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Analysis of the Contribution of China's Car-Sharing Service to Carbon Emission Reduction

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Abstract: In light of carbon peak and carbon neutrality goals, China has attached great importance to energy savings and carbon reduction. Carbon reduction in the transport sector is critical to achieving the two-carbon target, as it accounts for 9.41% of total carbon emissions. As the sharing economy grows, car sharing is considered to present excellent carbon reduction potential in the transportation sector. However, the current research is focused on car sharing usage, with a lack of research on the carbon reduction capability of car sharing in China. Hence, this study aims to investigate the carbon reduction capacity of car sharing, including usage rates of car-share services and changes in travel behavior, through an online questionnaire combined with carbon emission data from the transportation sector. The study aims to analyze the contribution of car-share services to carbon reduction in the transportation sector under the current model. The well-to-wheel (WTW) approach is employed, including the energy consumption of vehicles and carbon emissions in the production process. The research results indicate that the introduction of car-sharing services increases driving energy consumption; however, this increase is offset by the decrease in carbon emissions as a result of the production process. Therefore, the overall effect is a reduction in carbon emissions of 1.058971 million tons in 2021, accounting for 1.95 percent of total transport carbon emissions. In addition, the impact on different modes on carbon emission reduction is also explored in this study. The results demonstrate that the private car disposal rate shows the most significant influence on traffic carbon emissions; a 10% reduction in the number of private cars can lead to a 2.48% carbon reduction. The relevant conclusions of this study can provide support for the future development of car sharing in China and the reduction of carbon emissions in the transportation sector.

Keywords: car sharing; carbon emissions; sustainability assessment; sharing economy

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1. Introduction

Carbon emissions are an important topic in China with the proposal of carbon peaking and carbon neutrality goals. Based on the data released by the National Bureau of Statistics, energy consumption in the transportation, storage, and postal sectors accounted for 9.41 percent of the country's total in 2017. As one of the three significant energy consumption and carbon emission industries, the transportation industry is crucial in dealing with climate change. With the development of the internet, the sharing economy puts forward new solutions to reduce carbon emissions in the transportation sector. The sharing economy refers to the separation of the ownership of resources and the right to use them, which means that owners can share idle resources with others to create value and reap benefits [1]. This brings new experiences to participants and maximizes the utilization of idle resources. As a new mode of transportation in the sharing economy, car sharing plays an essential role in carbon reductions in the transportation sector and is an important future direction. Car sharing with new-energy vehicles not only increases the service efficiency of cars and indirectly promotes the development of new-energy vehicles, which protects the urban ecological environment, but also addresses defects such as fixed public transit platforms and inaccessible routes, meeting the requirement for convenience, comfort and privacy in transportation [2]. The concept of car sharing in Europe dates back to 1948, and sharing in the United States first appeared in 1983. In Germany, as of 2018, 677 cities had developed car sharing, with 171.5 million registered participants [3,4]. Car sharing in Asia began in Japan and Singapore. Car sharing is used more in densely populated areas because it can replace buying a car [5]. With the development of the internet, the system of sharing cars has become more flexible. At present, the existing car-sharing framework mainly has one-way, two-way and free floating models. In the European, American and Asian car-sharing companies, the free-floating car-sharing model is more popular. Due to the flexibility of picking up and returning cars, it has the advantages of high utilization rate, increased cost savings, more flexibility and fewer parking issues [6]. Carsharing emerged in China in 2015, and the number of registered car-sharing enterprises has shown a continuous upward trend since 2017, exceeding 400 by 2018. Meanwhile, the number of shared cars in operation has surpassed 100,000 (see Figure 1), and the market size of car sharing in China has reached 1.729 billion yuan, which indicates that China's car-sharing industry is entering a rapid development period [7]. Figure 2 shows a subset of existing car-sharing brands in China.

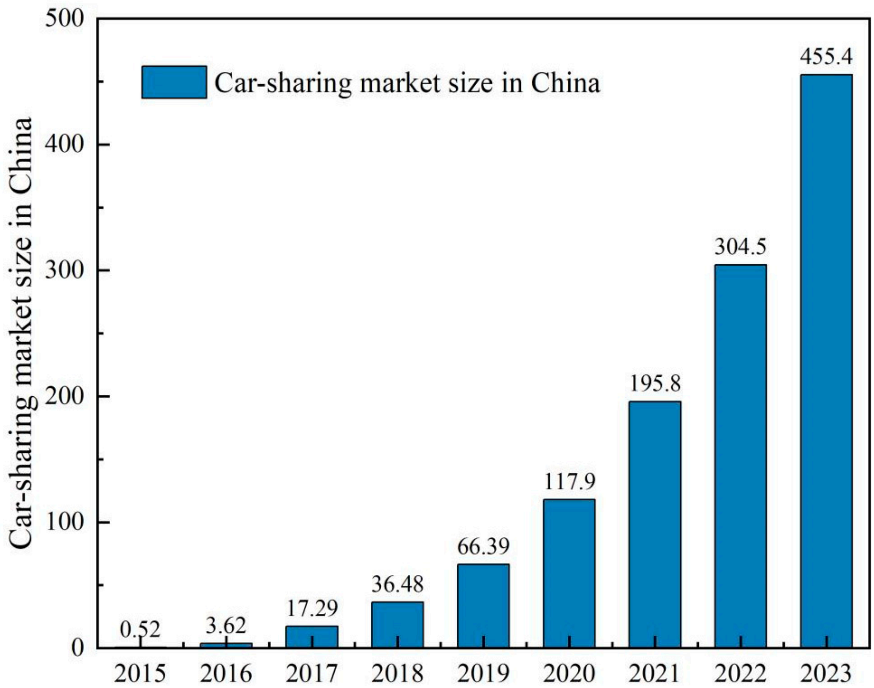

Figure 1. Car-sharing market size in China.

Figure 2. Car-sharing brands size in China.

Car sharing has a solid ability to reduce carbon emissions. Much research has been conducted on the carbon emission reduction potential at home and abroad. Chen and Kockelman [8] looked at the life-cycle impact of car sharing on energy use and greenhouse gas emissions in the United States, and the results showed a 51% reduction in both. Firnkom and Muller [9] analyzed one-way Car2Go car sharing in Germany, where car-share participants saw an average reduction of 312 to 146 kg CO_2 annually. Amatuni et al. [10] proposed a comprehensive model by comparing car sharing's annual travel distance and life-cycle emission factors in the Netherlands, San Francisco and Carigal. They concluded that the reduction of private cars is the main factor in carbon emission reductions in transportation, resulting in a reduction of 3–18% [10]. Marco Migliore [11] studied a car-sharing service in the city of Palermo, using the COPERT method, and showed that the use of car sharing has benefits in terms of reducing pollutant emissions, including 25% less PM_{10} and 38% less CO_2. Ana María Arbeláez Vélez [12] divided people into car-dependent and car-free individuals and investigated their car-sharing preferences. The results showed that the people who rely on cars reduced their mileage, while those who were not dependent increased their mileage. Meanwhile, the study also mentioned that carbon emissions could be reduced by increasing new-energy vehicles [12].

Car sharing can significantly reduce the number of private cars, decreasing the carbon emissions generated by car manufacturing and dramatically improving congestion, thus lowering total carbon emissions [2]. Car sharing can obviously lessen car ownership. Zhou et al. [13] studied the impact of car-sharing services on household vehicle ownership through the logit model and concluded that increasing public preference for car sharing can further the benefits of this service. Ke et al. [14] showed that car sharing can reduce car use, but only if there are a significant number of users, reducing car ownership. According to a survey of 941 people in Australia, Jain et al. [5] found that the number of car-sharing households was significantly lower than that of non-member households, and one third of households reduced their car ownership. Car sharing can significantly reduce car ownership. According to Gleave, new car-sharing members reduce car ownership by between 34% and 47% in Scotland. In France, the drop is estimated to be 23%, and it reaches 7–15% in Germany [15]. Car sharing can also delay new car purchases. In Scotland, 56% of car-share users said they were unlikely to buy a car. The reduction of private cars is also related to the number of car-sharing vehicles. Research on the number of private cars replaced by car sharing has been conducted. According to the published data, each shared car can reduce the number of cars purchased by 13 [16], which means that one million car-share vehicles would eliminate 13 million private cars. Kolleck [17] conducted an empirical study of the impact of car sharing on non-corporate car ownership and the car market in 35 large cities in Germany and found that every additional station car would reduce the number of private cars by 9.

When driving at a speed of 40–60 km/h, a car can reduce carbon emissions by 49,000 L per year. Taking GoFun as an example, the survey data indicate that the number of shared cars in Beijing is around 350, which would reduce carbon emissions by 17.233 million liters per year. In addition, car sharing also affects carbon emissions in terms of miles traveled, but the specific impact as determined by different studies varies widely [18]. Some studies suggest that car sharing can reduce the number of miles traveled, while others argue the opposite, pointing out that car sharing increases miles traveled due to its convenience. Shaheen and Cohen [19] reported that vehicle kilometers traveled in Europe have been reduced by 20 to 45% due to car sharing. Wu [20] found that new car-sharing users increased their mileage in London while long-time participants saw reduced travel distances. Car sharing can also affect carbon emissions by increasing the proportion of electric vehicles. By investigating people's preference for car sharing and using online questionnaires, Jiyeon Jung [21] found that the carbon emissions caused by the increase of miles brought about by car sharing were greater than the carbon emission reduction as a result of reduced car production. However, carbon emissions can be reduced by increasing the proportion of electric vehicles in car sharing [12,21,22]. However, the research results obtained from these related studies differ significantly due to the influence of regional, economic and human factors [23–25]. Therefore, it is urgent to expand Chinese data in this area to determine China's carbon reductions and contribution to the dual-carbon target.

Current studies on the carbon reduction of car sharing are mainly based in countries outside of China; however, the situation in these countries is significantly different from that in China. For example, car sharing is more frequently used in densely populated areas. The population in China is dense compared to other countries. Hence, Car sharing will develop better in China, as opposed to other less densely populated countries. In addition, the public transportation in China is more developed [2]. All these factors show the significant impact of the introduction of car sharing in China. Although car sharing started late in China, the development of the sharing economy, the strengthening of environmental awareness, and attention to energy conservation and emission reductions have created favorable conditions for car-sharing development in China. Much research has been carried out on the intention to use car sharing in China and the impact on private cars. Sun [26] surveyed students' preferences for car sharing at Dalian Maritime University and proposed effective measures to encourage students to use car sharing. According to Hui's [27] survey of users of Hangzhou's Fun Car-Sharing platform, 50% were willing to delay buying a car after using a car-sharing service. However, little research has been conducted on the carbon emission reductions caused by car sharing in China. Therefore, this study takes carbon reduction as the research object and analyzes the impact of car sharing on traffic carbon emissions, exploring the factors affecting carbon emissions as well the potential influence of effective policies aimed to help the transport sector reduce carbon emissions.

This paper calculates carbon emission levels following after the introduction of shared car services in order to analyze the contribution of car-sharing services to energy savings and carbon reduction in the transportation sector under the current model. Sensitivity analysis is carried out to analyze the factors affecting the carbon emissions of car-sharing services and calculates their impact degree, in order to identify the factors influencing the development of car sharing and to propose government policy directions in this regard.

This paper consists of the following three parts. Section 2 provides analysis of several factors affecting carbon emissions from car sharing and determines the impact of the introduction of shared car services on carbon emissions in the transportation sector. The rate at which people use car-sharing services and the changes in people's travel behavior after the introduction of car-sharing services were investigated through an online questionnaire. Section 3 presents the calculation results and the rate of reduction of traffic carbon emissions after the introduction of car sharing. Sensitivity analysis of several factors affecting the carbon emissions of car sharing is carried out, and the degree of influence of different factors on carbon emissions is obtained. Aimed at determining the influencing factors with regard to the carbon emissions of car sharing, this paper summarizes the reasons affecting changes in people's travel behavior and the use preference of car sharing, so as to provide direction for the promotion of car sharing in China as well as a reference for carbon reduction in the transportation sector.

2. Materials and Methods

2.1. Methodology

An online survey was conducted to collect data on individual modes of transportation, including car ownership, driving distance, time spent on public transport, etc. Changes in traffic behaviors were analyzed, and the environmental effects of these behavioral changes were investigated.

This study estimates the impact of car sharing on CO_2 emissions. Changes in the number of miles traveled and the number of private cars affect carbon emissions in the transport sector. When analyzing the GHG implications for car-sharing services, it is essential to understand the changes in individual transport behavior resulting from introducing car-sharing options. Car-sharing services can result in three transport behavior changes. Accordingly, the authors formulated three hypotheses: (1) car owners replace a private car with a car-sharing vehicle, which would reduce private car ownership and lead to changes in travel behavior; (2) non car-owners convert public transportation to shared car travel, which results in an increase in miles traveled; (3) the desire for ownership of a car changes; buying fewer cars reduces the carbon emissions implicit in the production process [28]. These behavioral changes all lead to noticeable impacts on carbon emissions, which are the focus of the following research. Figure 3 shows the factors that influence the carbon emissions of car sharing.

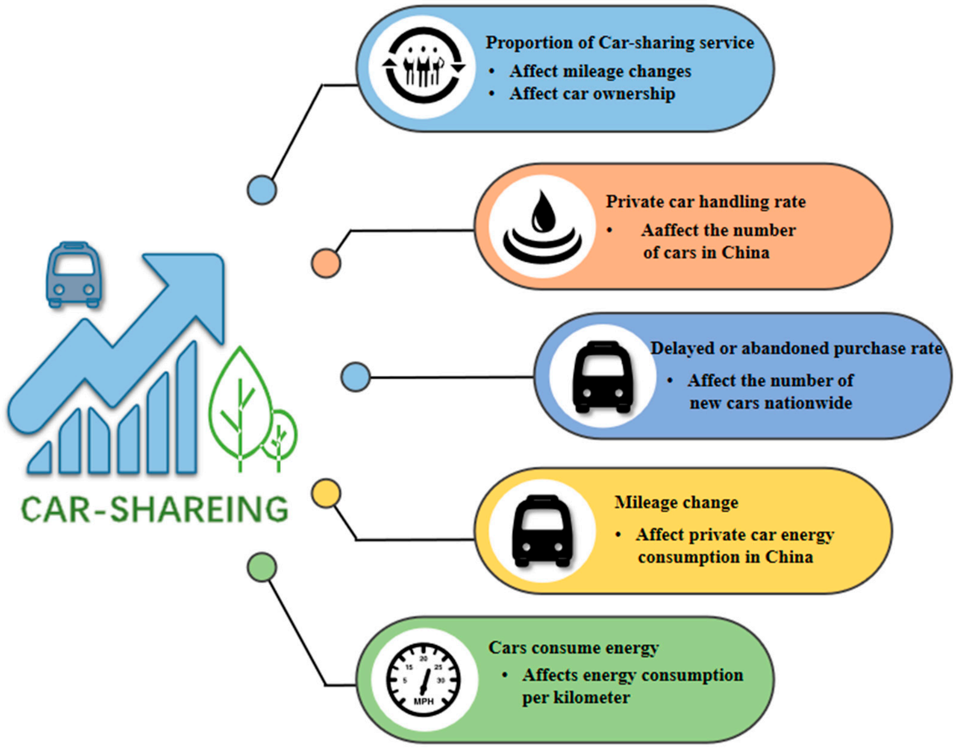

Figure 3. Factors affecting carbon emissions of car-sharing services.

2.1.1. Annual Mileage

Car sharing reduces private cars as an alternative to personal vehicles; however, car sharing leads to more miles traveled as an alternative to public transportation. The combination of the two has an impact on mileage. By asking people about their intention to use car-sharing services and when they started to use such services, the proportion of people who use car sharing can be determined, and the number of people who use car-sharing services is estimated. Subsequently, by investigating the changes in the number of journeys taken after people started using car-sharing services, the changes in people's travel modes can be quantitatively expressed. Based on these two types of data, the mileage changes caused by the transportation mode transformation after the introduction of car-sharing services can be obtained, which can be calculated using Equation (1).

$$CM = AM_{\mathrm{as}} - AM_{\mathrm{ac}} \tag{1}$$

where CM is the change in mileage, km; AM is annual mileage, km; AM_{as} is the assumed annual mileage, which is the yearly number of miles in the non-car-sharing scenario, km; AM_{ac} is actual annual mileage, km. AM_{as} can be obtained according to Equation (2).

$$AM_{as} = \frac{AM_{ac}}{P_u \times CMU + P_w \times 100\%} \tag{2}$$

where P_u is the probability of an individual choosing car sharing, %; P_w is the probability of an individual not using car sharing, %; CMU is the change in mileage after started to use car sharing, km. Since obtaining the national annual mileage data is difficult, the energy consumption during the driving process, namely 80% of the residential consumption of gasoline and diesel, is employed in this study.

2.1.2. National Car Ownership

Car-sharing services also reduce vehicle ownership, which can reduce carbon emissions at the manufacturing stage. Considering the impact of the introduction of car-sharing services on transportation carbon emissions, the whole life-cycle process should be considered, including the carbon emissions from the car production process and the carbon emissions of energy consumed by cars while driving. Carbon emissions from fuel combustion have been discussed. As for the change in carbon emissions caused by the change in the number of private cars, this study investigates two situations: (a) whether people are willing to sell their original private cars after using car-sharing services; and (b) whether users without cars are willing to delay or give up buying cars. Through the survey results, the change in the number of private cars can be obtained. The subjects were divided into car owners and non-car owners. For car owners, car sharing may cause the sale of their original cars, thus reducing car ownership.

$$RCO = CO_{as} - CO_{ac} \tag{3}$$

where RCO is the reduction in car ownership; CO_{as} is the assumed car ownership, which is the car ownership in the non-car-sharing scenario; CO_{ac} is the actual car ownership.

CO_{ac} can be calculated based on Equation (4).

$$CO_{as} = \frac{CO_{ac}}{P_{ou} \times PS + P_{od}} \tag{4}$$

where P_{ou} is the proportion of people who own a car and use car sharing, %; P_{od} is the proportion of people who own a car and do not use car sharing, %; PS is the percentage of people who choose to sell their cars after using car sharing, %.

For people who do not own cars, using car-sharing services may lead to a willingness to delay or forgo buying a car, which can also lead to car ownership changes, mainly affecting the number of new vehicles added.

$$RICO = ICO_{as} - ICO_{ac} \tag{5}$$

where $RICO$ is the reduction in the increment of car ownership; ICO_{as} is the assumed increment of car ownership, which is the increment of car ownership in the non-car-sharing scenario; ICO_{ac} is the actual increment of car ownership. ICO_{as} can be obtained from Equation (6).

$$ICO_{as} = \frac{ICO_{ac}}{P_{du} \times PF + P_{dd}} \tag{6}$$

where P_{ou} is the proportion of people who own a car and use car sharing, %; P_{od} is the proportion of people who own a car and do not use car sharing, %; PF is the percentage of people who are forgoing or delaying the purchase of a private car, %.

The reduction in carbon dioxide emissions based on the above changes in miles driven and car ownership is the current year's reduction as a result of car-sharing services, regardless of differences in fuel efficiency and lifespan between private ownership and car sharing.

2.2. Data Description

An online survey was designed to investigate individual behaviors related to transportation mode, preferences and willingness to use car-sharing services. The first section collected data on the sociodemographic characteristics of respondents: gender, age, location, occupation, household, personal income level and the number of family members. The second part addressed travel distance and transportation mode as well as the frequency of use of car sharing. The third part addressed car-sharing preference. The online survey was conducted by questionnaire in March 2022. According to the geographical location of respondents, target quota sampling was used to ensure the representativeness of the sample, as shown in Figure 4.

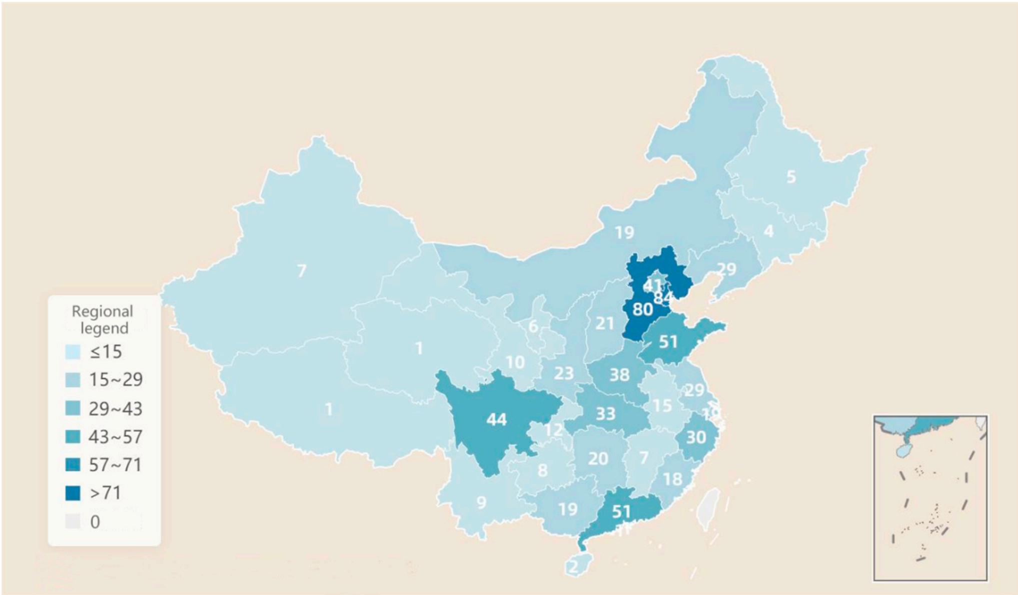

Figure 4. Map of China indicating respondent distribution.

Since it is difficult to obtain data on the number of miles traveled throughout the country throughout the year, this study uses transportation energy consumption as the basis for calculating carbon emissions. The carbon emissions from China's transport sector are calculated using the IPCC inventory method, that is, carbon emissions = activity level × carbon emission factor. The energy consumption in this paper is calculated using the Statistical Yearbook of China, in which 80% of gasoline and diesel are used as energy consumption during driving. Gasoline and diesel carbon emission factors were in accordance with IPCC: 2019 Improvements to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The carbon emissions of transportation can be obtained from Equation (7). The carbon emission implied by the automobile production process is calculated by the number of newly added private cars × the carbon emission of one vehicle production; the number of newly added private cars is in accordance with the China Statistical Yearbook, and the carbon emission of gasoline vehicle production is calculated by referring to the default carbon emission factor of 550 kg CO_2e per vehicle production as recommended in the Technical Specification for Carbon Emission Accounting of Passenger Vehicle Life Cycle.

$$CE_T = GC \times CEF_{GC} + DC \times CEF_{GC} \tag{7}$$

where CE_T is the carbon emission during driving; GC is gasoline consumption; CEF_{GC} is the gasoline carbon emission factor; DC is diesel fuel consumption; CEF_{DC} is the diesel oil carbon emission factor;

The reduction of carbon emissions in the transportation sector is the combination of the change in carbon emissions caused by miles traveled and the change in carbon emissions caused by private car ownership. The reduction of carbon emissions can be obtained from Equation (8).

$$CR_T = CM \times CE_T + RCO \tag{8}$$

where CR_T is the amount of carbon reduction in transportation; CR_P is the carbon reduction associated with producing a car.

2.3. Survey Design

This study analyzes consumer preferences for attributes that explain and influence car-sharing use. Because car-sharing services are used only by people with a driver's license, only 738 out of 753 questionnaires were included. Thus, the data of 738 people were used to conduct an empirical study on car-sharing services. The demographic characteristics of survey respondents are shown as Table 1. The first part collected the social and demographic characteristics of the interviewees, including gender, age, location, occupation, family and personal income level, as well as the number of family members, aiming to analyze the acceptance and preference of people from different social backgrounds for car sharing, to predict the development of car sharing in China. To prevent unbalanced population distribution in regions with different economic development levels, regions were divided into super first-tier cities, new first-tier cities, second-tier cities, third-tier cities, fourth-tier cities and wireless cities, according to their economic development levels. Then, quota sampling was carried out according to the population of the city to ensure that the sample was representative.

Table 1. Demographic characteristics of survey respondents.

Demographic Variable	Category	Respondents	Percentage
	Total	**753**	**100.00%**
Gender	Female		59.89%
	Male		40.11%
Age	<18	15	1.99%
	18~30	627	83.27%
	30~45	88	11.69%
	45~60	20	2.66%
	>60	3	0.40%
Education	Graduate degree	204	27.64%
	Undergraduate degree	497	67.34%
	Below secondary education	37	5.01%
Occupation	Self-employed	27	27.37%
	Full-time professional	202	3.66%
	Student/Jobless	509	68.97%
Income	<3000	468	63.41%
	3000~8000	172	23.31%
	8000~20,000	79	10.70%
	>20,000	19	2.57%
Number of family members	1	28	3.79%
	2	49	6.64%
	3	250	33.88%
	4	283	38.35%
	>4	128	17.34%

The second part addressed people's understanding and acceptance of car sharing and people's mileage before and after using car sharing based on survey data such as frequency and distance of car sharing trips. The influence of car sharing on the number of private cars is analyzed through the changes in people's traffic behaviors after using car sharing, such as getting rid of their cars and foregoing buying cars.

The third part explored the motivation of people to use car sharing and the reasons for not using car sharing. Meanwhile, the factors influencing people's use of car sharing were investigated, including service quality, the convenience of taking back the car, the associated fees, etc. Respondents were given the opportunity to share ideas for improvement of car sharing as well as possible policy directions. Respondents were asked if they would like to use the service. Those who answered that they did not want to use car-sharing options were classified as "no option" in the subsequent analysis, and it was assumed that they retained their existing traffic behaviors. The basic methodology used in this study is presented in Figure 5.

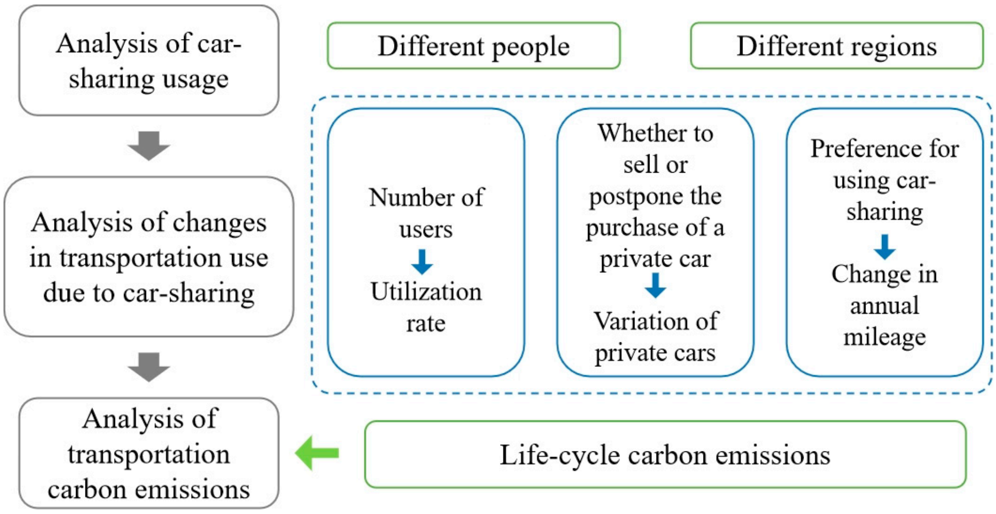

Figure 5. The basic methodology used in this study.

3. Results

Among the 738 valid questionnaires investigated, 187 people choose to use car-sharing services, accounting for 27.62%. Among them, 30.56% were in first-tier cities, and only 20.41% were in fourth-tier and fifth-tier cities. This indicates that the use of car sharing is closely related to economic development, which may mean that more vehicles are available in first-tier cities. More car-sharing services have been linked to higher levels of education in the area as a whole. The related studies show that there is a higher acceptance of car-sharing services among those with higher degrees.

3.1. Mileage

Car-sharing services change the way people travel and thus affect traffic emissions; for example, for a person without a car, car-sharing services would transform the method of traveling from walking and taking public transportation to car sharing, thereby increasing mileage. The increase in energy consumption for travel increases carbon emissions accordingly. For car-free people who use car sharing, the total mileage of driving vehicles (or taxis) increases by 16.65% after using car sharing. This corroborates Wu's findings, which show that people drive more miles when they use car sharing [20], as 85.56% think that car sharing provides convenience for their life.

Car-sharing services also lead people to sell their old cars or plan to abandon or delay the purchase of private vehicles, moving from the use of private vehicles toward sharing cars or public transport. This reduces driving frequency, thereby decreasing the energy used by vehicles and the carbon emissions from transport. The changes in the number of people using car-sharing services and the amount and rate of carbon emission reduction are shown in Table 2.

Table 2. Influence of car-sharing service on carbon emission of miles traveled.

Year	Transportation Energy Carbon Emissions (Ten Thousand Tons)	Percentage of Car-Sharing Services	Carbon Reduction Ratio of Transportation	Carbon Reduction Amount of Transportation (Ten Thousand Tons)
2015	8696.6	0.40%	0.04%	3.40
2016	9015.9	1.46%	0.14%	12.93
2017	9567.3	2.66%	0.26%	24.91
2018	10,015.4	7.30%	0.71%	71.40
2019	10,676.2	13.55%	1.31%	140.29
2020	11,119.6	19.12%	1.85%	N/A
2021	11,619.4	24.70%	2.37%	N/A

3.2. Number of Private Cars

The impact of car-sharing services on private car ownership can be divided into two aspects. On the one hand, car-sharing services can lead to people selling their old cars and thus reducing private car ownership; however, the data are less definitive than in previous studies. In a survey of car owners who use car-sharing services, out of 129 valid questionnaires, only seven people chose to sell their car, while 122 people chose not to. This may be due to people's perceived power in car ownership; that is, selling a car makes people feel insecure. On the other hand, car-sharing services will provide convenience for those who do not own a car, so they choose to give up or postpone the purchase of private cars, thus reducing the ownership of private cars by decreasing the number of new private car purchases. In this study, among 57 surveys, four people gave up buying, accounting for 7.02%, 38.60% chose to postpone buying, and 31 people still decided to buy a vehicle. The number of people who delayed or gave up buying cars accounts for 45.61% of those without cars.

With the introduction of car-sharing services, the trend of private car consumption basically shows a downward trend; the number of private cars owned from 2015 to 2021 is shown in Figure 6. The number of newly added private cars in 2021 was 17 million. The people using car-sharing services accounted for 24.68% of the population without a car. It can be seen that car-sharing services reduced the number of newly added private cars by 2.13 million in 2021. Thereby, the carbon emissions saved by delaying or foregoing the purchase of private cars in 2021 could reach 8.328 million tons, as shown in Figure 6. The carbon reduction data for other years are also provided in Table 3.

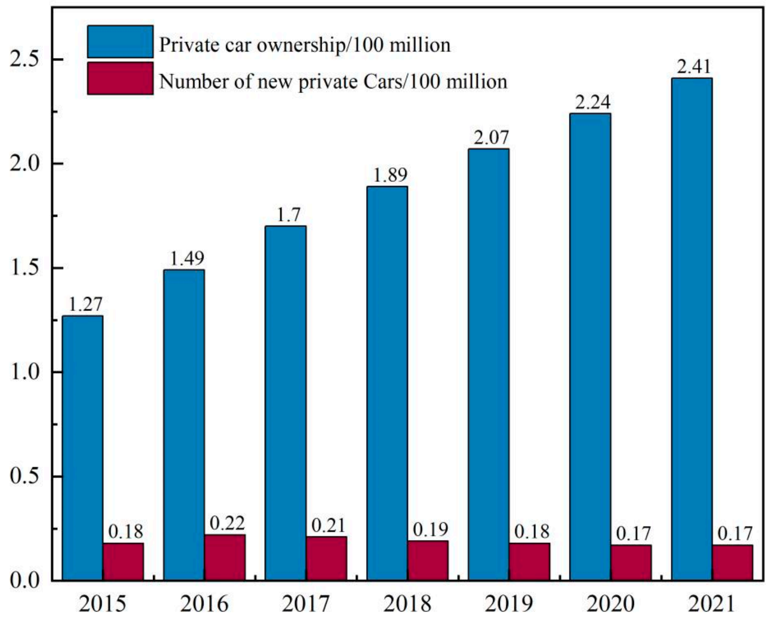

Figure 6. Influence of car-sharing services on the number of private cars.

Table 3. Carbon reduction brought about by the reduction of private cars.

Year	Total Number of Private Cars Reduced (100 Million)	Total Carbon Reduction (Ten Thousand Tons)	Effect
2015	0.0024	92.65	1.32%
2016	0.0048	186.99	2.17%
2017	0.0169	662.59	8.07%
2018	0.0408	1596.53	21.48%
2019	0.0530	2073.44	29.45%
2020	0.0581	2272.24	33.69%
2021	0.0598	2339.13	35.68%

3.3. Carbon Emissions

Car-sharing services influence carbon emissions and lead to carbon reduction. The calculation results are presented in Table 3. There is a lack of traffic emissions statistics for 2020 and 2021 because of a lack of recent data. However, the carbon reduction ratio of transportation can reflect the carbon reduction ability. Meanwhile, it should be noted that the carbon reduction ratio of transportation represents the carbon emissions of private cars rather than the whole transportation sector. Car-sharing services affect only the travel of personal vehicles and have little influence on travel behavior with regard to trucks, buses and railways.

The results show that car-sharing services can lead to a 2.37% carbon reduction in the current scenario and in the 2021 scenario. This is similar to the research results of Wu, though the results of this study are less conclusive those of Wu's study, which may be due to the fact that China's national conditions are different from other countries. China's car sharing started late, and although the development was rapid, the overall scale is still much smaller than that of other countries. Meanwhile, China's public transportation is relatively developed, and the accessibility of public transportation and the development of car sharing have a restraining trend [15].

3.4. Sensitivity Analysis

Sensitivity analysis is a widely used method to analyze impact factors in engineering calculations. Sensitivity analysis centers around the sensitivity factor, which has important influence among many uncertain factors. Its influence degree or sensitivity degree with regard to benefits is analyzed and the extent to which the target factor can have an impact under the condition that other factors remain at the baseline is examined. Sensitivity analysis in this paper is used to analyze the impact of different factors on car-sharing services, so as to determine the carbon reduction potential of car-sharing services. This paper aims to discuss how much impact car sharing will have on the carbon emissions of the transportation sector if the usage pattern of car sharing is changed, the usage rate of car sharing is increased, the mileage driven is reduced or the number of private cars is affected. Based on the summary of relevant studies and the analysis of the results in Section 2, transport carbon emissions are obviously related to the proportion of shared car use, personal car disposal rate, purchase delay rate, change in mileage and energy consumption. Therefore, the ratio of shared car use, private car handling rate, purchase delay rate, mileage change and energy consumption are selected as the leading sensitivity indicators in this study.

Assuming that the behavioral preferences of car-sharing users remain unchanged, the sensitivity of total carbon emissions to the following factors can be obtained and analyzed: (1) improvement of vehicle energy structure: sharing cars changes energy consumption by increasing the proportion of electric vehicles, thus reducing energy consumption and affecting carbon emissions; (2) increasing the user number: changing the proportion of people using car-sharing services affects the number of private cars and the mileage; (3) transformation of car buying behavior: car owners sell their original private cars, and non-car owners delay or give up buying private cars, which reduces carbon emissions at the production stage; (4) shift of travel behavior: shortening travel mileage reduces carbon emissions.

Assuming other factors remain unchanged, this paper calculates the degree of change in carbon emissions by increasing or decreasing the proportion of shared car use, private car disposal rate, purchase delay rate, mileage change and energy consumption by 10%. The influence degree of this factor on carbon emission is analyzed. Table 4 shows the impact of the proportion of shared car use, private car disposal rate, purchase delay rate, change in mileage and energy consumption on carbon reduction in the transport sector. The comparison of the influence of each factor is shown in Figure 7. The personal car disposal rate strongly influences traffic carbon emissions compared with other factors. The following sections provide a detailed analysis of the critical factors to obtain more meaningful conclusions, which can guide the development of car sharing and the formulation of related policies.

Table 4. The influence of various factors on traffic carbon emissions.

	Carbon Emissions				
	Production Phase (10^4 t)	Operation Phase (10^4 t)	Total (10^4 t)	Carbon Reduction Ratio	Change in Carbon Reduction Ratio
Baseline scenario (2021)	2339.13	275.4456	2063.68	1.95%	
Increase in mileage of 10%	2339.13	542.5704	1796.56	1.70%	−0.25%
Increase in the number of users by 10%	2587.44	302.2736	2285.17	2.16%	0.21%
Increase in the sale of private cars by 10%	5245.85	275.4456	4970.40	4.69%	2.74%
Increase in deferred purchases by 10%	2550.40	275.4456	2274.95	2.15%	0.20%
Reduction of car energy consumption by 10%	2339.126	247.9011	2091.22	1.97%	0.03%

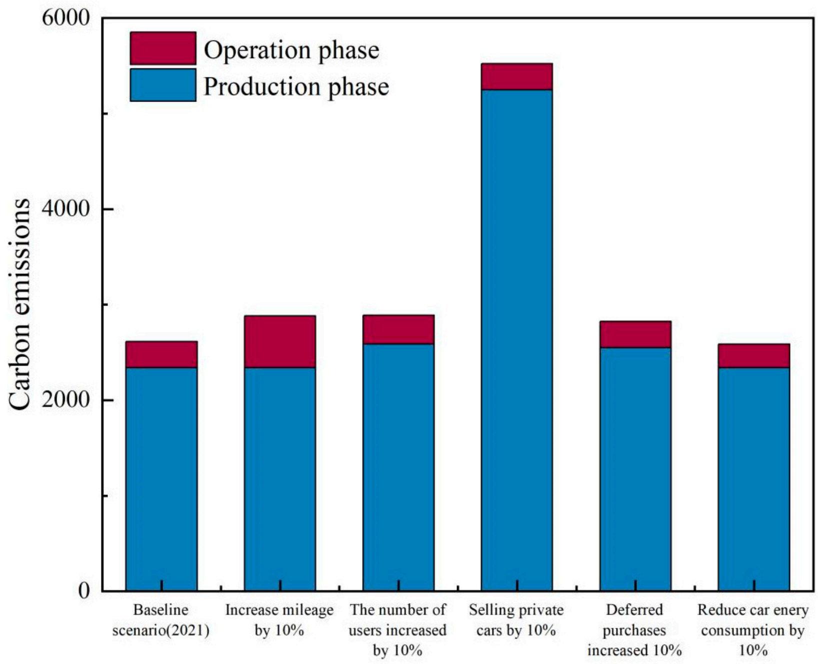

Figure 7. The influence of various factors on traffic carbon emissions.

3.4.1. Proportion of Car-Sharing Service

As shown in Table 4, a 10% increase in users would result in a 0.21% reduction in carbon emissions. The following reviews the factors influencing the use of car sharing, combined with the research of other authors, and proposes policies that promote the future of car sharing in China. The main factors affecting car-sharing service users are as follows. Stefanol [29] and Daejin [30] showed that gender, age, travel frequency, travel type and travel cost would impact travelers' willingness to participate in car sharing. Gender, education level, perception of car-sharing information and information accuracy affect the intensity and intention of car sharing in the future. Wu [20] believed that increasing travelers' willingness can be achieved by encrypting time-sharing rental car placement and shortening the time out of the car. Zhou [31] quantitatively analyzed the factors affecting travelers' willingness to use from the perspective of personal attributes, travel attributes and perceived attributes. In addition to individual characteristics, six psychological factors, including ease of renting, travel comfort, the rationality of charging, perceived risk, attitude and subjective norms, are also essential factors in travelers' car-sharing behaviors, as shown in Figure 8. Meanwhile, other factors also affect the use of car-sharing services. Ding [32] added that public transport's comfort, reliability, accessibility and safety affect travelers' choices. and proposed, through evolutionary game theory, that car-sharing parking problems should be actively addressed to promote the development of car-sharing services.

Figure 8. Factors influencing the usage rates of car sharing.

College students are considered a promising customer group of car-sharing services in China due to their high travel demands and lack of private cars. As mentioned in the previous paragraph, education level has a great impact on the intention to use car-sharing services, and college students, as a group with high education, have a high acceptance of new things, which makes them inclined to use car-sharing services. At the same time, age statistics also show that college students are more inclined to accept car-sharing services. In addition, increasing the proportion of college students will promote the development of car-sharing services. Zhou [31] studied the intention of college students to use car-sharing services and showed that providing them with commuting subsidies would provide an incentive to participate in car sharing. Sun [26] investigated the desire of college students at Dalian Maritime University to use car-sharing services. The study showed that the willingness of college students and the number of travel partners were more affected by the capital costs than the time costs involved. This is because college students have less money than they have time. Sun proposed that the car-sharing service utilization rate can be improved for college students by providing test-drive services, allowing differentiated charging standards for student memberships, and offering a discount for high-occupancy vehicles.

Therefore, to actively promote car-sharing services, it is recommended that car-sharing companies increase the number of car-sharing users, especially college students, by lowering fees. In addition, improving the operating comfort and internal cleanliness of vehicles can improve travel comfort. In addition, improving the convenience of returning the car through a reasonable return mode and flexible parking mechanism can also promote the use of car sharing. On the subjective side, perceived risk and the perception of car-sharing information also greatly affect the promotion of car sharing. Improving travel safety and providing reasonable compensation for investment are conducive to reducing people's perceived risk. Legislation to fully protect the rights and interests of travelers can promote the reduction of perceived risks, which is conducive to the expansion of car-sharing services. Strengthening the publicity of car sharing and improving the perception of car-sharing information will lead to increased enthusiasm to use car sharing. In view of the potential usage by college students, enterprises can implement differentiated charging standards for college students, and government departments can provide commuting subsidies for college students who use car-sharing services.

3.4.2. Private Car Handling Rate

The impact of private cars on the transport sector's carbon emissions is mainly achieved by reducing carbon emissions in the production stage of vehicles. Hence, the carbon emissions of the whole life cycle of the vehicle should be considered, as shown in Figure 9. The higher the disposal rate of private cars, the lower the carbon emissions caused by the production of cars. Although private cars that are sold have already produced carbon emissions, these private cars will be bought by users who need to buy cars, reducing the demand for new cars and the number of produced cars. Every 10% increase in the proportion of people selling private cars can bring about a 2.74% carbon emission reduction, the highest among all the impact factors A large number of car owners using car sharing will result in a considerable carbon emission reduction.

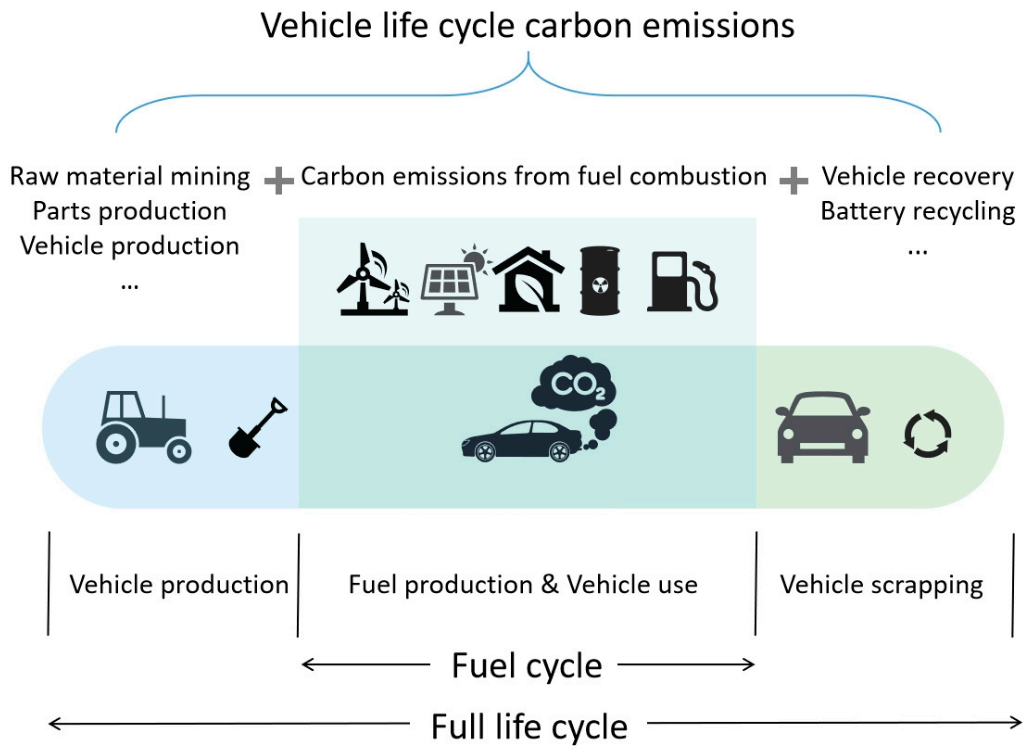

Figure 9. Vehicle life-cycle carbon emissions.

Many studies have been conducted on the factors affecting the disposal rate of private cars. Relinquishing ownership of a vehicle while emphasizing the right to use the vehicle is a theme of China's motorization development. Under the situation of solid demand for one car in big cities and the gradual entry of a second car into families, the active introduction of environmentally friendly car-sharing services can address residents' demand for motorization; the resulting potential effect has significance in reducing urban greenhouse gas emissions.

3.4.3. Delayed or Abandoned Purchase Rate

Delaying or giving up on buying private cars after using a car-sharing service may cause carbon emission reductions. Similar to selling private cars, carbon emissions can be decreased with a decrease in the number of private cars. However, this depends on the number of new vehicles purchased. Therefore, although the delay or abandonment of intention to purchase is high, the resulting impact on carbon emissions is not significant. If the delayed or abandoned purchase rate could increase by 10%, it could bring a 0.20% reduction in carbon emissions. The changes in the number of private cars after using car-sharing services are presented in Figure 10.

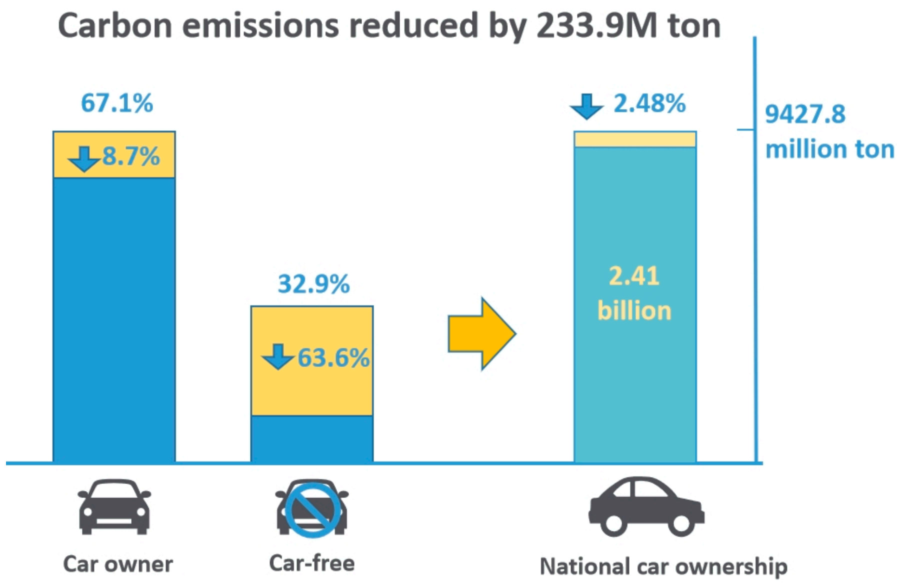

Figure 10. Changes in the number of private cars after use of car-sharing services (A downward arrow indicates a decrease).

Delaying or giving up the purchase of private cars can reduce the carbon emissions from transportation. Research has been done on the reduction of people's desire to buy private cars. Ding [32] found that young people pay more attention to convenience when traveling, and the parking environment and the number of restrictions influence their intention to buy cars. Hui [27] analyzed the willingness of car-sharing users in Hangzhou to postpone buying cars and showed that car sharing presented a positive effect on delaying private car purchase. The delayed or abandoned purchase rate is related to motivation for joining a shared car, satisfaction with using the shared car, frequency of using the shared car, the purpose of travel and whether the purchase plan is determined. Satisfaction is an essential factor that influences the delay in buying a car. Car-sharing companies should produce more reliable and high-quality cars to be launched in business districts to attract more people for work-related travel. Zhou [33] analyzed the influencing factors of urban residents' intention to buy cars. The empirical results showed that policy and institutional support had the most substantial positive promoting effect on acceptance and perception of service quality, significantly affecting residents' intention to give up or delay buying cars. In contrast, perceived usefulness had an inhibiting effect. The purchasing purpose in first-tier cities and the actions of non-purchasing groups are more easily affected by the quality of car-sharing services, while the purchasing choices of non-first-tier cities and purchasing groups are more significantly affected by the perceived ease of use of car-sharing services and the support of policies and institutions.

3.4.4. Mileage Change

Mileage is the most intuitive reflection of the change in carbon emissions. The introduction of car-sharing services will inevitably bring about changes in travel, which directly affects the total mileage of trips. More total miles require more energy consumption and result in more carbon emissions. Hence, a 10% increase in the total mileage of people using car-sharing services will lead to a 0.25% increase in carbon emissions, as shown in Figure 11, similar to Xu's research results [34]. Due to the convenience and economy of car-sharing services, the development of car-sharing services in China will strengthen the dependence on car use. Ref. [35] shows that network convenience, accessibility of public transport and overall satisfaction positively impact car use dependence. In contrast, annual household income has a significant negative impact on car use and is positively associated with accessibility of public transport. Therefore, to reduce carbon emissions caused by over-dependence on car use, the scale of car sharing, the network and the background of public transport service should be the focus of the government's attention.

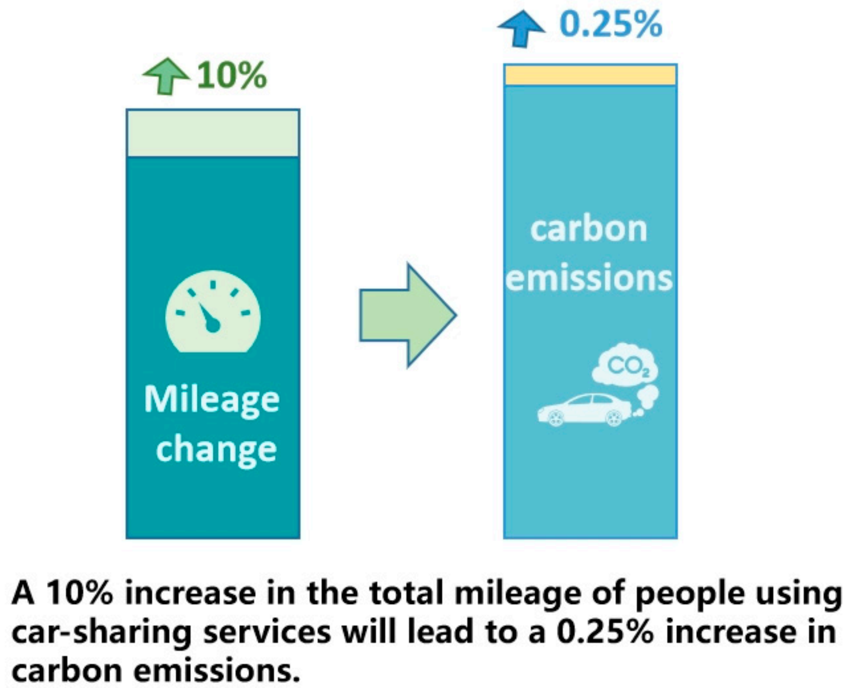

Figure 11. The impact of mileage changes on transport carbon emissions (An upward arrow indicates an increase).

3.4.5. Cars Consume Energy

Car energy consumption affects the carbon emissions of car-sharing services. Electric vehicles have lower energy consumption and carbon emissions than fossil-fuel vehicles. Wang's research [36] shows that electric vehicles demonstrate 33% of fossil-energy consumption and 18% carbon emission reduction. More significant energy saving and emission reduction benefits may be possible in the future due to substantially reduced battery energy consumption. It is expected that carbon emissions will be reduced by 40% by 2030; carbon reduction capacity is more evident in the case of congestion. Therefore, as more electric vehicles are introduced into car-sharing services, the proportion of electric vehicles increases, leading to carbon emission reductions.

This paper provides the carbon-saving potential of quantitatively changing the proportion of electric vehicles used as shared vehicles. If the increase of electric vehicles results in the average energy consumption of car-sharing services being reduced by 10%, a 1.97% carbon reduction can be obtained, as shown in Figure 12. As EVs provide higher fuel efficiency, EV purchase should be subsidized to achieve a higher proportion of daily trips covered by EVs. Driving behavior also affects the energy consumption of cars. The average speed should be maintained at 10–40 km/h, and the accelerator pedal should be limited to 10–20% at the initial stage. Reducing speed changes can decrease the energy consumption of electric vehicles. Hence, for electric vehicles, attention should be paid to the control of the average speed at the stopping stage. Nevertheless, too-low average speed will lead to increased energy consumption; and safety and comfort are also affected by severe deceleration. The average speed should be controlled at 20–30 km/h during stopping. Moreover, stopping methods that avoid extreme acceleration can also be a future area of research. To reduce the driving energy consumption of electric vehicles during the running stage, a reasonable driving speed should be maintained. In a traffic environment with no speed limit, the energy consumption of 100 km within the speed range of 40~60 km/h is best. In addition, it is necessary to control the degree of the accelerator pedal, which is best kept to between 10% and 20% for 100 km to realize the lowest energy consumption [37].

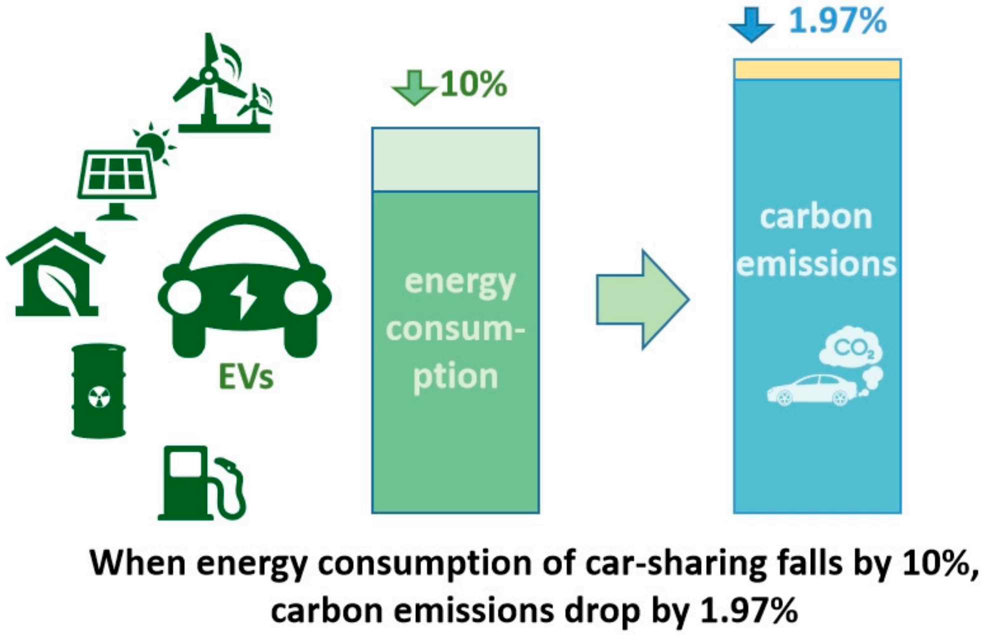

Figure 12. The impact of improving vehicle energy efficiency on transport carbon emissions (A downward arrow indicates a decrease).

4. Discussion and Conclusions

4.1. Discussion

The introduction of car-sharing services has the effect of increasing the number of miles driven, which is mainly due to the increase in trips due to the addition of new users; this is in accordance with Wu [20]'s study, which found increased carbon emissions as a result of car sharing. However, car sharing also leads to the reduction of private car ownership. The impact in China is smaller than that in other countries [7–10,12,13]; this is because the national conditions of China and other countries are different. Car-sharing services in China are still in their infancy. In addition, car-sharing services can also affect carbon emissions by influencing the number of electric vehicles. A 10% increase in fuel efficiency will bring a 1.97% carbon reduction, which confirms Zhou's research [33].

According to the above analysis, the private car purchase rate has the highest impact. A 10% increase in private car processing would result in an additional 2.74% carbon reduction, more than double the carbon reduction of existing car sharing. In addition, high fuel efficiency also greatly promotes carbon reduction; when the average energy consumption is reduced by 10%, the transport sector's carbon emissions will be reduced by 1.97%. The increase in the number of users, the change in the number of miles driven and the rate of deferral of purchases also contribute 0.21%, 0.25% and 0.2% to transport carbon emissions; though these percentages are relatively small, they represent a large impact on the overall transport sector.

4.2. Conclusions

This study examines the contribution of China's car-sharing service on carbon emission reduction. The consumer preferences and the probability of choosing car sharing or giving up private car ownership by using car-sharing services are analyzed. The additive effect of increasing mileage and the reduction of vehicle ownership are discussed. The impact of the number of users and the energy efficiency are also discussed. Feasible suggestions for promoting the development of car sharing in China to car-sharing companies and government departments are provided. The results show that the reduction in greenhouse gas emissions from vehicles not purchased or produced exceeds the additional greenhouse gas emissions from switching from public transport or private cars to car sharing. This indicates that the condition of existing car-sharing services can effectively reduce greenhouse gas emissions, which is consistent with other related results. The study estimates that the region's vehicle forfeiture rate was 2.48 percent, including those who chose to get rid of their cars after using shared vehicles and those without cars who decided to give up or delay buying cars. Studying the life-cycle carbon emissions of car sharing can provide insight into the true impact of car sharing on the environment, thus providing more effective policies for sustainable social and transport systems.

Moreover, car sharing can affect carbon emissions by changing the proportion of electric vehicles on the road. Since car sharing may not be as fuel-efficient as private cars, the higher the proportion of electric vehicles in a car-sharing fleet, the more significant the impact on the environment. Unlike private cars, car-sharing vehicles are assigned by service providers, which allows customers to choose from a limited range of shared vehicles suppliers offer. To reduce the negative environmental impact of car sharing, more efficient vehicles (such as those with a higher fuel efficiency or longer life cycle) can be selected. It is important to create an environment where more people can choose electric car-sharing vehicles for emission reduction. Moreover, an environmentally friendly mix of power generation may be the most suitable choice for car sharing.

4.3. Limitations and Future Research Topics

Limitations of the study include that the we only considered CO_2 emissions to assess environmental impact, excluding social and economic effects, such as personal interest in obtaining a car you do not need to own. As mentioned earlier, other aspects associated with car sharing have many positive effects, such as increased personal mobility at a lower cost than owning a private car. However, this paper only analyzes three main factors related to environmental impact and suggests how to operate car-sharing services in a more environmentally friendly way. In addition, this study estimates changes in behavior associated with the introduction of car-sharing services and subsequent changes in carbon emissions. Nevertheless, when calculating the carbon emission impact, other unique features of car-sharing services are not taken into account, namely the impact that the life of the shared car may have on car production. Car sharing results in a shorter service life of cars due to many people sharing vehicles. As a result, vehicles are replaced more frequently than private cars, making it more feasible to update car-sharing vehicles with the latest environmentally friendly technology, with more positive environmental effects. The service life of car sharing can be extended. Unlike with private cars, the disposal of vehicles is the responsibility of car-sharing operators. Thus, the vehicle can be used for its maximum product life until it is no longer technically feasible. Thereby, more specific car-sharing characteristics can be considered in further research for more accurate assessment.

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