2.4. Policy influence

The role of urban planning policies and practices in promoting sharing mobility is crucial. Effective planning policies can help to create an environment that is conducive to the growth and success of carsharing services and can help to overcome potential barriers to adoption (Vanheusden et al., 2022).

City and national governance factors, such as parking policies, congestion charging, or taxation of carsharing services, can affect the proliferation of carsharing solutions in urban (Correia and Viegas, 2011b; Akyelken et al., 2018). Policies at the city level such as the creation of low-emission zones, increased cooperation with public transport, public awareness campaigns, and urban parking fees can influence the proliferation of shared mobility. At the national level, travel-related benefits, which directly or indirectly influence the diffusion of carsharing, such as restrictions on private car travel, climate change targets, and environmental awareness, among others (Vanheusden et al., 2022).

In China, the increasing urbanization and demand for mobility have led to a supportive stance by the national government towards the development of carsharing services. The promotion of new energy carsharing aims to mitigate environmental pollution and traffic congestion by reducing vehicle ownership and delays in car purchases (Liao and Correia, 2020; Migliore et al., 2020; Mounce and Nelson, 2019; Martin et al., 2010). Since 2017, more than 30 provinces and cities in China have issued policies that support new energy carsharing operations or vehicle purchases (Ministry of Finance of the People's Republic of China, 2016).

Another important policy to promote the development of carsharing services is the implementation of restrictions on private car travel and ownership. Several cities in China have already adopted such policies, using auctions, lotteries, regional traffic restrictions, and quota allocations to limit the purchase and use of private vehicles. Additionally, many cities have imposed restrictions on local and non-local license plates while encouraging the use of new energy vehicles and shared vehicles (Ministry of Finance of the People's Republic of China, 2016). These policies are driving the growth of the carsharing market to some extent. In our study, we have used the implementation of license plate restrictions in a city as a proxy indicator for potential policy impact.

3. Research context and design

3.1. The background and related research of carsharing system in China

Since carsharing service emerged in China in 2010, it experienced significant and rapid growth. CC Clubs, the first carsharing company in China, was established in 2010 and experienced slow growth in its early years, with a fleet size of less than 1000 in 2013. In 2013, hundreds of companies began entering the carsharing business, including notable players such as Microbus, EVCARD, and GoFun. In 2017, the development of carsharing in China underwent a dramatic transformation, with the emergence of market grading and the gradual withdrawal of unprofitable companies from the market, the carsharing market is beginning to exhibit a steady growth trend.

According to a report released by the China Academy of Transportation Sciences, as of February 2019, the number of registered carsharing enterprises in China had exceeded 1600, with over 100 companies actively operating in the market, indicating a highly competitive environment (Yin et al., 2020). Over the years, and influenced by the pandemic, the shared car industry in 2020 witnessed significant differentiation. Some smaller or poorly managed enterprises gradually exited the market, while stronger companies such as GoFun, Laindongyun, Mofan Mobility, etc., continued to thrive and expand their operations (China Environmental Protection Foundation et al., 2021). In terms of regional distribution, South China, Southwest China and East China are the core regions for carsharing development, with active users accounting for 75.5% of the total (Foresight Industry Research Institute, 2020). Carsharing companies also adopt different expansion strategies in China. For example, GoFun mainly operates in the Pearl River Delta, Sichuan, and Chongqing regions, while EVCARD leads in the Yangtze River Delta.

The total monthly active users (MAUs) of carsharing platforms in China have exhibited a consistent upward trend. By December 2019, the total MAUs of carsharing services reached 3.476 million in China, reflecting a 38.6% increase from the beginning of 2019 (Foresight Industry Research Institute, 2020). Notably, the two largest carsharing platforms, GoFun and EVCARD, reported having one million MAUs each. In terms of regional distribution, the core regions for carsharing development are South China, Southwest China, and East China, accounting for 75.5% of the total carsharing users (Foresight Industry Research Institute, 2020). However, the outbreak of COVID-19 had a significant impact on the mobility industry, leading to a decrease in MAUs to 2.581 million in Feb 2020 (Foresight Industry Research Institute, 2020). As the situation improved, the MAUs gradually recovered to 3.68 million in April 2020 (Aurora Mobile, 2020). The proliferation of carsharing companies in China highlights the potential of shared mobility as a sustainable and efficient transportation solution.

Regarding prior research on carsharing development in China, numerous studies have focused on the carsharing service in major cities, such as Beijing (Feng et al., 2020; Shaheen and Martin, 2010), Shanghai (Duan et al., 2020; Hu et al., 2018b; Wang et al., 2012), and Hangzhou (Hui et al., 2017; Qian et al., 2017). Several publications have focused on user preferences and factors influencing the use of carsharing systems in individual cities (Bi et al., 2020; Hui et al., 2017; Luo et al., 2022; Wang et al., 2017; Ye et al., 2019; Jin et al., 2020; Xu et al., 2021; Yoon et al., 2019), as well as the different types of carsharing systems (Chen et al., 2018). In addition, studies have been conducted to develop the overall carsharing market in China (Jia et al., 2020; Shaheen and Cohen, 2007). Despite carsharing systems being established in most cities in China, there have been no systematic studies of multiple cities.

3.2. Measuring usage and efficiency

To further understand the differences in carsharing usage across Chinese cities and the city-level factors that influence the differences, we collected carsharing data in cities from one dominant carsharing company in China. The operator offers a station-based one-way carsharing service where users are free to pick up and drop off vehicles at any carsharing parking stations. Users can choose between a gasoline-powered vehicle or an electric vehicle depending on their needs and the availability in the station. The collected dataset included information on carsharing parking stations, station capacities, and the availability of vehicles in each parking station at a time interval of around five minutes. This time interval was based on previous studies and ensured an accurate identification of carsharing activities (O'brien et al., 2014). To minimize potential bias in analyzing carsharing demand, we monitored carsharing usage for four months from April to August 2019 in 61 cities, These cities include megacities, large and medium-sized cities, as well as provincial and national capitals. The trips of shared vehicles were aggregated to the city level for analysis (Fig. 1).

During data collection, all vehicle trips have been included, i.e., customer trips and rebalancing trips by the operator. Since, in operation, the rebalancing and recharging activities are often combined, we can utilize the observed difference of available mileages before and after a trip as an indicator to classify recharging or rebalancing trips. Also, because some customers may recharge or refill during a long-distance travel. Thus, we excluded long distance trips as rebalancing even though the remaining mileage increases. We used the median travel distance as the maximum relocation distance within a city. After filtering, the average proportion of customer trips among the captured trips within the city was found to be 75.9%.

We use the daily trip number to represent the usage of the carsharing systems. To measure the system efficiency, we used the vehicle utilization rate (VUR), which is calculated using the following equation:

$$VUR_i = \frac{U_i}{V_i}$$

where VUR_i is the vehicle utilization rate of city i, $U_i$is the carsharing daily trips of city i, and V_i is the number of shared vehicles of city i. The higher the rate, the more efficient the system is. Table 1 summarizes the dependent variables used in this study.

3.3. Influencing factors

3.3.1. Carsharing system characteristics

Carsharing system features can affect its usage and efficiency. Previous studies have used metrics to describe sharing systems (Gao et al., 2021), such as the average distance between stations to measure system size and compactness (O'brien et al., 2014). The parking lot to vehicle ratio is used to describe the number of available parking spaces for a given number of vehicles. It is a useful metric for assessing parking demand and supply and can help policymakers determine the adequacy of parking supply in a given area. Another metric is parking station density, which describes the number of carsharing sites per square kilometer and can help assess the accessibility and availability of carsharing in a region.

3.3.2. Urban factors

According to a previous review of urban shared mobility, we identified 10 urban factors from four categories that may influence carsharing usage: *urban socio-demographic*, *urban transit features*, *innovation adoption, policy adoption* (Table 1).

We selected explanatory factors that cover the fundamental attributes of cities, such as size, scale, and traffic, as well as factors that have been previously studied in the context of shared mobility, such as education level and policy influence. The city data are obtained from government statistics and the road information is from Open Street Map.

Information on vehicle plate purchase limitations was gathered from local government websites and reports. Subway construction can reflect a city's transportation needs and development, but its impact on a carsharing system remains uncertain. One hypothesis is that a subway system may complement carsharing trips, thus increasing the likelihood of using carsharing services. An alternative hypothesis is that a well-operated subway system may already meet citizens' travel needs, thereby reducing the demand for carsharing. We included these two variables, subway operation and vehicle plate restriction, as binary variables in the regression analysis.

3.3.3. Potential competing operators

Although our data is derived from a major carsharing operator in

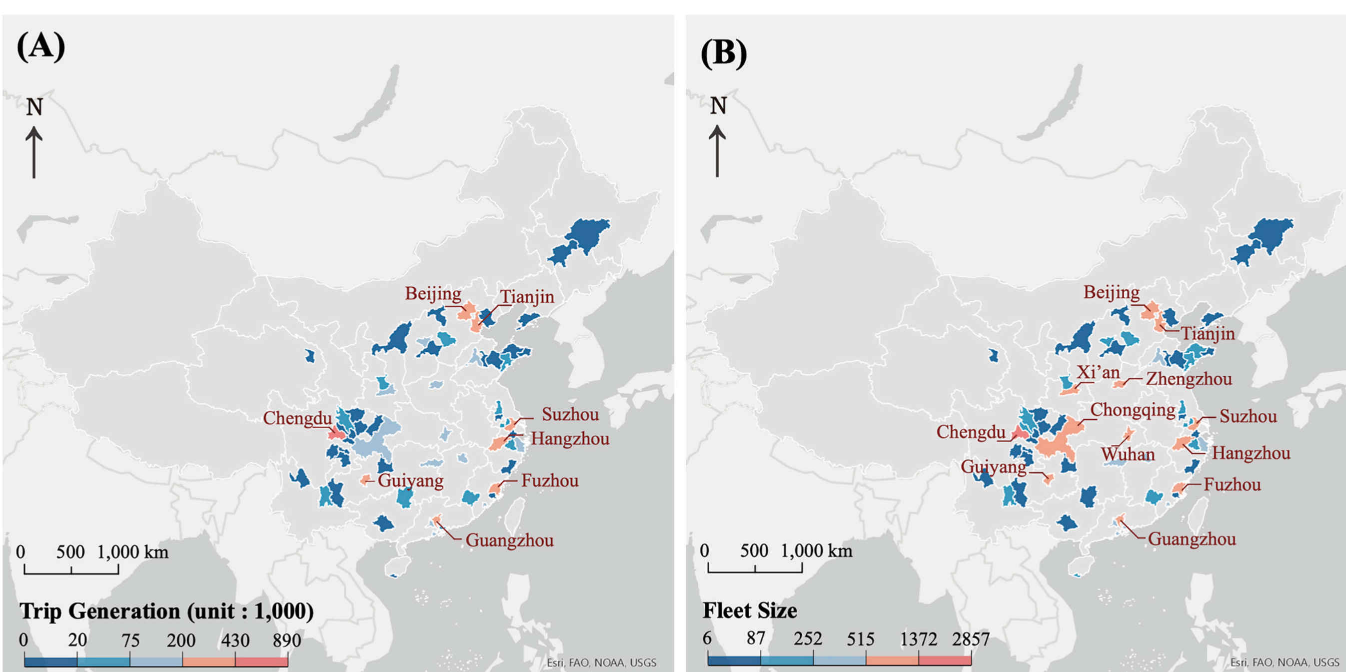

Fig. 1. The number of (A) carsharing trips and (B) shared vehicles during the study period.

Table 1
Summaty of dependent and independent variables.

Variables	Description	Mean	Std.	Min	Max	Data Sources
Dependent variables						
Average daily trip numbers	The average daily carsharing trips from 15 April to 13 August	705	1208	7	7456	GoFun
Average vehicle utilization rate	The average daily vehicle utilization rate from 15 April to 13 August	1.717	0.62	0.535	3.148	
Independent variables						
Carsharing system features						
Average parking station distance	The average distance between parking station in a system, km	0.846	0.515	0.323	2.447	GoFun
Parking lot to vehicle ratio	The ratio of total carsharing parking lots to fleet size in a system	4.214	1.455	1.804	11	
Parking station density	The density of car sharing station in a system, per km^2	0.275	0.288	0.009	1.322	
Urban Socio-demographic						
Population density	The urban population density, thousand per km^2	3.239	2.146	1.048	9.444	China Urban Construction Statistical Yearbook (2019)
GRP	The per capita Gross Regional Product, thousand yuan	92.868	43.722	31.019	203.489	
Average household size	The number of household members	2.513	0.192	2.21	2.99	
Urban transit features						
Road density	The ratio of the total urban road network length to the urban area, km/km2	2.196	1.633	0.03	8.316	Open Street Map
Bus efficiency	The number of annual ridership per bus, thousand	125.888	57.023	13.985	340.996	Local Government Statistical Yearbook (2019)
Taxi supply	Taxi ownership per capita	25.74	12.88	4.831	80.246	
Railway service or not	If there is railway service in city (1 = yes; else 0)			0	1	
Private car ownership	The total number of private car in city, thousand	1257.299	939.169	166	4134.6	
Innovation adoption						
Number of higher education institutions	The number of higher education institutions in city	11.902	13.875	0	67	Ministry of Education of the People's Republic of China
Policy adoption						
Vehicle limitation policy	If there is limitation policy on the purchase of vehicle plate (1 = yes; else 0)			0	1	Local Public Security Traffic Management Department
Competition factor						
Operator competitors	The number of competing car sharing operators in city	2.148	2.568	0	9	Web search

China, it is important to account for the potential influence of other operators in the results. Given the timeframe of carsharing's launch, some operators may have focused their operations only on major cities, such as EVCARD's early penetration of the Shanghai market. Therefore, to mitigate the impact of competition from other large operators, we excluded Shanghai from the study cities. For the remaining cities, we conducted a web search to collect information on the number of other carsharing operators reported in the media during the study period (Table A1) and used it as a control variable in our analysis.

3.4. Regression modeling

This study aims to explore the factors that influence the daily use and efficiency of carsharing, with a particular focus on urban characteristics and system features. The utilization and efficiency of carsharing may be subject to the influence of various factors such as the socio-economic development of the city, its population, built environment, and the size and operational strategy of the carsharing system. Cities with higher urban populations and better economic development tend to exhibit greater demand for carsharing services, while areas that lack sufficient public transport options or rely heavily on private vehicles may experience increased demand for carsharing. The provision of more comprehensive infrastructure by carsharing operators can potentially attract a greater number of prospective users. Nonetheless, the impact of these city-level factors on carsharing remains unclear, primarily due to the challenge of collecting carsharing data for a vast number of cities. In order to examine the assumptions, the ordinary least squares (OLS) regression model was employed. The identification of multicollinearity was accomplished by computing variance inflation factors (VIF).

In order to facilitate the assessment of the impact of variables on explanatory factors, we employ a logarithmic transformation of the variables. This transformation allows the resulting coefficients to represent the percentage change in the variables of interest within the system. Furthermore, since the response variables in this study do not follow a normal distribution, the application of a logarithmic transformation is utilized to meet the assumptions of the OLS model.

3.5. Non-linear effects

Previous related studies demonstrated that the connection between built environment characteristics and travel behavior is intricate and non-linear (Cheng et al., 2022; Ji et al., 2023; Duran-Rodas et al., 2019). For instance, the impact of the built environment may be negligible up to a certain level (Ji et al., 2023), and land use density showed an inverted u-shape association with the ridership (Chen and Ye, 2021). Consequently, neglecting these non-linear relationships may render strategic interventions ineffective in enhancing system usage or efficiency. We examined the potential nonlinear relationship between system and city characteristics and carsharing trip numbers at the city level, given the significant implications of this issue for the planning and implementation of shared mobility.

To explore the potential non-linear effects of various factors on carsharing trip numbers, we employed random forest regression (RFS). RFS is a supervised machine learning algorithm that employs ensemble learning to make more accurate predictions by identifying the effective ranges and thresholds of the factors (Breiman, 1996, 2001). Previous studies have effectively employed this model to predict response variables in transportation, such as the availability of shared bicycles (Almannaa et al., 2021; Ashqar et al., 2017; Feng and Wang, 2017).

4. Results

4.1. Carsharing system characteristics

The objective of this section is to understand and compare the usage of carsharing systems. Our studied cities have an average of 317 shared vehicles and 237 stations, with a few cities having less than 50 shared vehicles. Notably, there is a wide variation in supply and demand for shared vehicles across cities, as shown in Fig. 2. Chengdu is among the top cities with 2857 shared vehicles, a daily usage of approximately 7455 trips, and a daily VUR of about 2.61 times.

To provide a clearer picture of the size of the study cities and the data, we categorize them into megacities, metropolis, large cities, medium-sized cities, and small cities based on their population size in the figure. Although a large population can provide potential users for carsharing services, the size of a city's population does not appear to be a distinct factor in explaining carsharing trip numbers. Megacities such as Shenzhen and Chongqing do not have a user base proportional to their city size, which may be due to the presence of other operators in the city. Therefore, we will control for the number of other carsharing operators in the city in the regression analysis.

The number of carsharing trips is significantly associated with the system features, particularly the station number and fleet size. The count of parking stations includes all carsharing facilities established by the operator within the target city. This encompasses both vehicles and stations that were operational and available, even if they were not actively used by customers during the study period.

The parking lot to vehicle ratio, or the ratio of the number of parking lots to the fleet size, is a crucial aggregated characteristic of shared mobility systems (refer to Fig. 2B). This ratio is similar to the Maximum Normalized Available Bicycles (NAB) in previous studies (O'brien et al., 2014). Throughout all the cities included in this study, the parking lot to vehicle ratio ranged from 1.8 to 11, with most cities having three to five parking lots per shared vehicle. Sufficient space arrangements enable users to easily locate available vehicles and parking spaces, reducing parking difficulties and time. In the systems we studied, the parking lot to vehicle ratio shows a weak negative correlation with the trip numbers, suggesting that the excessive number of parking lots put in seems to have little influence on demand.

The differences in VURs between systems are considerably smaller than those for daily use, and their correlation of around 0.597 is not particularly high. The VURs of the studied systems range from approximately 0.53 to 3.14, with a mean value of approximately 1.7. System VURs have a weak correlation with station density, approximately 0.291, and a negative correlation with the parking lot to vehicle ratio, but also only around 0.37. Some cities have more efficient systems despite having less infrastructure. Guiyang, with the highest VUR, has an average of 3.14 vehicle turns per day, but its station density is only about 0.3. Operators need to pay closer attention to operational development in these cities, which often has the potential to generate more demand.

4.2. Regression results

4.2.1. Carsharing system usage

Models (1) and (2) in Table 2 provide the modeling results for carsharing daily usage. The primary objective of the first model is to examine the influence of system facilities on daily usage, and the second model investigates the impact of urban socio-demographic factors, urban transit, and other city characteristics on daily usage while controlling for the effect of other competing operators in the city. The model fit for the first model, which solely considers system characteristics reached 0.771. By contrast, the adjusted R-squared value increased to 0.939 after incorporating other city features in the second model.

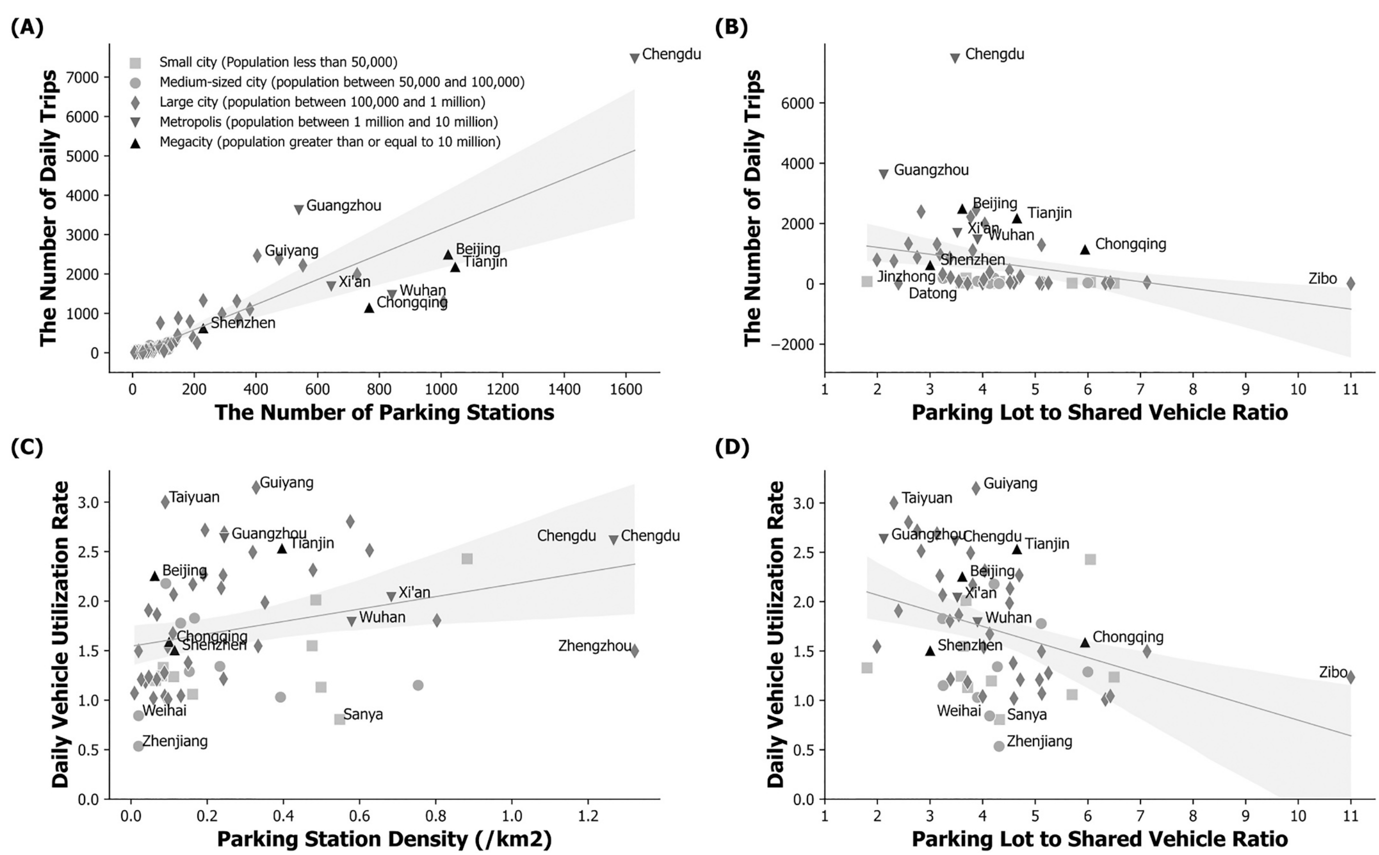

Fig. 2. System characteristics of carsharing in 61 Chinese cities from 15 April 2019 to 11 August 2019.

Table 2
Regression models results of carsharing daily usage and efficiency.

	Ln (Average daily usage)		Ln (Average daily VUR)	
	(1)	(2)	(3)	(4)
	β(s.e.)	β(s.e.)	β(s.e.)	β(s.e.)
Carsharing system features				
ln (Average parking station distance)	−1.278***	−0.415*	−0.139	−0.0184
	(0.341)	(0.237)	(0.112)	(0.136)
ln (Parking lot to vehicle ratio)	−1.764***	−1.467***	−0.317**	−0.260*
	(0.396)	(0.259)	(0.130)	(0.150)
ln (Parking station density)	0.337**	0.847***	0.0646	0.142**
	(0.151)	(0.106)	(0.0494)	(0.0612)
Urban socio-demographic				
ln (Population density)		−0.835***		−0.0846
		(0.134)		(0.0773)
ln (GRP)		0.205		0.000378
		(0.215)		(0.124)
ln (Average household size)		−0.869		−0.774
		(1.107)		(0.638)
Urban transit features				
ln (Road density)		−0.0270		−0.0608
		(0.0926)		(0.0534)
ln (Bus efficiency)		0.286*		0.0626
		(0.155)		(0.0893)
ln (Taxi supply)		−0.606***		−0.112
		(0.170)		(0.0979)
Railway service (yes/no)		0.383		0.136
		(0.263)		(0.151)
ln (Private car ownership)		0.350**		−0.0205
		(0.143)		(0.0827)
Innovation adoption				
ln (Number of higher education institutions)		0.454***		0.0530
		(0.125)		(0.0721)
Policy adoption				
Vehicle limitation policy (yes/no)		0.864***		0.201
		(0.276)		(0.159)
Control variables				
ln (Number of operator competitors)	0.965***	0.200	0.113*	0.0247
	(0.173)	(0.154)	(0.0567)	(0.0888)
(Constant)	6.991***	6.119***	0.892***	1.792**
	(0.617)	(1.427)	(0.202)	(0.823)
Summary statistics				
Observations	61	61	61	61
Adj R-squared	0.771	0.939	0.376	0.488

Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

The system features have a significant impact on daily usage. Smaller average distance among parking stations, higher station density, and lower parking lot to vehicle ratios (a higher number of vehicles) are associated with higher daily usage. As the average distance between sites in the system decreases by a percent, usage will increase by 1.278%. Additionally, for each 1% decline in the ratio of vehicles in the system, the average daily usage will rise by 1.764%. In cities, for every 1% increase in carsharing station density, the average daily use increases by 0.337%.

After controlling for system features and competing operational factors, many urban characteristics show significant influences on daily usage. Contrary to the expected hypothesis, population density is negatively associated with daily usage. Economic development in cities is not significantly, albeit positively, associated with daily usage. The average household size is found insignificant in the results.

The city's transit is closely linked with carsharing daily use. The average daily use increases by 0.286% when the number of buses operating in a city rises by 1%. Conversely, cities with a high supply of taxis exhibit lower usage of shared vehicles, with each 1% increase in taxis significantly reducing average daily use by 0.606%. Cities with a higher number of private cars generally indicate a greater inclination towards car travel among citizens, implying a potentially higher demand for carsharing services. The average daily use increases by approximately 0.35% as the percentage of private car ownership within the city increases. The availability of railway services has a positive, albeit insignificant, effect on daily use. The results highlight the interactions of carsharing with other transportation modes such as buses, taxis, and private cars. For operators, there is strategic value in targeting urban areas with a heavy reliance on taxis or a high potential for converting private car trips into carsharing usage. Innovation acceptance, indicated by number of higher education institutions, also significantly influenced carsharing trip numbers. Each additional higher education institution in a city affects a 0.454% rise in carsharing demand. Another important variable for carsharing trip generation was vehicle license plate restrictions. A city's restricted license plate policy influences those needing a vehicle to use carsharing affecting in 0.864% increase in daily usage.

4.2.2. *Carsharing system efficiency*

Models (3) and (4) in Table 2 present the results of daily VURs. Similar to the daily usage models, both models focus on infrastructure and social characteristics, respectively, while controlling for the influence of competitors. Notably, the fit of the model that solely considers system facilities is only 0.376, while the model that takes into account urban characteristics explains the VUR to a degree of only 0.488.

The impact of system characteristics on VUR is largely consistent with that of daily usage, with station density remaining the most significant and influential factor. An average increase in VUR of 0.142% corresponds to each 1% increase in station density, which is reasonable since denser sites are more likely to facilitate the rent and return of vehicles. Unexpectedly, urban factors had a very limited role in explaining the VUR of the system. The other factors exert a similar impact on VUR as on daily usage, except for the number of private cars, although the effect is also minimal.

4.3. *Non-linear effects*

We utilized two random forest regression models to investigate the potential non-linear relationship between carsharing trip numbers and explanatory variables. The daily usage model achieved R2 values of 0.91 and mean absolute error (MAE) of 174.81, while the VUR model produced R2 values of 0.89 and MAE of 0.17. To explore the effective ranges and thresholds of system and urban characteristics that could promote carsharing trip numbers, we employed Partial Dependence Plots (PDPs). PDPs are a commonly used visualization tool that reveals the marginal effect of a single feature on the predicted outcome of a model while holding all other features constant. Fig. 3 depicts several PDPs that exhibit non-linear relationships between variables and can provide useful guidance for establishing a carsharing system.

Our analysis of non-linear relationships revealed that the direction of the relationship between system facilities and daily use and efficiency is essentially the same. Specifically, we found that the relationship between the average distance between stations and daily usage and efficiency decreases rapidly from a minimum value to around 0.5 km, and gradually becomes smoother from 0.5 km onwards, emphasizing the importance of system compactness.

Furthermore, we observed that the effect of parking lot to vehicle ratio on VUR decreases rapidly as the ratio of spaces to vehicles in the system increases and becomes stable when one vehicle in the system corresponds to more than five spaces. However, we did not observe a particularly pronounced non-linear effect of this metric on daily use.

The density of parking stations has a significant positive impact on

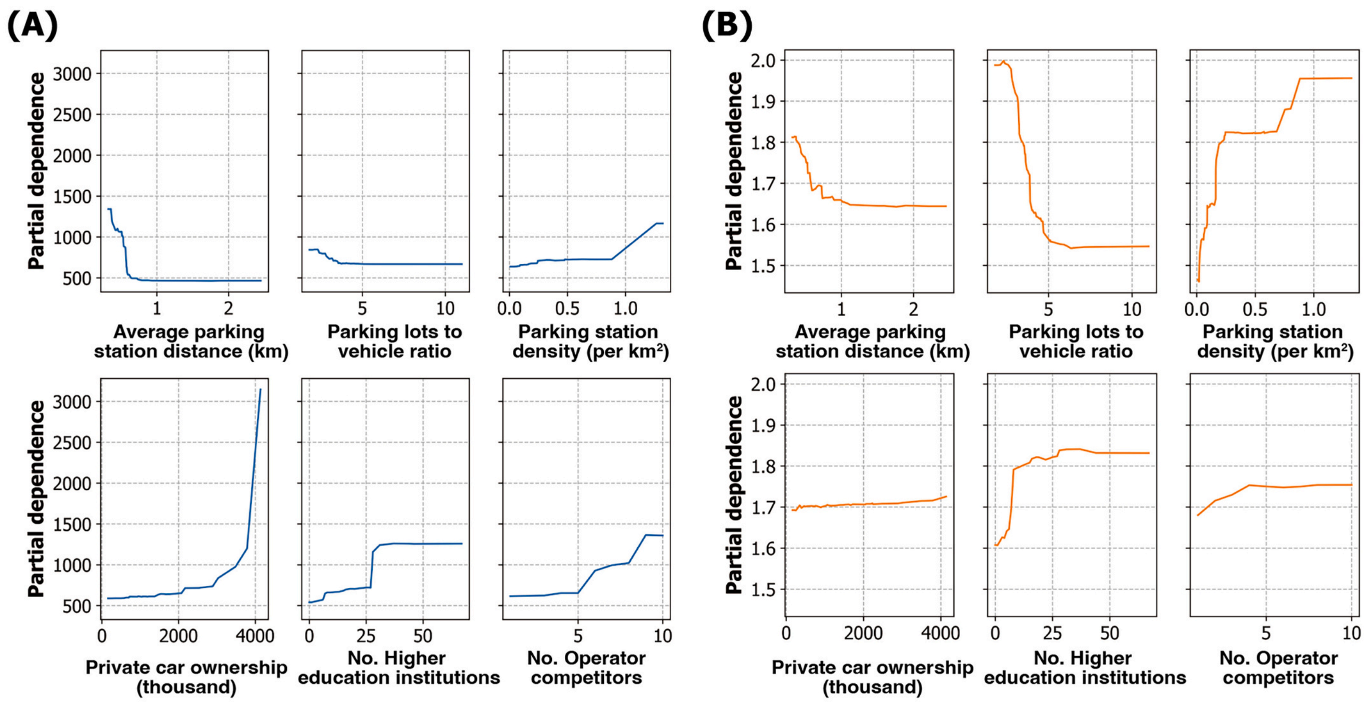

Fig. 3. Nonlinear effects of system and urban variables on (A) daily usage (B) vehicle utilization rate (VUR).

daily usage. We also observed that efficiency growth stabilizes when there is more than 1 station per square kilometer. These findings provide valuable insights into the key factors that drive carsharing trip numbers and can inform the design and implementation of carsharing systems that are both efficient and effective.

Among the urban factors studied, only urban private car ownership, the number of higher education institutions, and the number of competitors exhibited a relatively clear non-linear relationship with carsharing trip numbers (Fig. 3). Private car ownership within the city showed an exponential increase in the impact on daily use after exceeding 300,000 cars but had little impact on VUR. There is an increase of around 1000 trips when the number of higher education institutions exceeded 25, and a critical point of impact on VUR at around 13 institutions, beyond which there was no further increase in the impact on VUR. Lastly, the number of competitors in the carsharing market had a gradual but positive impact on system use, with a greater influence on daily usage than on VUR.

In summary, despite the non-linear relationship, the overall impacts on carsharing usage are positive and consistent with the findings of the linear regression. It is important to note that our findings are based on a limited number of observations and the fact that the urban system is not yet saturated. Therefore, it is not certain whether the system has reached a threshold of growth, and the impacts on the system may continue to evolve as the density of sites increases. These results highlight the need for ongoing research to better understand the dynamics of carsharing trip numbers and the role of urban factors in shaping transportation systems, as well as the potential for continued growth and optimization in the carsharing market.

5. Discussion

5.1. Interpretation

The response and usage patterns of transportation services vary significantly across different urban contexts. Furthermore, due to the diversity of urban environments and the levels of competition among carsharing operators within cities, the extent and factors influencing the use of carsharing services also exhibit notable differences. Therefore, conclusions drawn from single-city studies may have limited generalizability. In this section, we present a summary of several findings and compare and analyze them with previous studies to identify similarities and differences, as well as to establish the broader implications of our research.

Population density is often considered as one of the most important factors in the functioning of carsharing systems. Population density at the city level is negatively correlated with daily carsharing use, which is not in line with previous neighborhood-level studies ((Prieto et al., 2017; Rabbitt and Ghosh, 2013; Rickenberg et al., 2013)). Our study found the population density showed a significant and negative association with carsharing trips, but no significant effect on system efficiency. This suggests that at the city level, population might not be an important factor contributing to more usage. The number of potential customers may better explain overall usage than the population.

The development of a carsharing market is always influenced by local transportation services. Earlier studies have reported inconsistent findings on the relationship between city transit and carsharing services (Becker et al., 2017a, 2017b; Campisi et al., 2020; Ceccato and Diana, 2018; Ferrero et al., 2018). Our study found that the railway service is positively associated with carsharing usage, which is consistent with the findings of Ceccato and Diana (2018). Our results showed that there is a negative relationship between both carsharing trip numbers and efficiency and taxi supply. Conversely, a survey conducted in Australia found that households that used carsharing were also more likely to use taxis (Zhou et al., 2020). The extent and nature of the relationship between these two mobility options require further exploration.

5.2. Future research

Future research could explore the following aspects. Firstly, factors influencing carsharing use at fine scales and across different time periods can be studied. Urban factors may impact carsharing services differently at different scales. For example, the presence of rail services in a city is not significant for overall daily use, but the presence of rail services near a carsharing station may have a significant impact on its usage. Therefore, future research can explore in a finer spatial scale about the differences of urban factors on carsharing systems.

Secondly, the relationships between carsharing and other modes, such as public transit, taxis, and other ride-sharing services, are less investigated. Studying these intermodal relationships can gain a more comprehensive understanding of how carsharing fits into the city transportation system. By examining the relationships, researchers can identify the factors that influence users' travel choices and develop more effective strategies to promote sustainable transportation in a city.

Thirdly, our study findings suggest that carsharing operators' investments and deployment strategies have a significant impact on carsharing services. Currently, supply analysis of the carsharing market is particularly crucial in China as the market is still in an early period, and the supply and diffusion of carsharing services are not yet fully understood.

Fourthly, given the impact of the pandemic on carsharing, it is essential to consider the potential changes that may arise in the development of carsharing. Changes in government policies, technological innovations, and business strategies during the pandemic may result in significant shifts in the market, including changes in market size, share, and user demand and behavior. Therefore, to better understand the future trends and changes that the carsharing industry may undergo, there is a need for forward-looking analyses in the post-pandemic era context.

Fifthly, future research needs to prioritize the management and sustainability research of carsharing. During the data collection processing, we found that a proportion of stations in cities were underutilized for almost four months, resulting in inefficient use of resources. Thus, future research should delve deeper into the management issues of carsharing, including vehicle scheduling, parking station management, and maintenance, to improve resource efficiency and service quality. Additionally, the sustainability of carsharing also encompasses its environmental impact. Therefore, future research should explore the environmental implications and sustainability of shared vehicles, including energy consumption and emission profiles of both traditional and new energy-shared vehicles.

5.3. Strength and limitations

This study represents a significant advancement in our understanding of carsharing by encompassing a broader scope of cities in China. Previous investigations in this field have predominantly focused on individual cities or a small number of cities, hard to recognize the potential influence of city-level factors on carsharing utilization. Consequently, this research sheds light on the vital considerations that governments and investors must undertake when contemplating the implementation of carsharing initiatives, particularly when faced with limited initial information.

Nevertheless, our study has some limitations in variables that may affect carsharing usage and efficiency. Regarding carsharing systems, factors such as membership numbers, user characteristics, and system services and operations could be further investigated. However, due to the lack of a unified data source for the study cities, aspects related to the traveling habits of city residents, individual preferences, and urban traffic conditions were not included in our analysis.

Relying solely on educational institutions may be insufficient to capture the complete essence of innovation acceptance. To comprehensively evaluate the innovation openness of a city, it would be more effective to survey the acceptance of carsharing or new technologies among its citizens. Nevertheless, due to the extensive scope of our study involving multiple cities, conducting such surveys is not feasible. In future research, it would be beneficial to consider incorporating real innovation adoption.

The impact of competing operators on our statistics of daily usage could be more effectively represented by the number of users or the number of vehicles deployed, but we could only use the number of operators as a control variable due to the difficulty of re-collecting data at this time. Despite these limitations, our data regressions and comparisons generated some useful findings.

6. Conclusion

Carsharing services are becoming increasingly popular in many Chinese cities due to the government's environmentally friendly energy and transport policies. However, the development of carsharing across cities and the factors that impact usage and efficiency have not been fully understood. Therefore, this study seeks to provide a quantitative analysis of the multiple city-level factors that affect the carsharing system in China. The study covers a wide range of cities and variables and provides insights into the differences in carsharing development among Chinese cities.

In this study, we collected data on carsharing systems in 61 cities across China and conducted extensive analysis of various aspects of its usage and efficiency. Our findings indicate that the supply and demand of carsharing services differ significantly across cities and that the features and strategy of urban carsharing systems have a notable impact on demand and efficiency.

We examined the impacts of both system characteristics and urban factors on carsharing usage and efficiency. Urban transport, educational attainment, and vehicle restriction policies are found to have significant associations with carsharing usage. But no urban factors are seen statistically significant associations with the efficiency. Cities that rely on private cars tend to see higher usage of carsharing services, while the number of taxis in a city is negatively correlated to carsharing use. Additionally, carsharing is more popular in cities that have more universities and in those with restrictions on private car ownership, suggesting some policies for the promotion of carsharing. Compared with urban factors, the facilities, and layout of the system, have a significant positive relationship with the use and efficiency of the system. Additionally, the presence of other competitors within the city was positively associated with the carsharing usage.

In addition, we explored the non-linear relationships between some key variables and system usage and efficiency. Interestingly, the impact of the parking lots to vehicle ratio on the VUR declines rapidly after exceeding 5, indicating marginal benefits of increasing facilities. We also find that the carsharing usage rises sharply after the number of private cars exceeds 4 million. Cities with more than 25 higher education institutions show a significant increase in the use and efficiency of the system.

Our findings have significant implications for carsharing development. Future research can continue to explore the factors of carsharing at various spatial and temporal scales, and investigate the inter-modal relationships with other modes, to develop effective strategies for promoting carsharing and urban sustainable transportation.

CRediT authorship contribution statement

Jinyan Zu: Conceptualization, Methodology, Data curation, Writing – original draft. **Hui Kong:** Supervision, Writing – review & editing. **Yang Xu:** Supervision, Writing – review & editing. **Xiaohu Zhang:** Conceptualization, Supervision, Validation, Writing – review & editing.

Data availability

Data will be made available on request.

Acknowledgements

This article was supported by the National Natural Science Foundation of China (Grant No. 42371190).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

org/10.1016/j.jtrangeo.2024.103897.

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