sustainability

MDPI

*Article*

# $CO_2$ Emission Reduction Potential of Road Transport to Achieve Carbon Neutrality in China

**Jieshuang Dong, Yiming Li, Wenxiang Li * and Songze Liu**

Business School, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China; dongjs@usst.edu.cn (J.D.); 202531033@st.usst.edu.cn (Y.L.); 1935021716@st.usst.edu.cn (S.L.)
* Correspondence: liwx@usst.edu.cn

**Abstract:** Under the targets of peaking $CO_2$ emissions and carbon neutrality in China, it is a matter of urgency to reduce the $CO_2$ emissions of road transport. To explore the $CO_2$ emission reduction potential of road transport, this study proposes eight policy scenarios: the business-as-usual (BAU), clean electricity (CE), fuel economy improvement (FEI), shared autonomous vehicles (SAV), $CO_2$ emission trading (CET) (with low, medium, and high carbon prices), and comprehensive (CS) scenarios. The road transport $CO_2$ emissions from 2020 to 2060 in these scenarios are calculated based on the bottom-up method and are evaluated in the Low Emissions Analysis Platform (LEAP). The Log-Mean Divisia Index (LMDI) method is employed to analyze the contribution of each factor to road transport $CO_2$ emission reduction in each scenario. The results show that $CO_2$ emissions of road transport will peak at 1419.5 million tonnes in 2033 under the BAU scenario. In contrast, the peaks of road transport $CO_2$ emissions in the CE, SAV, FEI, CET-LCP, CET-MCP, CET-HCP, and CS scenarios are decreasing and occur progressively earlier. Under the CS scenario with the greatest $CO_2$ emission reduction potential, $CO_2$ emissions of road transport will peak at 1200.37 million tonnes in 2023 and decrease to 217.73 million tonnes by 2060. Fuel structure and fuel economy contribute most to the emission reduction in all scenarios. This study provides possible pathways toward low-carbon road transport for the goal of carbon neutrality in China.

**Keywords:** road transport $CO_2$ emissions; Low Emissions Analysis Platform (LEAP); Log-Mean Divisia Index (LMDI) method; carbon neutrality

check for updates

**Citation:** Dong, J.; Li, Y.; Li, W.; Liu, S. $CO_2$ Emission Reduction Potential of Road Transport to Achieve Carbon Neutrality in China. *Sustainability* **2022**, *14*, 5454. https://doi.org/10.3390/su14095454

Academic Editor: Marco Raugei

Received: 20 March 2022
Accepted: 28 April 2022
Published: 1 May 2022

## 1. Introduction

With improvements in people's living standards, China's vehicle population is increasing yearly. Consequently, $CO_2$ emissions from road transport are showing an increasing trend. According to data from the International Energy Agency, in 2019, $CO_2$ emissions generated by the global transport sector accounted for approximately 1/4 (24.2%) of total global $CO_2$ emissions, with emissions of approximately 8 million tonnes, of which emissions in the road transportation sector were approximately 6.5 billion tonnes, accounting for 81% of the whole transportation sector [1]. In addition, $CO_2$ emissions from the transport sector have increased at the fastest rate in recent decades. This proportion is expected to increase to 41% by 2030. To address global climate change, China proposed to achieve the goals of $CO_2$ emission peaking by 2030 and carbon neutrality by 2060. Therefore, reducing transport $CO_2$ emissions is essential for achieving the goal of carbon neutrality [2,3], especially for the road transport sector.

Due to the uncertainty in policies, the future trend of road transport $CO_2$ emissions is ambiguous. Therefore, it is a matter of urgency to make reliable predictions on road transport $CO_2$ emissions and propose effective ways toward low-carbon road transport. Presently, most existing studies focus on the $CO_2$ emissions of transportation companies, disregarding private transportation. In addition, certain emerging scenarios, such as electric vehicles with cleaner power, shared autonomous vehicles, and $CO_2$ emission trading markets, are rarely considered. Therefore, research on road transport $CO_2$ emissions under the target of carbon neutrality is still insufficient.

To fill these gaps, this study aims to explore the $CO_2$ emission reduction potential of road transport to achieve carbon neutrality in China. First, we propose eight policy scenarios: the business-as-usual (BAU), clean electricity (CE), fuel economy improvement (FEI), shared autonomous vehicles (SAV), $CO_2$ emission trading (CET) (with low, medium, and high carbon prices), and comprehensive (CS) scenarios. Second, we analyze the $CO_2$ emission reduction of road transport in each scenario and identify the key factors that contribute to emission reduction. Last, we make several policy suggestions to reduce $CO_2$ emissions of road transport for the goal of carbon neutrality in China. The main contributions of this study are as follows:

- First, taking into account private road transport, the total $CO_2$ emissions of China's road transport can be calculated and predicted more comprehensively and accurately.
- Second, future policy scenarios with emerging technologies and markets that are aimed at significantly enhancing the $CO_2$ emission reduction potential of road transport are introduced.
- Third, the contribution of key factors that influence road transport $CO_2$ in different scenarios are decomposed to support policy design and decision-making.

The remainder of this study is organized as follows: Section 2 reviews existing research on road transport $CO_2$ emissions. Section 3 elaborates on the method and model for the analysis of road transport $CO_2$ emissions. Section 4 presents several policy scenarios and related parameters. Section 5 analyzes and discusses the research results of this study. Section 6 summarizes the main findings and makes policy suggestions.

## 2. Literature Review

### *2.1. Calculation of Road Transport $CO_2$ Emissions*

Given the complexity and dispersion of transportation $CO_2$ emissions, there are still great challenges in the quantitative assessment of road transport $CO_2$ emissions. Referring to the national greenhouse gas inventory guidelines of the Intergovernmental Panel on Climate Change (IPCC), the current calculation methods of $CO_2$ emissions from mobile sources mainly include the "top-down" and "bottom-up" approaches [4]. The "top-down" method calculates the road transport $CO_2$ emissions by multiplying the total consumption of various fuels by their corresponding $CO_2$ emission factors [5]. For the "bottom-up" method, the vehicle mileages, fuel structures, and fuel economy of various types of vehicles should be collected to calculate the total $CO_2$ emissions of road transport [6]. For comparison, the "top-down" method has advantages in data collection and calculation, while the "bottom-up" method provides more details about the contribution of $CO_2$ emissions. In practice, researchers usually combine both approaches to calculate $CO_2$ emissions from road transport [7]. For a life cycle assessment of road transport $CO_2$ emissions, the "life cycle" method should be used to calculate the total $CO_2$ emissions of upstream, midstream, and downstream industries associated with road transport, including the production, transportation, use, disposal of vehicle, and fuels [8]. Due to the lack of data on private transport, most of the existing empirical studies of road transport $CO_2$ emissions focus on operational transportation, such as buses, taxis, intercity passenger transport, intercity freight transport, etc. To fill this gap, this study accounts for both operational and private transport and analyzes the $CO_2$ emission reduction potential of different road transport subsectors.

### *2.2. Influencing Factors of Road Transport $CO_2$ Emissions*

Presently, many scholars are committed to studying the influencing factors of road transport $CO_2$ emissions and have produced more systematic research results in this field. For example, Zhang et al. [9] divided the main factors affecting transport carbon dioxide emissions into three categories: demand-side factors, supply-side factors, and environmental measurement factors. To further analyze the impact of different factors on road transport $CO_2$ emissions, the $CO_2$ emission contribution of each factor can be obtained by the Log-Mean Divisia Index (LMDI) method, and targeted policy suggestions can be presented. Based on this method, Liu et al. [10] investigated the main factors of $CO_2$ emissions in the field of transportation and formulated corresponding energy-saving policies in China. Quan et al. [11] analyzed the influences of the $CO_2$ emission factor, energy intensity, energy structure, economic level, and population on $CO_2$ emissions from China's logistics industry. However, most of the existing studies neglect the influence of power generation. With the substantial increase in the market share of electric vehicles in the future, the emission factor of power generation will also become a key factor affecting the $CO_2$ emissions of road transportation. Therefore, this study will explore the contribution of clean electricity to the $CO_2$ emission reduction of road transport.

### *2.3. Emission Reduction Potential of Low-Carbon Transport Policy*

The formulation and implementation of low-carbon transport policies are the main ways to promote the low-carbon transition of transport. Many studies analyze the road transport emission reduction potential under different low-carbon transport scenarios. In these studies, the impacts of various policies and combinations, such as fuel tax, fuel labeling, new car purchase tax reduction, high emission vehicle purchase penalty tax, vehicle scrapping incentive, and vehicle transport restriction, on transport $CO_2$ emissions have been widely analyzed and discussed [12–21]. The bottom-up models, such as the Transport and Mobility Leuven (TREMOVE), Integrated Land Use and Transport Modeling System (TRANUS), Integrated MARKAL-EFOM System (TIMES), and Low Emissions Analysis Platform (LEAP), can be used to evaluate the emission reduction potential of low-carbon transport policies. Local parameters such as vehicle population, vehicle structure, fuel economy, and emission factors are usually inputted into the model [22–24]. Among them, the LEAP is one of the most popular analytical methods because it requires less data and can provide a comprehensive scenario analysis. For example, based on the LEAP, Feng et al. [25] analyzed the trend of energy demand, pollutants, and carbon emissions in China's transportation sector under three policy scenarios: pollution reduction (PR), low carbon (LC), and the deep-seated low carbon (DLC) scenarios. Pang et al. [26] analyzed the impact of three scenarios with different policies and measures on greenhouse gas emissions from road transport in Lanzhou, China, from 2015 to 2040 based on the LEAP. However, most scenarios in the existing studies did not include certain future policy scenarios, such as electric vehicles with cleaner power, shared autonomous vehicles, $CO_2$ emission trading markets, etc. Therefore, the emission reduction potential of road transport may be underestimated [27]. To help reach the goal of carbon neutrality in China, this study will propose more emerging and comprehensive policy scenarios and assess the $CO_2$ emission reduction potential of road transport under these scenarios.

## **3. Methods**

### *3.1. Research Framework*

To evaluate the $CO_2$ emission reduction potential of China's road transport sector and the contribution of various influencing factors, this study integrates the LEAP with the LMDI method. The research framework is shown in Figure 1. First, the future population of China is predicted based on the death rate and birth rate of the historical population. Meanwhile, the future vehicle population is predicted based on the Gompertz model. Second, we set eight policy scenarios with different parameters, such as vehicle structure, vehicle mileage, fuel economy, and emission factors. Third, the LEAP is used to predict $CO_2$ emissions of road transport in China from 2020 to 2060 and analyze the $CO_2$ emission reduction potential of different scenarios. Last, the LMDI method is applied to calculate the contribution of various factors to $CO_2$ emission reduction in each scenario.

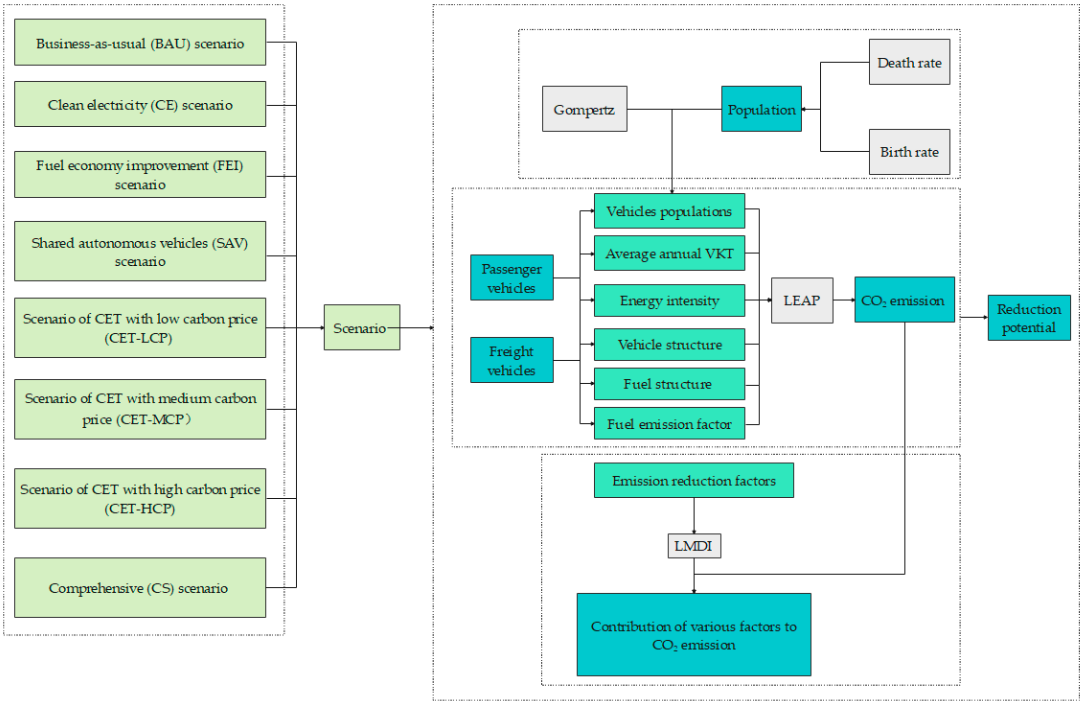


**Figure 1.** Research framework.

### 3.2. Road Transport $CO_2$ Emission Calculation

In this study, the $CO_2$ emissions of road transport are calculated by the bottom-up method. This method calculates road transport $CO_2$ emissions based on the "ASIF" framework [2,3], where "A" represents the travel activity, "S" represents the mode share, "I" represents the energy intensity of each mode, fuel, and vehicle type, and "F" represents and carbon content of each fuel to total emissions. The road transport $CO_2$ emissions include emissions from both passenger and freight transport. The equation is expressed as follows:

$$C = C_P + C_T \tag{1}$$

where $C_P$ is the total $CO_2$ emissions of road passenger transport, $C_T$ is the total $CO_2$ emissions of road freight transport, and $C$ is the total $CO_2$ emissions of road transport.

The equation for calculating passenger transport $CO_2$ emissions is expressed as follows:

$$C_P = \sum_{i=1}^{4} \sum_{k=1}^{3} N_P S_i M_i Q_{ik} F_{ik} E_k \tag{2}$$

where $i$ = 1, 2, 3, and 4 refer to mini, small, medium, and large passenger vehicle types, respectively; $k$ = 1, 2, and 3 represent fuel types of gasoline, electricity, and hybrid, respectively; $N_P$ is the total number of passenger vehicles; $S_i$ is the proportion of passenger vehicles of type $i$; $M_i$ is the average annual VKT of vehicles of type $i$; $Q_{ik}$ is the proportion of fuels of type $k$ for vehicles of type $i$; $F_{ik}$ is the fuel economy of vehicles of type $i$ with fuel type $k$; and $E_k$ is the $CO_2$ emission factor of fuel of type $k$.

The equation for calculating freight transport $CO_2$ emissions is expressed as follows:

$$C_T = \sum_{j=1}^{4} \sum_{h=1}^{4} N_T S_j M_j Q_{jh} F_{jh} E_h \tag{3}$$

where $j$ = 1, 2, 3, 4 refer to mini, light, medium, and heavy freight vehicles, respectively; $h$ = 1, 2, 3, 4 represent fuel types of diesel, gasoline, electricity, and natural gas, respectively; $N_t$ is the total number of freight vehicles; $S_j$ is the proportion of freight vehicles of type $j$; $M_j$ is the average annual VKT of trucks of type $j$; $Q_{jh}$ is the proportion of fuels of type $h$ for freight vehicles of type $j$; $F_{jh}$ is the fuel economy of trucks of type $j$ with fuel type $h$; and $E_h$ is the $CO_2$ emission factor of fuel of type $h$.

According to Equations (1)–(3), Equation (1) is equivalent to:

$$C = \sum_{i=1}^{4}\sum_{k=1}^{3} N_P S_i M_i Q_{ik} F_{ik} E_k + \sum_{j=1}^{4}\sum_{h=1}^{4} N_T S_j M_j Q_{jh} F_{jh} E_h \quad (4)$$

### 3.3. Low Emissions Analysis Platform (LEAP)

The LEAP is mainly aimed at the whole process of terminal energy consumption and comprehensively evaluates the influence of various technologies and policies on energy conservation and emission reduction from the aspects of energy supply structure, energy technology level, energy demand, etc., which is more consistent with the content and goal of research on the low-carbon development path of urban transportation [28–30]. The LEAP is a medium- and long-term modeling tool. In most studies that use the LEAP, the prediction period is generally 20 to 50 years. Therefore, this study uses the LEAP to predict the changing trend of China's road transport $CO_2$ emissions in different policy scenarios from 2020 to 2060. The parameter settings of these scenarios are introduced in the next section. We can then analyze the characteristics of peak $CO_2$ emissions years and trends in different scenarios and compares them with the BAU scenario.

### 3.4. Log-Mean Divisia Index (LMDI) Method

The LMDI method is a complete decomposition analysis method without residual error [31]. Using the LMDI method, the contribution of different factors to $CO_2$ emission reduction can be examined. This study decomposes the change in road transport $CO_2$ emissions from base year 0 to target year $t$ into six parts of contribution, as shown in Equation (5).

$$\Delta C = C^t - C^0 = \Delta C_N + \Delta C_S + \Delta C_Q + \Delta C_F + \Delta C_M + \Delta C_E \quad (5)$$

where $C^t$ represents the $CO_2$ emissions of road transport in the target year; $C^0$ represents the $CO_2$ emissions of road transport in the base year; $\Delta C_N$ represents the contribution of vehicle population; $\Delta C_S$ represents the contribution of vehicle structure; $\Delta C_Q$ represents the contribution of fuel structure; $\Delta C_F$ represents the contribution of fuel economy; $\Delta C_M$ represents the contribution of average annual VKT, and $\Delta C_E$ represents the contribution of fuel $CO_2$ emission factors.

According to the decomposition method of the LMDI, each item on the right side of Equation (5) can be expressed as follows:

$$\Delta C_N = \sum_{i=1}^{4} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln(\frac{N_P^t}{N_P^0}) + \sum_{j=1}^{4} \frac{C_j^t - C_j^0}{\ln C_j^t - \ln C_j^0} \ln(\frac{N_T^t}{N_T^0}) \quad (6)$$

$$\Delta C_S = \sum_{i=1}^{4} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln(\frac{S_i^t}{S_i^0}) + \sum_{j=1}^{4} \frac{C_j^t - C_j^0}{\ln C_j^t - \ln C_j^0} \ln(\frac{S_j^t}{S_j^0}) \quad (7)$$

$$\Delta C_Q = \sum_{i=1}^{4}\sum_{k=1}^{3} \frac{C_{ik}^t - C_{ik}^0}{\ln C_{ik}^t - \ln C_{ik}^0} \ln(\frac{Q_{ik}^t}{Q_{ik}^0}) + \sum_{j=1}^{4}\sum_{h=1}^{4} \frac{C_{jh}^t - C_{jh}^0}{\ln C_{jh}^t - \ln C_{jh}^0} \ln(\frac{Q_{jh}^t}{Q_{jh}^0}) \quad (8)$$

$$\Delta C_F = \sum_{i=1}^{4}\sum_{k=1}^{3} \frac{C_{ik}^t - C_{ik}^0}{\ln C_{ik}^t - \ln C_{ik}^0} \ln(\frac{F_{ik}^t}{F_{ik}^0}) + \sum_{j=1}^{4}\sum_{h=1}^{4} \frac{C_{jh}^t - C_{jh}^0}{\ln C_{jh}^t - \ln C_{jh}^0} \ln(\frac{F_{jh}^t}{F_{jh}^0}) \quad (9)$$

$$\Delta C_M = \sum_{i=1}^{4} \frac{C_i^t - C_i^0}{\ln C_i^t - \ln C_i^0} \ln(\frac{M_i^t}{M_i^0}) + \sum_{j=1}^{4} \frac{C_j^t - C_j^0}{\ln C_j^t - \ln C_j^0} \ln(\frac{M_j^t}{M_j^0}) \quad (10)$$

$$\Delta C_E = \sum_{i=1}^{4}\sum_{k=1}^{3}\frac{C_{ik}^t - C_{ik}^0}{\ln C_{ik}^t - \ln C_{ik}^0}\ln(\frac{E_k^t}{E_k^0}) + \sum_{j=1}^{4}\sum_{h=1}^{4}\frac{C_{jh}^t - C_{jh}^0}{\ln C_{jh}^t - \ln C_{jh}^0}\ln(\frac{E_h^t}{E_h^0}) \tag{11}$$

To further compare and analyze the relative contribution of each factor under different scenarios, this study calculates the contribution rate of each factor to the total change of road transport $CO_2$ emissions as follows:

$$CR(l) = \Delta C_l / \Delta C \tag{12}$$

where $CR(l)$ is the contribution rate of factor $l$ and $\Delta C_l$ is the $CO_2$ emission contribution of factor $l$. If $CR(l) > 0$, then the influencing factor $l$ may drive the increase of $CO_2$ emissions. Otherwise, it contributes to reducing $CO_2$ emissions.

## 4. Scenario Setting

This study aims to analyze the $CO_2$ emission reduction potential of road transport from 2020 to 2060. Therefore, different policy scenarios, such as the business-as-usual (BAU), clean electricity (CE), fuel economy improvement (FEI), shared autonomous vehicles (SAV), $CO_2$ emission trading (CET) (with low, medium and high carbon prices), and comprehensive (CS) scenarios, are established based on the key influencing factors of road transport $CO_2$ emissions. The relevant scenario parameters involved in this study include vehicle structure, fuel economy, fuel emission factor, average annual VKT of vehicles, etc. The settings of these scenarios are presented hereafter.

### 4.1. Business-as-Usual (BAU) Scenario

In the BAU scenario, we assume the $CO_2$ emission of road transport keeps the historical development trend with no additional policy implemented in the future. According to the national statistical yearbook, China's total population in 2020 was 1.412 billion, with a birth rate of 8.52‰ and a death rate of 7.09‰. This research set the initial death rate DR(0) = 7.09‰, which increases yearly with an increment of 0.17‰, and the initial birth rate BR(0) = 8.52‰, which decreases yearly with a decrease of 0.2‰. The projection of the population of China from 2010 to 2060 in the BAU scenario is shown in Figure 2.

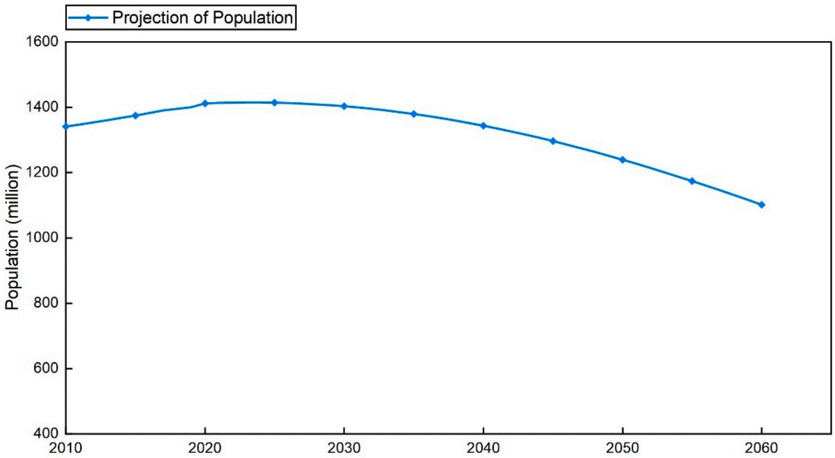


**Figure 2.** Projection of the population of China from 2010 to 2060 in the BAU scenario.

Based on the forecast of the International Energy Agency [32–34], the car ownership per thousand people in China will be approximately 494 in 2050. Therefore, the number of vehicles per 1000 people in China in the BAU scenario in 2060 is set to 500 cars per 1000 people [35]. The Gompertz model is then used to predict the vehicle population in China from 2020 to 2060 based on historical data from 2010 to 2020. The projections of China's vehicle population, freight vehicle population, and passenger vehicle population from 2010 to 2060 are shown in Figure 3.

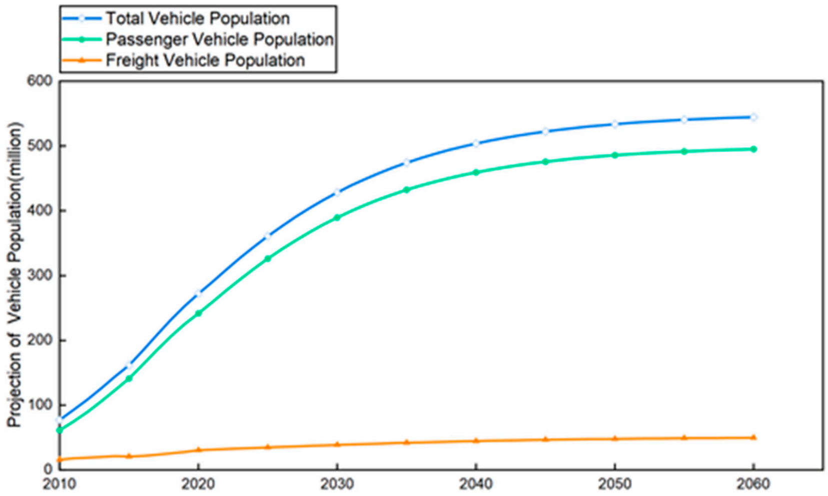


**Figure 3.** Projection of the vehicle population of China from 2010 to 2060 in the BAU scenario.

Based on historical data and related studies [36–41], we predict the vehicle structure, fuel structure, fuel economy, average annual VKT, and fuel emission factor of road transport from 2020 to 2060 for the BAU scenario. The settings of these parameters for passenger transport and freight transport in BAU scenarios are summarized in Tables 1 and 2.

**Table 1.** Parameter settings of passenger transport in the BAU scenario.

| Influencing Factors of $CO_2$ Emission | Vehicle Type | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| Passenger vehicle population (ten thousand) | All | All | 24,166.2 | 38,958.2 | 45,927.4 | 48,574.4 | 49,510.0 |
| Vehicle structure | Mini | All | 0.65% | 0.10% | 0.01% | 0.00% | 0.00% |
| | Small | All | 98.40% | 99.13% | 99.22% | 99.23% | 99.23% |
| | Medium | All | 0.28% | 0.38% | 0.52% | 0.58% | 0.62% |
| | Large | All | 0.67% | 0.38% | 0.26% | 0.19% | 0.15% |
| Fuel structure | Mini, Small, and Medium | Gasoline | 98% | 86% | 68% | 34% | 0% |
| | | Electricity | 1.6% | 12.74% | 30.72% | 64.68% | 100% |
| | | Hybrid | 0.4% | 1.26% | 1.28% | 1.32% | 0% |
| | Large | Gasoline | 75% | 50% | 30% | 15% | 0% |
| | | Electricity | 25% | 50% | 70% | 85% | 100% |
| Fuel economy | Mini | Gasoline (L/100 km) | 5.20 | 4.03 | 3.84 | 3.67 | 3.53 |
| | | Electricity (kWh/100 km) | 8.70 | 6.73 | 6.40 | 6.13 | 5.89 |
| | | Hybrid (L/100 km) | 2.81 | 2.18 | 2.07 | 1.98 | 1.91 |
| | Small | Gasoline (L/100 km) | 8.30 | 7.50 | 6.75 | 6.00 | 5.30 |
| | | Electricity (kWh/100 km) | 13.00 | 10.00 | 9.00 | 8.20 | 7.80 |
| | | Hybrid (L/100 km) | 4.22 | 3.36 | 2.75 | 2.60 | 2.58 |
| | Medium | Gasoline (L/100 km) | 17.10 | 15.20 | 14.80 | 14.60 | 14.50 |
| | | Electricity (kWh/100 km) | 120.00 | 116.00 | 110.00 | 100.00 | 92.00 |
| | | Hybrid (L/100 km) | 9.24 | 8.22 | 8.00 | 7.89 | 7.84 |
| | Large | Gasoline (L/100 km) | 21.80 | 19.40 | 18.90 | 18.50 | 18.20 |
| | | Electricity (kWh/100 km) | 144.00 | 140.00 | 135.0 | 128.00 | 122.00 |
| Average annual VKT (km) | Mini | All | 10,000 | 8917 | 7917 | 7000 | 6500 |
| | Small | All | 12,000 | 10,700 | 9500 | 8500 | 7500 |
| | Medium | All | 35,000 | 35,750 | 36,500 | 37,250 | 38,000 |
| | Large | All | 48,300 | 48,900 | 49,200 | 49,500 | 49,800 |
| Fuel emission factor | All | Gasoline (kg/L) | 2.42 | 2.42 | 2.42 | 2.42 | 2.42 |
| | All | Electricity (kg/kWh) | 0.71 | 0.52 | 0.46 | 0.4 | 0.38 |

**Table 2.** Parameter settings of freight transport in the BAU scenario.

| Influencing Factors of $CO_2$ Emission | Vehicle Type | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| Freight vehicle population (ten thousand) | All | All | 3042.6 | 3861.4 | 4453.5 | 4793.3 | 4957.4 |
| Vehicle structure | Mini | Diesel | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Light | | 40.20% | 37.68% | 33.75% | 29.12% | 24.50% |
| | Medium | | 5.70% | 3.00% | 1.70% | 1.10% | 0.50% |
| | Heavy | | 54.10% | 59.33% | 64.55% | 69.78% | 75.00% |
| | Mini | Gasoline | 5.50% | 4.00% | 2.40% | 1.20% | 0.00% |
| | Light | | 94.50% | 96.00% | 97.60% | 98.80% | 100.00% |
| | Medium | | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Heavy | | 0.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Mini | Electricity | 99.50% | 83.38% | 67.25% | 51.13% | 35.00% |
| | Light | | 0.50% | 7.88% | 15.25% | 22.63% | 30.00% |
| | Medium | | 0.00% | 5.00% | 10.00% | 15.00% | 20.00% |
| | Heavy | | 0.00% | 3.75% | 7.50% | 11.25% | 15.00% |
| | Mini | Natural gas | 0.10% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Light | | 3.80% | 2.50% | 1.60% | 0.80% | 0.00% |
| | Medium | | 0.40% | 0.00% | 0.00% | 0.00% | 0.00% |
| | Heavy | | 95.70% | 97.50% | 98.40% | 99.20% | 100.00% |
| Fuel structure | All | Diesel | 69.60% | 60.00% | 51.00% | 43.00% | 35.00% |
| | All | Gasoline | 27.90% | 19.30% | 14.00% | 12.00% | 10.00% |
| | All | Electricity | 0.70% | 13.40% | 24.00% | 32.00% | 40.00% |
| | All | Natural gas | 1.80% | 7.30% | 11.00% | 13.00% | 15.00% |
| Fuel Economy | Mini | Diesel (L/100 km) | 6.80 | 6.10 | 5.80 | 5.60 | 5.50 |
| | | Gasoline (L/100 km) | 9.60 | 8.60 | 7.40 | 5.80 | 4.20 |
| | | Natural gas ($m^3$/100 km) | 8.40 | 7.50 | 6.68 | 5.84 | 5.00 |
| | | Electricity (kWh/100 km) | 18.50 | 17.40 | 16.00 | 15.20 | 14.70 |
| | Light | Diesel (L/100 km) | 8.70 | 7.80 | 7.40 | 7.10 | 7.00 |
| | | Gasoline (L/100 km) | 11.00 | 9.90 | 8.84 | 7.72 | 6.60 |
| | | Natural gas ($m^3$/100 km) | 11.20 | 10.10 | 8.94 | 7.82 | 6.70 |
| | | Electricity (kWh/100 km) | 125.00 | 119.00 | 113.00 | 106.00 | 102.00 |
| | Medium | Diesel (L/100 km) | 15.50 | 14.70 | 14.00 | 13.40 | 12.90 |
| | | Natural gas ($m^3$/100 km) | 17.50 | 15.70 | 14.02 | 12.26 | 10.50 |
| | | Electricity (kWh/100 km) | 132.00 | 128.00 | 123.00 | 114.00 | 111.00 |
| | Heavy | Diesel (L/100 km) | 32.60 | 30.80 | 29.30 | 28.00 | 27.00 |
| | | Natural gas ($m^3$/100 km) | 30.80 | 27.80 | 24.66 | 21.58 | 18.50 |
| | | Electricity (kWh/100 km) | 150.00 | 146.00 | 140.00 | 132.00 | 129.00 |
| Average annual VMT (km) | Mini | All | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 |
| | Light | All | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 |
| | Medium | All | 24,000 | 25,627 | 27,498 | 29,288 | 31,000 |
| | Heavy | All | 40,000 | 40,500 | 41,143 | 41,786 | 42,500 |
| Fuel emission factor | All | Diesel (kg/L) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |
| | All | Gasoline (kg/L) | 2.42 | 2.42 | 2.42 | 2.42 | 2.42 |
| | All | Natural gas (kg/$m^3$) | 2.62 | 2.62 | 2.62 | 2.62 | 2.62 |
| | All | Electricity (kg/kWh) | 0.71 | 0.52 | 0.46 | 0.4 | 0.38 |

### *4.2. Clean Electricity (CE) Scenario*

Presently, China's energy structure is dominated by coal. Therefore, the power of electric vehicles is mainly generated from coal and the $CO_2$ emissions of electric vehicles are still high. With the diffusion of electric vehicles in the future, the influence of the electricity emission factor on road transport $CO_2$ emission will be more significant. This study proposes a clean electricity (CE) scenario where renewable energy power generation will be rapidly developed and widely adopted. In the CE scenario, the $CO_2$ emission factor of electricity should decrease more significantly compared with the BAU scenario. Therefore, the $CO_2$ emission factors of electricity in the CE scenario are assumed to decrease 2.5 times as fast as in the BAU scenario. The specific parameters that change compared with the BAU scenario are shown in Table 3. The rest of the parameters are the same as those in the BAU scenario.

**Table 3.** Parameter settings in the CE scenario.

| Influencing Factors of $CO_2$ Emission | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|
| $CO_2$ emission factor of electricity (kg/kWh) | 0.71 | 0.32 | 0.23 | 0.16 | 0.14 |

### 4.3. Fuel Economy Improvement (FEI) Scenario

As one of the main factors affecting $CO_2$ emissions, the fuel economy of vehicles will be improved with the continuous development of automobile conservation technology in the future. Therefore, we propose a fuel economy improvement (FEI) scenario where the fuel economy of vehicles will be increased faster than that in the BAU scenario. Due to the differences in power types and engine technology, the room for improvement in the fuel economy of freight vehicles is usually larger than that of passenger vehicles. Thus, we set the improvement rate of fuel economy for passenger vehicles and freight vehicles in the FEI scenario to be 1.5 times and 1.8 times, respectively, that in the BAU scenario. The specific parameters that change compared with the BAU scenario are shown in Table 4. The rest of the parameters are the same as those in the BAU scenario.

**Table 4.** Parameter settings in the FEI scenario.

| Influencing Factors of $CO_2$ Emission | Vehicle Type | | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|---|
| Fuel economy | Passenger vehicle | Mini | Gasoline (L/100 km) | 5.20 | 3.54 | 3.28 | 3.07 | 2.89 |
| | | | Electricity (kWh/100 km) | 8.70 | 5.90 | 5.48 | 5.12 | 4.83 |
| | | | Hybrid (L/100 km) | 2.81 | 1.91 | 1.77 | 1.66 | 1.56 |
| | | Small | Gasoline (L/100 km) | 8.30 | 7.13 | 6.08 | 5.09 | 4.23 |
| | | | Electricity (kWh/100 km) | 13.00 | 8.75 | 7.47 | 6.49 | 6.02 |
| | | | Hybrid (L/100 km) | 4.22 | 2.99 | 2.21 | 2.03 | 2.01 |
| | | Medium | Gasoline (L/100 km) | 17.10 | 14.32 | 13.76 | 13.48 | 13.34 |
| | | | Electricity (kWh/100 km) | 120.00 | 114.05 | 105.30 | 91.24 | 80.49 |
| | | | Hybrid (L/100 km) | 9.24 | 7.74 | 7.44 | 7.29 | 7.21 |
| | | Large | Gasoline (L/100 km) | 21.80 | 18.29 | 17.59 | 17.03 | 16.62 |
| | | | Electricity (kWh/100 km) | 144.00 | 138.04 | 130.70 | 120.66 | 112.26 |
| | Freight vehicle | Mini | Diesel (L/100 km) | 6.80 | 5.59 | 5.10 | 4.79 | 4.64 |
| | | | Gasoline (L/100 km) | 9.60 | 7.87 | 6.00 | 3.85 | 2.14 |
| | | | Natural gas ($m^3$/ 100 km) | 8.40 | 6.84 | 5.55 | 4.35 | 3.28 |
| | | | Electricity (kWh/100 km) | 18.50 | 16.56 | 14.23 | 12.98 | 12.22 |
| | | Light | Diesel (L/100 km) | 8.70 | 7.14 | 6.49 | 6.03 | 5.88 |
| | | | Gasoline (L/100 km) | 11.00 | 9.09 | 7.41 | 5.80 | 4.36 |
| | | | Natural gas ($m^3$/100 km) | 11.20 | 9.29 | 7.45 | 5.84 | 4.42 |
| | | | Electricity (kWh/100 km) | 125.00 | 114.39 | 104.20 | 92.84 | 86.62 |
| | | Medium | Diesel (L/100 km) | 15.50 | 14.09 | 12.90 | 11.92 | 11.13 |
| | | | Natural gas ($m^3$/100 km) | 17.50 | 14.37 | 11.72 | 9.19 | 6.94 |
| | | | Electricity (kWh/100 km) | 132.00 | 124.88 | 116.33 | 101.32 | 96.57 |
| | | Heavy | Diesel (L/100 km) | 32.60 | 29.43 | 26.89 | 24.78 | 23.21 |
| | | | Natural gas ($m^3$/100 km) | 30.80 | 25.59 | 20.60 | 16.18 | 12.24 |
| | | | Electricity (kWh/100 km) | 150.00 | 142.87 | 132.46 | 119.12 | 114.28 |

### *4.4. Shared Autonomous Vehicles (SAV) Scenario*

The emerging shared autonomous vehicles may steer a revolution in passenger transport. According to related research [42–45], people will give up purchasing private cars if shared mobility and autonomous driving services are widely adopted in the future. Since the shared autonomous vehicles usually have high capacity, the vehicle structure of passenger transport will change significantly. In addition, shared autonomous vehicles can also improve transport efficiency and fuel economy of vehicles. Therefore, we propose a shared autonomous vehicles (SAV) scenario where the vehicle population of passenger vehicles, the structure of passenger vehicles, and the average annual VKT of passenger vehicles are changed compared with the BAU scenario. In the SAV scenario, the car ownership per 1000 people is set to 400 in 2060, which is less than that in the BAU scenario. Besides, the proportion of medium and large passenger vehicles is greater than that in the BAU scenario. The proportion of medium and large passenger vehicles is assumed to increase 0.5 times as fast as in the BAU scenario. In addition, we set the improvement rate of fuel economy for vehicles in the SAV scenario to be 1.25 times that in the BAU scenario. The specific parameters that change compared with the BAU scenario are shown in Table 5. The rest of the parameters are the same as those in the BAU scenario.

**Table 5.** Parameter settings in the SAV scenario.

| **Influencing Factors of $CO_2$ Emission** | **Vehicle Type** | | **Fuel Type** | **2020** | **2030** | **2040** | **2050** | **2060** |
|---|---|---|---|---|---|---|---|---|
| Passenger vehicle population (ten thousand) | All | | All | 24,166.2 | 34,848.5 | 38,095.5 | 38,854.2 | 38,991.0 |
| Vehicle structure | Passenger vehicle | Mini | All | 0.65% | 0.30% | 0.13% | 0.06% | 0.03% |
| | | Small | All | 98.40% | 98.77% | 98.81% | 98.81% | 98.81% |
| | | Medium | All | 0.28% | 0.43% | 0.65% | 0.77% | 0.84% |
| | | Large | All | 0.67% | 0.50% | 0.41% | 0.35% | 0.32% |
| Fuel economy | Passenger vehicle | Mini | Gasoline (L/100 km) | 5.20 | 3.78 | 3.55 | 3.36 | 3.19 |
| | | | Electricity (kWh/100 km) | 8.70 | 6.31 | 5.92 | 5.61 | 5.33 |
| | | | Hybrid (L/100 km) | 2.81 | 2.04 | 1.92 | 1.82 | 1.73 |
| | | Small | Gasoline (L/100 km) | 8.30 | 7.31 | 6.41 | 5.53 | 4.73 |
| | | | Electricity (kWh/100 km) | 13.00 | 9.35 | 8.20 | 7.30 | 6.85 |
| | | | Hybrid (L/100 km) | 4.22 | 3.17 | 2.46 | 2.30 | 2.28 |
| | | Medium | Gasoline (L/100 km) | 17.10 | 14.76 | 14.27 | 14.03 | 13.91 |
| | | | Electricity (kWh/100 km) | 120.00 | 115.02 | 107.63 | 95.52 | 86.06 |
| | | | Hybrid (L/100 km) | 9.24 | 7.98 | 7.71 | 7.58 | 7.52 |
| | | Large | Gasoline (L/100 km) | 21.80 | 18.84 | 18.23 | 17.75 | 17.39 |
| | | | Electricity (kWh/100 km) | 144.00 | 139.02 | 132.83 | 124.28 | 117.03 |
| | Freight vehicle | Mini | Diesel (L/100 km) | 6.80 | 5.94 | 5.57 | 5.33 | 5.21 |
| | | | Gasoline (L/100 km) | 9.60 | 8.36 | 6.93 | 5.11 | 3.40 |
| | | | Natural gas ($m^3$/100 km) | 8.40 | 7.29 | 6.31 | 5.33 | 4.39 |
| | | | Electricity (kWh/100 km) | 18.50 | 17.13 | 15.43 | 14.47 | 13.88 |
| | | Light | Diesel (L/100 km) | 8.70 | 7.59 | 7.10 | 6.75 | 6.63 |
| | | | Gasoline (L/100 km) | 11.00 | 9.64 | 8.37 | 7.06 | 5.80 |
| | | | Natural gas ($m^3$/100 km) | 11.20 | 9.84 | 8.45 | 7.14 | 5.89 |
| | | | Electricity (kWh/100 km) | 125.00 | 117.54 | 110.18 | 101.70 | 96.93 |
| | | Medium | Diesel (L/100 km) | 15.50 | 14.51 | 13.65 | 12.92 | 12.32 |
| | | | Natural gas ($m^3$/100 km) | 17.50 | 15.28 | 13.26 | 11.21 | 9.23 |
| | | | Electricity (kWh/100 km) | 132.00 | 127.02 | 120.84 | 109.88 | 106.28 |
| | | Heavy | Diesel (L/100 km) | 32.6 | 30.36 | 28.53 | 26.95 | 25.75 |
| | | | Natural gas ($m^3$/100 km) | 30.8 | 27.09 | 23.32 | 19.73 | 16.27 |
| | | | Electricity (kWh/100 km) | 150.00 | 145.02 | 137.60 | 127.84 | 124.21 |

### 4.5. $CO_2$ Emission Trading (CET) Scenario

$CO_2$ emissions trading is a cost-effective climate policy to reduce greenhouse gas emissions. Although the road transport sector has not currently been incorporated into the emission trading system, it is very likely to be implemented in the future with the development of emerging technology and the maturity of the carbon market. This study proposes a $CO_2$ emissions trading (CET) scenario with different levels of carbon prices (low, mid, and high). According to related research [46], the carbon price of CET can stimulate vehicle users to choose low-carbon vehicles (with fuel types of electricity, hybrid, and natural gas) and decrease the average annual VKT. The higher the price, the greater the influences.

In the $CO_2$ emissions trading scenario with low carbon prices (CET-LCP), the proportion of low-carbon vehicles is set to 1.25 times that in the BAU scenario and the average annual VKT of vehicles in 2060 is set to 0.85 times that in the BAU scenario. In the $CO_2$ emissions trading scenario with mid carbon prices (CET-MCP), the proportion of low-carbon vehicles is set to 1.5 times that in the BAU scenario and the average annual VKT of vehicles in 2060 is set to 0.75 times that in the BAU scenario. In the $CO_2$ emissions trading scenario with high carbon prices (CET-HCP), the proportion of low-carbon vehicles is set to 2 times that in the BAU scenario and the average annual VKT of vehicles in 2060 is set to 0.65 times that in the BAU scenario. The specific parameters of the three scenarios that change compared with the BAU scenario are shown in Tables 6–8. The rest of the parameters are the same as those in the BAU scenario.

**Table 6.** Parameter settings in the CET-LCP scenario.

| **Influencing Factors of $CO_2$ Emission** | **Vehicle Type** | | **Fuel Type** | **2020** | **2030** | **2040** | **2050** | **2060** |
|---|---|---|---|---|---|---|---|---|
| Fuel structure | Passenger vehicle | Small and medium | Gasoline | 98.00% | 82.50% | 60.00% | 17.50% | 0.00% |
| | | | Electricity | 1.60% | 15.93% | 38.40% | 80.85% | 100.00% |
| | | | Hybrid | 0.40% | 1.58% | 1.60% | 1.65% | 0.00% |
| | | Large | Gasoline | 75.00% | 37.50% | 12.50% | 0.00% | 0.00% |
| | | | Electricity | 25.00% | 62.50% | 87.50% | 100.00% | 100.00% |
| | Freight vehicle | | Diesel | 69.60% | 56.08% | 44.13% | 34.20% | 24.31% |
| | | | Gasoline | 27.90% | 18.04% | 12.12% | 9.55% | 6.94% |
| | | | Natural gas | 1.80% | 9.13% | 13.75% | 16.25% | 18.75% |
| | | | Electricity | 0.70% | 16.75% | 30.00% | 40.00% | 50.00% |
| Average annual VMT (km) | Passenger vehicle | Mini | All | 10,000 | 8881 | 7763 | 6644 | 5525 |
| | | Small | All | 12,000 | 10,594 | 9188 | 7781 | 6375 |
| | | Medium | All | 35,000 | 34,325 | 33,650 | 32,975 | 32,300 |
| | | Large | All | 48,300 | 46,808 | 45,315 | 43,823 | 42,330 |
| | Freight vehicle | Mini | All | 20,000 | 19,250 | 18,500 | 17,750 | 17,000 |
| | | Light | All | 20,000 | 19,250 | 18,500 | 17,750 | 17,000 |
| | | Medium | All | 24,000 | 24,588 | 25,175 | 25,763 | 26,350 |
| | | Heavy | All | 40,000 | 39,031 | 38,063 | 37,094 | 36,125 |

**Table 7.** Parameter settings in the CET-MCP scenario.

| **Influencing Factors of $CO_2$ Emission** | **Vehicle Type** | | **Fuel Type** | **2020** | **2030** | **2040** | **2050** | **2060** |
|---|---|---|---|---|---|---|---|---|
| Fuel structure | Passenger vehicle | Small and medium | Gasoline | 98.00% | 79.00% | 52.00% | 1.00% | 0.00% |
| | | | Electricity | 1.60% | 19.11% | 46.08% | 97.02% | 100.00% |
| | | | Hybrid | 0.40% | 1.89% | 1.92% | 1.98% | 0.00% |
| | | Large | Gasoline | 75.00% | 25.00% | 0.00% | 0.00% | 0.00% |
| | | | Electricity | 25.00% | 75.00% | 100.00% | 100.00% | 100.00% |
| | Freight vehicle | | Diesel | 69.60% | 52.17% | 37.27% | 25.41% | 13.61% |
| | | | Gasoline | 27.90% | 16.78% | 10.23% | 7.09% | 3.89% |
| | | | Natural gas | 1.80% | 10.95% | 16.50% | 19.50% | 22.50% |
| | | | Electricity | 0.70% | 20.10% | 36.00% | 48.00% | 60.00% |

**Table 7.** *Cont.*

| Influencing Factors of CO$_2$ Emission | Vehicle Type | | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|---|
| Average annual VMT (km) | Passenger vehicle | Mini | All | 10,000 | 8719 | 7438 | 6156 | 4875 |
| | | Small | All | 12,000 | 10,406 | 8813 | 7219 | 5625 |
| | | Medium | All | 35,000 | 33,375 | 31,750 | 30,125 | 28,500 |
| | | Large | All | 48,300 | 45,563 | 42,825 | 40,088 | 37,350 |
| | Freight vehicle | Mini | All | 20,000 | 18,750 | 17,500 | 16,250 | 15,000 |
| | | Light | All | 20,000 | 18,750 | 17,500 | 16,250 | 15,000 |
| | | Medium | All | 24,000 | 23,813 | 23,625 | 23,438 | 23,250 |
| | | Heavy | All | 40,000 | 37,969 | 35,938 | 33,906 | 31,875 |

**Table 8.** Parameter settings in the CET-HCP scenario.

| Influencing Factors of CO$_2$ Emission | Vehicle Type | | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|---|
| Fuel structure | Passenger vehicle | Small and medium | Gasoline | 98.00% | 74.80% | 42.40% | 0.00% | 0.00% |
| | | | Electricity | 1.60% | 22.93% | 55.30% | 98% | 100.00% |
| | | | Hybrid | 0.40% | 2.27% | 2.30% | 2.00% | 0.00% |
| | | Large | Gasoline | 75.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | | Electricity | 25.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| | Freight vehicle | | Diesel | 69.60% | 44.34% | 23.54% | 7.82% | 0.00% |
| | | | Gasoline | 27.90% | 14.26% | 6.46% | 2.18% | 0.00% |
| | | | Natural gas | 1.80% | 14.60% | 22.00% | 26.00% | 27.27% |
| | | | Electricity | 0.70% | 26.80% | 48.00% | 64.00% | 72.73% |
| Average annual VMT (km) | Passenger vehicle | Mini | All | 10,000 | 8556 | 7113 | 5669 | 4225 |
| | | Small | All | 12,000 | 10,219 | 8438 | 6656 | 4875 |
| | | Medium | All | 35,000 | 32,425 | 29,850 | 27,275 | 24,700 |
| | | Large | All | 48,300 | 44,318 | 40,335 | 36,353 | 32,370 |
| | Freight vehicle | Mini | All | 20,000 | 18,250 | 16,500 | 14,750 | 13,000 |
| | | Light | All | 20,000 | 18,250 | 16,500 | 14,750 | 13,000 |
| | | Medium | All | 24,000 | 23,038 | 22,075 | 21,113 | 20,150 |
| | | Heavy | All | 40,000 | 36,906 | 33,813 | 30,719 | 27,625 |

## 4.6. Comprehensive (CS) Scenario

The CS scenario is the combination of the CE, SAV, FEI, and CET-HCP scenarios proposed above. In this scenario, all six factors affecting road transport CO$_2$ emissions—vehicle population, vehicle structure, fuel structure, fuel emission factor, fuel economy, and average annual VKT—are changed. The specific parameters that change compared with the BAU scenario are shown in Tables 9 and 10. The rest of the parameters are the same as those in the BAU scenario.

**Table 9.** Parameter settings of passenger vehicles in the CS scenario.

| Influencing Factors of CO$_2$ Emission | Vehicle Type | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| Passenger vehicles population (ten thousand) | All | All | 3042.6 | 5133.3 | 6864.9 | 7512.9 | 8731.0 |
| Vehicle structure | Passenger vehicle | Mini | All | 0.65% | 0.30% | 0.13% | 0.06% |
| | | Small | All | 98.40% | 98.77% | 98.81% | 98.81% |
| | | Medium | All | 0.28% | 0.43% | 0.65% | 0.77% |
| | | Large | All | 0.67% | 0.50% | 0.41% | 0.35% |
| Vehicle structure | Mini | All | 0.65% | 0.04% | 0.00% | 0.00% | 0.00% |
| | Small | All | 98.40% | 98.77% | 98.81% | 98.81% | 98.81% |
| | Medium | All | 0.28% | 0.69% | 0.78% | 0.83% | 0.86% |
| | Large | All | 0.67% | 0.51% | 0.42% | 0.36% | 0.32% |

**Table 9.** *Cont.*

| Influencing Factors of $CO_2$ Emission | Vehicle Type | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| Fuel structure | Small and medium | Gasoline | 98.00% | 74.80% | 42.40% | 0.00% | 0.00% |
| | | Electricity | 1.60% | 22.93% | 55.30% | 98% | 100.00% |
| | | Hybrid | 0.40% | 2.27% | 2.30% | 2.00% | 0.00% |
| | Large | Gasoline | 75.00% | 0.00% | 0.00% | 0.00% | 0.00% |
| | | Electricity | 25.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| Fuel economy | Mini | Gasoline (L/100 km) | 5.20 | 3.54 | 3.28 | 3.07 | 2.89 |
| | | Electricity (kWh/100 km) | 8.70 | 5.90 | 5.48 | 5.12 | 4.83 |
| | | Hybrid (L/100 km) | 2.81 | 1.91 | 1.77 | 1.66 | 1.56 |
| | Small | Gasoline (L/100 km) | 8.30 | 7.13 | 6.08 | 5.09 | 4.23 |
| | | Electricity (kWh/100 km) | 13.00 | 8.75 | 7.47 | 6.49 | 6.02 |
| | | Hybrid (L/100 km) | 4.22 | 2.99 | 2.21 | 2.03 | 2.01 |
| | Medium | Gasoline (L/100 km) | 17.10 | 14.32 | 13.76 | 13.48 | 13.34 |
| | | Electricity (kWh/100 km) | 120.00 | 114.05 | 105.30 | 91.24 | 80.49 |
| | | Hybrid (L/100 km) | 9.24 | 7.74 | 7.44 | 7.29 | 7.21 |
| | Large | Gasoline (L/100 km) | 21.80 | 18.29 | 17.59 | 17.03 | 16.62 |
| | | Electricity (kWh/100 km) | 144.00 | 138.04 | 130.70 | 120.66 | 112.26 |
| Average annual VMT (km) | Mini | All | 10,000 | 8556 | 7113 | 5669 | 4225 |
| | Small | All | 12,000 | 10,219 | 8438 | 6656 | 4875 |
| | Medium | All | 35,000 | 32,425 | 29,850 | 27,275 | 24,700 |
| | Large | All | 48,300 | 44,318 | 40,335 | 36,353 | 32,370 |
| Fuel emission factor | All | Electricity (kg/kWh) | 0.71 | 0.32 | 0.23 | 0.16 | 0.14 |

**Table 10.** Parameter settings of freight vehicles in the CS scenario.

| Influencing Factors of $CO_2$ Emission | Vehicle Type | Fuel Type | 2020 | 2030 | 2040 | 2050 | 2060 |
|---|---|---|---|---|---|---|---|
| Fuel structure | All | Diesel | 69.60% | 44.34% | 23.54% | 7.82% | 0.00% |
| | All | Gasoline | 27.90% | 14.26% | 6.46% | 2.18% | 0.00% |
| | All | Natural gas | 1.80% | 14.60% | 22.00% | 26.00% | 27.27% |
| | All | Electricity | 0.70% | 26.80% | 48.00% | 64.00% | 72.73% |
| Fuel economy | Mini | Diesel (L/100 km) | 6.80 | 5.59 | 5.10 | 4.79 | 4.64 |
| | | Gasoline (L/100 km) | 9.60 | 7.87 | 6.00 | 3.85 | 2.14 |
| | | Natural gas ($m^3$/100 km) | 8.40 | 6.84 | 5.55 | 4.35 | 3.28 |
| | | Electricity (kWh/100 km) | 18.50 | 16.56 | 14.23 | 12.98 | 12.22 |
| | Light | Diesel (L/100 km) | 8.70 | 7.14 | 6.49 | 6.03 | 5.88 |
| | | Gasoline (L/100 km) | 11.00 | 9.09 | 7.41 | 5.80 | 4.36 |
| | | Natural gas ($m^3$/100 km) | 11.20 | 9.29 | 7.45 | 5.84 | 4.42 |
| | | Electricity (kWh/100 km) | 125.00 | 114.39 | 104.20 | 92.84 | 86.62 |
| | Medium | Diesel (L/100 km) | 15.50 | 14.09 | 12.90 | 11.92 | 11.13 |
| | | Natural gas ($m^3$/100 km) | 17.50 | 14.37 | 11.72 | 9.19 | 6.94 |
| | | Electricity (kWh/100 km) | 132.00 | 124.88 | 116.33 | 101.32 | 96.57 |
| | Heavy | Diesel (L/100 km) | 32.60 | 29.43 | 26.89 | 24.78 | 23.21 |
| | | Natural gas ($m^3$/100 km) | 30.80 | 25.59 | 20.60 | 16.18 | 12.24 |
| | | Electricity (kWh/100 km) | 150.00 | 142.87 | 132.46 | 119.12 | 114.28 |
| Average annual VMT (km) | Mini | All | 20,000 | 18,250 | 16,500 | 14,750 | 13,000 |
| | Light | All | 20,000 | 18,250 | 16,500 | 14,750 | 13,000 |
| | Medium | All | 24,000 | 23,038 | 22,075 | 21,113 | 20,150 |
| | Heavy | All | 40,000 | 36,906 | 33,813 | 30,719 | 27,625 |
| $CO_2$ emission factor | All | Electricity (kg/kWh) | 0.71 | 0.32 | 0.23 | 0.16 | 0.14 |

## 5. Results and Discussions

### *5.1. $CO_2$ Emissions of Subsectors of Road Transport in Different Scenarios*

Based on the methods and data introduced above, $CO_2$ emissions from all passenger vehicles and freight vehicles in road transport can be calculated. For better comparison, we further divide passenger transport into subsectors of mini, small, medium, and large passenger vehicles and freight transport into subsectors of mini, light, medium, and heavy freight vehicles. Based on the LEAP, we can analyze $CO_2$ emissions from different subsectors of road transport in China from 2020 to 2060 under the eight policy scenarios proposed above. The results are shown in Figure 4.

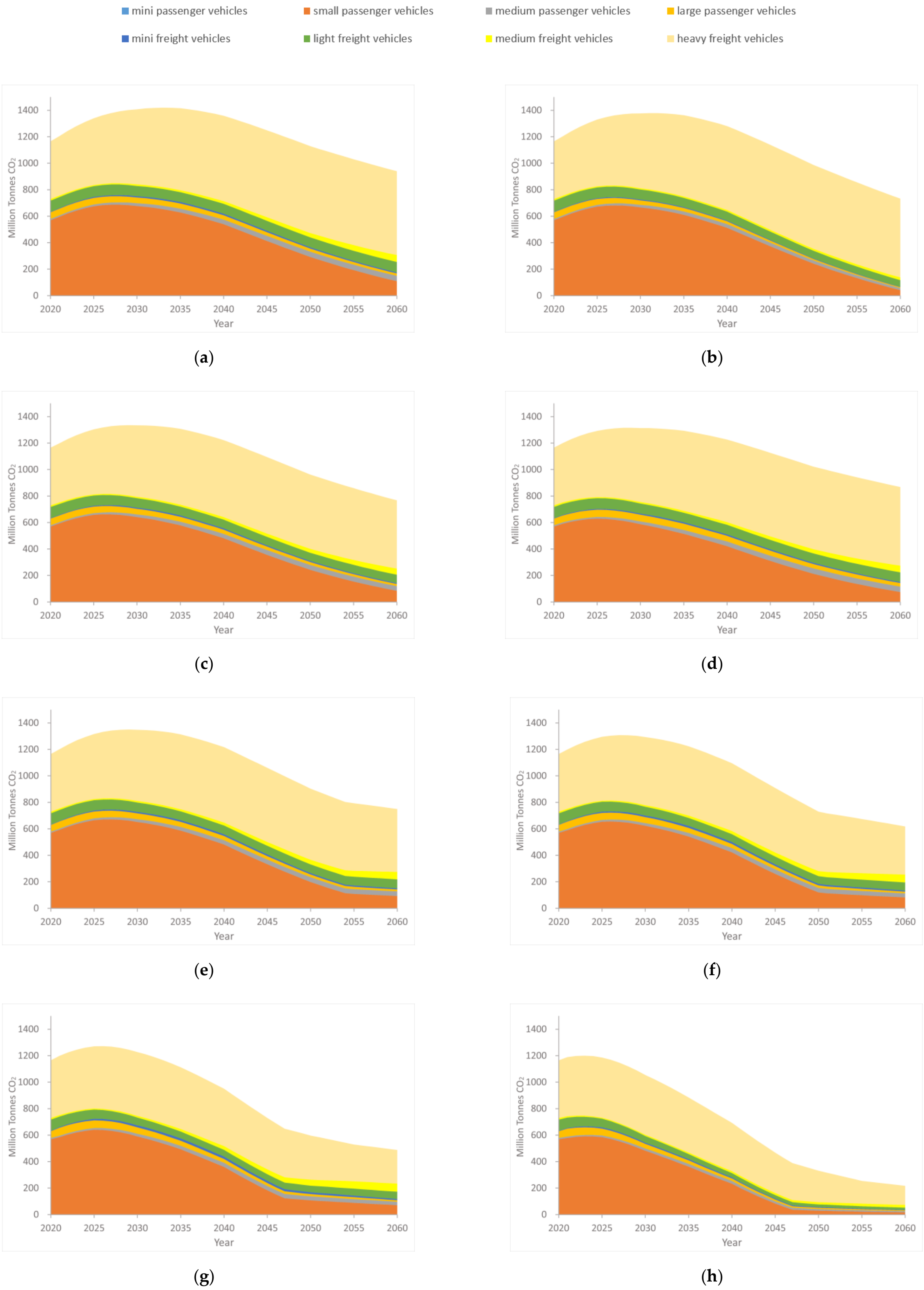
Figure 4a shows that the total $CO_2$ emissions of road transport in the BAU scenario initially increase and then decrease yearly after reaching a peak of 1419.50 million tonnes in 2033. The $CO_2$ emissions of passenger transport increase and then decrease, from 54.08% in 2020 to 17.82% in 2060. On the other hand, the $CO_2$ emissions of freight transport grow steadily from 45.92% in 2020 to 82.18% in 2060. Before 2034, the $CO_2$ emissions of passenger transport are greater than those of freight transport. After 2034, the $CO_2$ emissions of passenger transport are gradually less than those of freight transport and continue to decline. The $CO_2$ emissions of small passenger vehicles and heavy freight vehicles are relatively large. While the $CO_2$ emissions of small passenger vehicles begin to decline after reaching a peak of 686.27 million tonnes in 2028, the growth trend of freight transport $CO_2$ emissions gradually slows down and begins to decline after 2056. The $CO_2$ emissions of other types of vehicles account for a relatively small proportion, with the trend relatively stable.

Figure 4b shows that in the CE scenario, due to the wide application of clean electricity for passenger vehicles, the reduction in passenger transport $CO_2$ emissions is significant. However, the $CO_2$ emission reduction of freight transport is small since the implementation of electric vehicles in freight transportation is more difficult. Figure 4c shows that the FEI scenario has promoted a great reduction in $CO_2$ emissions for all subsectors, with the $CO_2$ emission peak dropping significantly and the rate of $CO_2$ emission reduction accelerating after the peak. According to Figure 4d, in the SAV scenario, due to a decrease in the number of passenger vehicles and a change in vehicle structure, with an improvement in the fuel economy of vehicles, $CO_2$ emissions of passenger vehicles are significantly reduced compared with the BAU scenario. A comparison of Figure 4e–g shows that in the CET scenario, with an increase in carbon prices , the reduction of road transport $CO_2$ emissions becomes increasingly obvious. This is especially the case in the CET-HCP scenario, where the road transport $CO_2$ emissions will begin to decrease yearly after 2026 and will only be 488.10 million tonnes in 2060. Figure 4h clearly shows that in the CS scenario, under the combined effect of various emission reduction policies, the downward trend of $CO_2$ emissions from road transport is the quickest and the emission reduction is the most significant for passenger transport and freight transport.

### *5.2. $CO_2$ Emission Reduction Potential of Road Transport in Different Scenarios*

#### 5.2.1. Total $CO_2$ Emissions of Road Transport in Different Scenarios

Based on the LEAP, the total $CO_2$ emissions of China's road transport in different scenarios from 2020 to 2060 can also be analyzed and compared, as shown in Figure 5. The $CO_2$ emission gaps between the BAU scenario and other scenarios are then regarded as the $CO_2$ emission reduction potential.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**) (**h**)

**Figure 4.** Projection of $CO_2$ emissions from subsectors of road transport in different scenarios. (**a**) Business-as-usual (BAU) scenario; (**b**) Clean electricity (CE) scenario; (**c**) Fuel economy improvement (FEI) scenario; (**d**) Shared autonomous vehicles (SAV) scenario; (**e**) Scenario of CET with low carbon prices (CET-LCP); (**f**) Scenario of CET with medium carbon prices (CET-MCP); (**g**) Scenario of CET with high carbon prices (CET-HCP); (**h**) Comprehensive (CS) scenario.

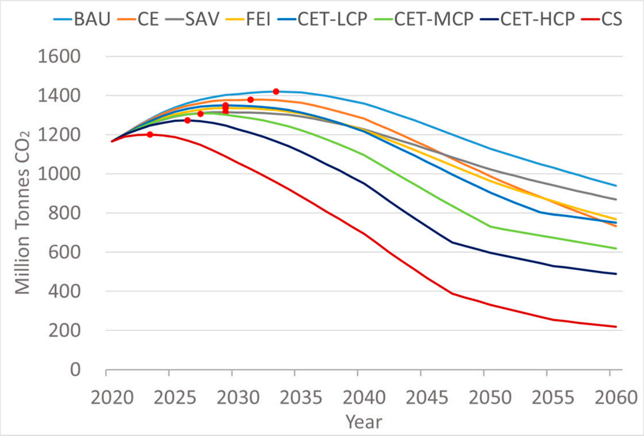


**Figure 5.** Projection of total $CO_2$ emissions from road transport in different scenarios.

Compared with the BAU scenario, the $CO_2$ emission reduction of road transport in the CE scenario is not significant before 2031 due to the relatively low penetration rate of electric vehicles. However, with the expansion of the vehicle electrification scale, the $CO_2$ emission of electric vehicles from power generation becomes one of the main emission sources in road transport. Therefore, the $CO_2$ emission reduction potential in the CE scenario is increasing yearly and even surpasses that in the FEI, SAV, and CET-LCP scenarios by 2060. The $CO_2$ emission reduction in the FEI scenario is relatively steady every year due to the continuing improvement in the fuel economy of vehicles, whereas the $CO_2$ emission reduction potential in the SAV scenario is gradually decreasing yearly since the vehicle population tends to be saturated. In the CET scenarios, the $CO_2$ emission reduction of road transport is gradually increasing. A comparison of CET-LCP, CET-MCP, and CET-HCP scenarios reveals that the $CO_2$ emission reduction potential increases with the rise of carbon prices. Among all the scenarios, the CS scenario has the greatest potential for road transport $CO_2$ emission reduction with all the policies implemented.

For better evaluation and comparison of the $CO_2$ emission reduction potential under different scenarios, the key numerical results are listed in Table 11. It shows that the peak years of $CO_2$ emission are becoming earlier from the BAU scenario to the CS scenario. The cumulative $CO_2$ emission in different scenarios are ranked as follows: BAU > CE > SAV > FE I > CET-LCP > CET-MLP > CET-HCP > CS. Among them, the CS scenario has the greatest potential for $CO_2$ emission reduction. In the CS scenario, $CO_2$ emissions of road transport will peak at 1200.37 million tonnes in 2023 and decrease to 217.73 million tonnes by 2060. The reduction rate of road transport $CO_2$ emission from the carbon peak year to 2060 can be up to 82%. From 2020 to 2060, the cumulative $CO_2$ emissions in the CS scenario are only 28,572.73 million tonnes. Compared with the BAU scenario, the cumulative $CO_2$ emission reduction is 22,501.22 million tonnes in the CS scenario.

**Table 11.** Comparison of road transport $CO_2$ emissions under different scenarios from 2020 to 2060.

| **Scenarios** | **Peak Year of $CO_2$ Emission** | **$CO_2$ Emission Peak (Million Tonnes)** | **Cumulative $CO_2$ Emission (Million Tonnes)** | **Cumulative $CO_2$ Emission Reductions Compared with the BAU Scenario (Million Tonnes)** | **$CO_2$ Emission Reduction Rate from Carbon Peak Year to 2060** |
|---|---|---|---|---|---|
| BAU | 2033 | 1419.50 | 51,073.75 | - | 34% |
| CE | 2031 | 1378.69 | 47,460.70 | 3613.05 | 47% |
| SAV | 2029 | 1315.47 | 47,274.21 | 3799.54 | 34% |
| FEI | 2029 | 1335.51 | 46,320.29 | 4753.46 | 43% |
| CET-LCP | 2029 | 1350.32 | 45,587.65 | 5486.10 | 44% |
| CET-MCP | 2027 | 1307.91 | 41,560.01 | 9513.74 | 53% |
| CET-HCP | 2026 | 1272.22 | 37,110.66 | 13,963.08 | 62% |
| CS | 2023 | 1200.37 | 28,572.73 | 22,501.22 | 82% |

#### 5.2.2. Comparison with Previous Studies

In this study, we separately calculated $CO_2$ emissions of passenger transport and freight transport and obtained the total $CO_2$ emissions of road transport. In this section, we compare the results with some previous studies on the $CO_2$ emissions of passenger transport and freight transport in China. For example, Peng et al. [47] predicted that the direct $CO_2$ emissions of the road transport sector in mainland China will peak at 1500 million tonnes around 2030 and gradually decline to 1341.3 million tonnes in 2050 in the reference scenario. In the BAU and low carbon scenarios, the direct $CO_2$ emissions further decrease to 892.6 and 620.6 million tonnes in 2050, respectively. Gambhir et al. [48] demonstrated that road transport $CO_2$ emissions in China could decrease from 2080 million tonnes in the BAU scenario to 1240 million tonnes in the low carbon scenario by 2050. Yan et al. [49] indicated that $CO_2$ emissions of China's road transport sector in 2030 would reach 1303.7 million tonnes in the BAU scenario, which will be reduced to 783.1 million tonnes in the best-case scenario. Through the comparison, it can be found that the $CO_2$ emission reduction potential of China's road transport in our study is much greater than that in the previous studies. It indicates that the policy scenarios in our studies may have more significant effects on the $CO_2$ emission reduction of road transport.

### 5.3. Factor Contribution to Road Transport $CO_2$ Emission Reduction

Based on the LMDI method, the factors contributing to the emission reduction of road transport from the peak year to 2060 are composed for each scenario, as shown in Figures 6–13.

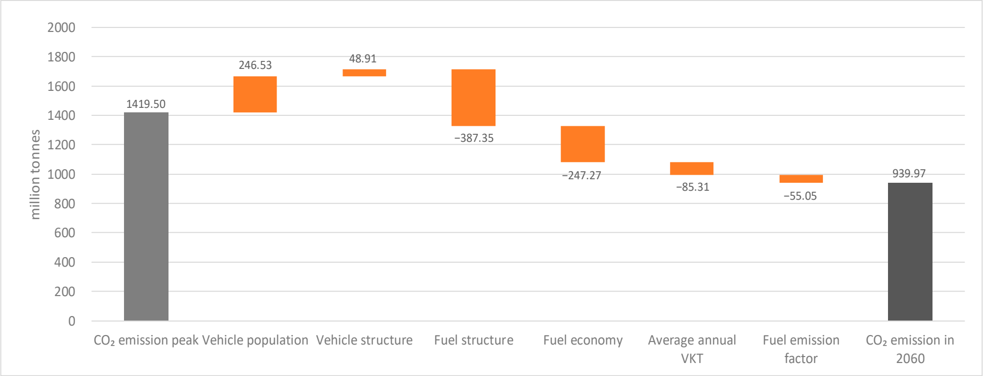


**Figure 6.** Factor contribution to road transport $CO_2$ emission reduction in the BAU scenario.

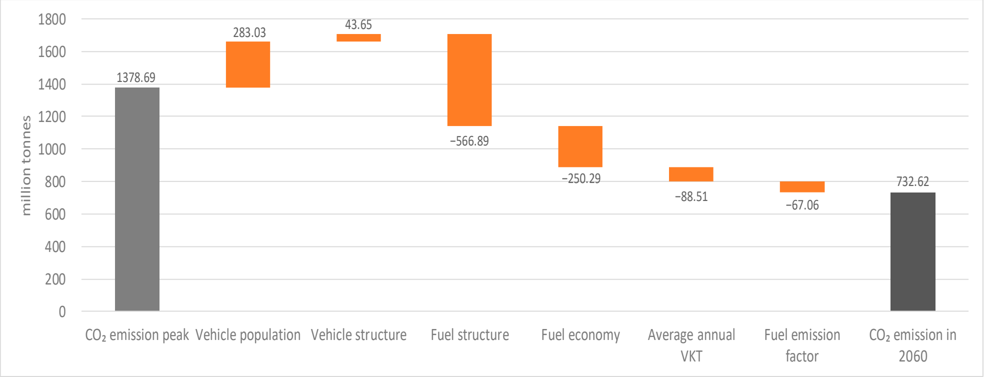


**Figure 7.** Factor contribution to road transport $CO_2$ emission reduction in the CE scenario.

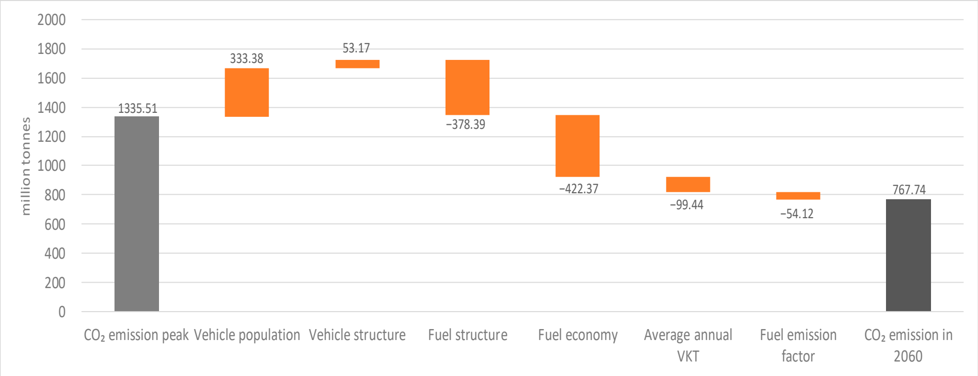


**Figure 8.** Factor contribution to road transport $CO_2$ emission reduction in the FEI scenario.

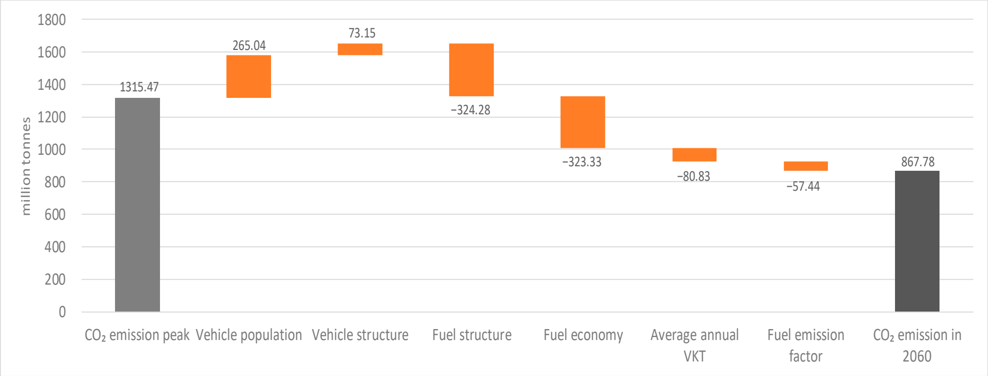


**Figure 9.** Factor contribution to road transport $CO_2$ emission reduction in the SAV scenario.

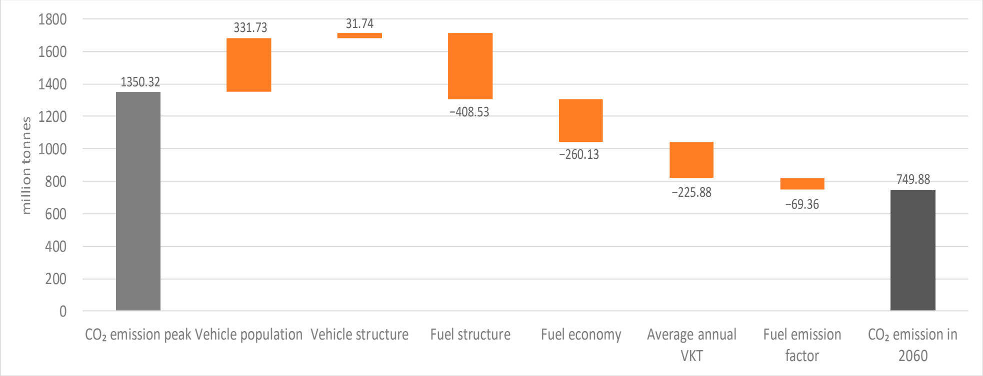


**Figure 10.** Factor contribution to road transport $CO_2$ emission reduction in the CET-LCP scenario.

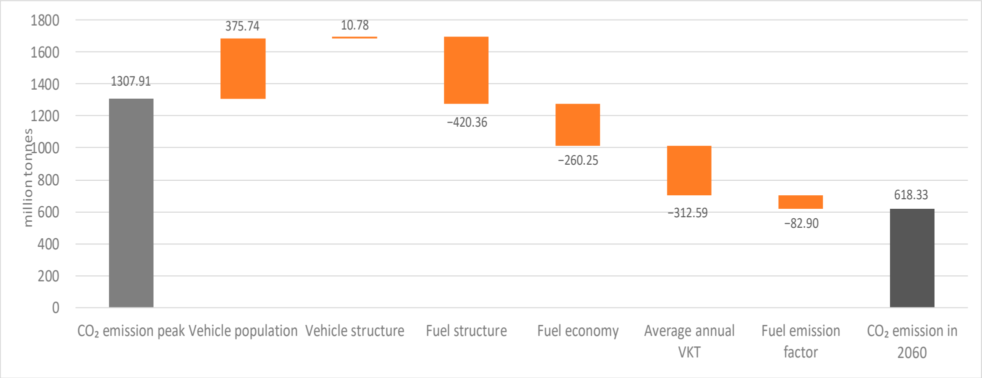


**Figure 11.** Factor contribution to road transport $CO_2$ emission reduction in the CET-MCP scenario.

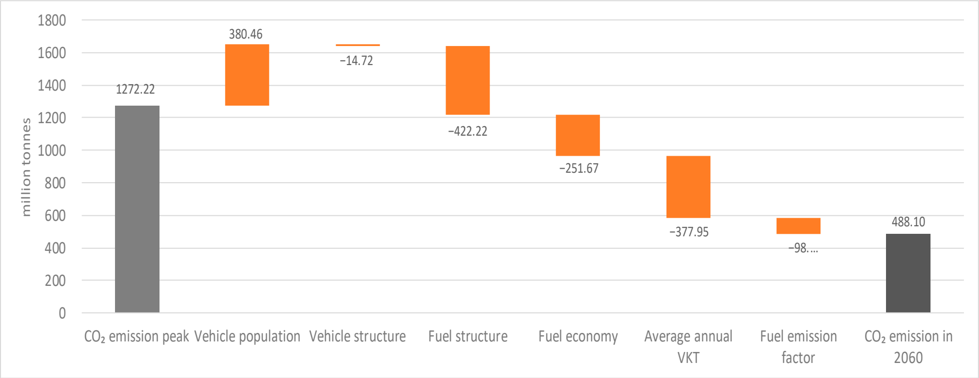


**Figure 12.** Factor contribution to road transport $CO_2$ emission reduction in the CET-HCP scenario.

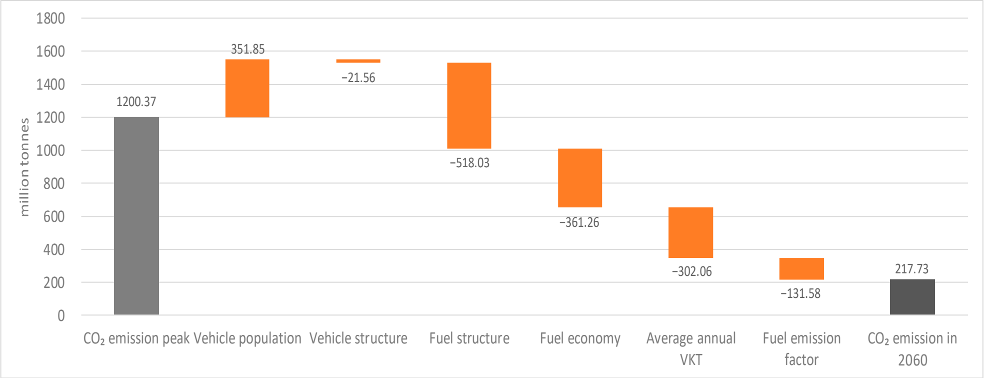


**Figure 13.** Factor contribution to road transport $CO_2$ emission reduction in the CS scenario.

As shown in Figure 6, among the various influencing factors of $CO_2$ emissions in the BAU scenario, the increase in vehicle population has a positive role in promoting an increase in $CO_2$ emissions, with the contribution of $CO_2$ emissions being as high as 246.53 million tonnes, which is the main reason for the increase in road transport $CO_2$ emissions. Besides, the vehicle structure also has a positive role in promoting an increase in $CO_2$ emissions. However, vehicle structure's contribution is only 48.91 million tonnes, substantially less than the influence of the vehicle population. The factors that contribute to the reduction of $CO_2$ emissions include the average annual VKT, fuel structure, fuel economy, and fuel emission factor. With an increase in the proportion of electric vehicles and other clean-energy vehicles, an improvement in fuel economy, and a decrease in the electricity $CO_2$ emission factor, road transport $CO_2$ emissions will be reduced. The most influential factor of $CO_2$ emission reduction is fuel structure, with its contribution reaching 387.35 million tonnes in the BAU scenario.

According to Figures 7–13, the contribution of factors to the road transport $CO_2$ emission reduction varies from scenario to scenario. In the CE scenario, the emission reduction contribution of the fuel emission factor increased by 12.01 million tonnes compared with the BAU scenario due to cleaner electricity used in the electric vehicles. Similarly, the contribution of fuel economy factors to emission reduction in the FEI scenario increased from 247.27 million tonnes (BAU) to 422.37 million tonnes since the additional improvement in the fuel economy of vehicles. The role of the vehicle population in the increase of road transport $CO_2$ emissions is weakened in the SAV scenario because of the reduced demand for private cars. The distributions of the factor contribution to road transport $CO_2$ emission reduction in the three CET scenarios are similar. Fuel structure is the driving factor of $CO_2$ emission reduction in CET scenarios with market-based incentives for low-carbon vehicles. In the CS scenario, the contribution of all factors to the road transport $CO_2$ emission reduction is enhanced.

To comparatively analyze the relative contribution of various factors, the contribution rates of each factor under different policy scenarios are shown in Figure 14. In all scenarios, the contribution rate of the vehicle population to $CO_2$ emissions is positive and greater than 0.35, which restrains the reduction of road transport $CO_2$ emissions. However, the average annual VKT, fuel structure, fuel economy, and fuel emission factor contribute to reducing road transport $CO_2$ emissions, which can promote the reduction of road transport $CO_2$ emissions. Fuel structure and fuel economy are the most important factors that restrain road transport $CO_2$ emissions. The contribution rate of fuel structure is up to −0.88 in the CE scenario, with the contribution rate of fuel economy up to −0.74 and −0.72 in the SAV and FE scenarios, respectively.

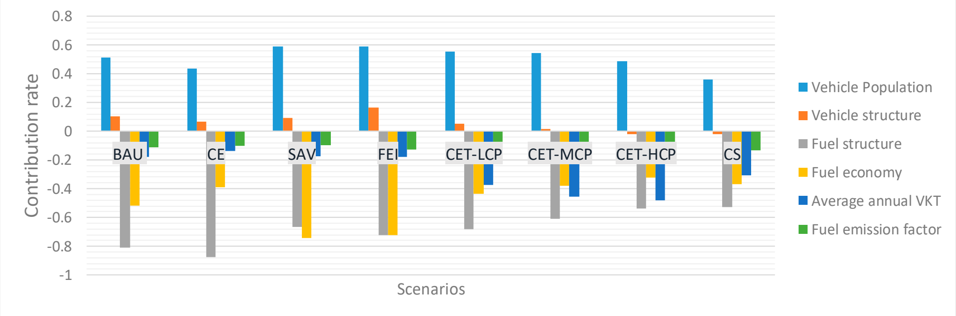


**Figure 14.** Contribution degree of factors to road transport $CO_2$ emissions.

To sum up, the vehicle population has the greatest impact on road transport $CO_2$ emission, followed by the vehicle structure, fuel economy, fuel structure, and average annual VKT. The emission reduction contribution of the fuel emission factor is relatively small, but with an increase in the proportion of electric vehicles, the fuel emission factor will be important and non-negligible in the medium and long term for the reduction of road transport $CO_2$ emission. Therefore, to achieve a deep and comprehensive reduction in road transport $CO_2$ emissions, all the factors discussed above should be considered when developing a low-carbon policy for road transport.

## 6. Conclusions and Policy Implications

To help achieve the goal of carbon neutrality in China, this study proposed eight policy scenarios to reduce $CO_2$ emissions of road transport. These scenarios are defined by several key factors that influence road transport $CO_2$ emissions, such as vehicle population, vehicle structure, fuel structure, fuel economy, average annual VKT, and fuel emission factors. Based on the scenarios set on the LEAP, road transport $CO_2$ emissions in China are analyzed from 2020 to 2060 for each scenario. Compared with the BAU scenario, the $CO_2$ emission reduction potential of the other seven scenarios is evaluated. Furthermore, the factors contributing to the emission reduction of road transport from the peak year to 2060 are composed using the LMDI method. The main findings are summarized as follows:

(1) Due to the widespread adoption of electric vehicles for passenger transport, they have a greater potential to reduce $CO_2$ emissions than freight transport in the field of road transport, especially for small passenger vehicles.

(2) The total $CO_2$ emissions of road transport will peak at 1419.5 million tonnes in 2033 for the BAU scenario. In contrast, the peaks of road transport $CO_2$ emissions for the CE, SAV, FEI, CET-LCP, CET-MCP, CET-HCP, and CS scenarios are decreasing and occur progressively earlier, as early as 2023.

(3) Compared with the BAU scenario, the cumulative $CO_2$ emission reductions of road transport from 2020–2060 for the other seven scenarios can be up to 22,501.22 million tonnes. The $CO_2$ emission reduction potential of the seven scenarios can be ranked as follows: CS > CET-HCP > CET-MCP > FEI > CET-LCP > SAV > CE. This finding

indicates that $CO_2$ emission trading may be more effective than other policies, with a combination of policies the best.

(4) Based on the decomposition of factors that contribute to the $CO_2$ emission reduction of road transport from the peak year to 2060 for each scenario, it is concluded that fuel structure and fuel economy contribute most to the emission reduction, whereas the increase in vehicle population restrains the $CO_2$ emission reduction.

The above findings also provide certain policy implications for the government to design a pathway toward low-carbon road transport under the goal of $CO_2$ emission peak and carbon neutrality in China. The specific policy suggestions are as follows:

(1) The power industry needs to vigorously increase the proportion of clean energy in power generation, including photovoltaic, hydroelectric, wind, and nuclear powers, to further reduce $CO_2$ emissions of electric vehicles.
(2) The government should formulate relevant policies to encourage vehicle manufacturers to improve the fuel economy of both traditional internal combustion engine vehicles and new energy vehicles to reduce the energy consumption and $CO_2$ emissions of road transportation.
(3) Since private vehicles account for a large proportion of passenger transport in China, the government could implement downstream emission trading for road transport to encourage more consumers to purchase new energy vehicles.
(4) To ensure the achievement of the targets of peak $CO_2$ emissions and carbon neutrality in China, a comprehensive policy package should be designed considering all the contributing factors to the emission reduction of road transport.

This study also has some limitations. Due to the immature technology and the high cost of hydrogen and other synthetic fuel cell vehicles, the future development of these vehicles is uncertain and difficult to predict. In addition, the proportion of these vehicles is currently negligible. Therefore, this study does not include hydrogen and other synthetic fuels in the fuel structure. The COVID-19 pandemic situation may reduce the traffic demand of road transport during the prevention and control period. However, the period was short and the impact was moderate across the year 2020. Therefore, this study does not consider the consequence of the COVID-19 pandemic in the scenario analysis of the road transport $CO_2$ emissions in China from 2020 to 2060, since we use the average annual VKT in the calculation. These limitations should be further addressed in future studies.

**Author Contributions:** Methodology, J.D. and W.L.; data curation, Y.L.; writing—original draft preparation, Y.L. and S.L.; writing—review and editing, W.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was sponsored by the National Natural Science Foundation of China (Grant No.: 52002244); Chenguang Program (Grant No.: 20CG55) supported by Shanghai Education Development Foundation and Shanghai Municipal Education Commission; and Shanghai Pujiang Program (Grant No.: 2020PJC083).

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| | |
|---|---|
| $C$ | total $CO_2$ emissions of road transport |
| $C_P$ | total $CO_2$ emissions of road passenger transport |
| $C_T$ | total $CO_2$ emissions of road freight transport |
| $N_P$ | passenger vehicle population |
| $S_i$ | proportion of passenger vehicles of type *i* |
| $M_i$ | average annual VKT of type *i* vehicles |

| | |
|---|---|
| $Q_{ik}$ | proportion of fuels of type $k$ for vehicles of type $i$ |
| $F_{ik}$ | fuel economy of vehicles of type $i$ with fuel type $k$ |
| $E_k$ | $CO_2$ emission factor of fuel of type $k$ |
| $N_T$ | freight vehicle population |
| $S_j$ | proportion of freight vehicles of type $j$ |
| $M_j$ | average annual VKT of trucks of type $j$ |
| $Q_{jh}$ | proportion of fuels of type $h$ for freight vehicles of type $j$ |
| $F_{jh}$ | fuel economy of trucks of type $j$ with fuel type $h$ |
| $E_h$ | $CO_2$ emission factor of fuel of type $h$ |
| $\Delta C$ | total contribution of each factor to road transport $CO_2$ emissions |
| $\Delta C_N$ | contribution of vehicle population to road transport $CO_2$ emissions |
| $\Delta C_S$ | contribution of vehicle structure to road transport $CO_2$ emissions |
| $\Delta C_Q$ | contribution of fuel structure to road transport $CO_2$ emissions |
| $\Delta C_F$ | contribution of fuel economy to road transport $CO_2$ emissions |
| $\Delta C_M$ | contribution of average annual VKT to road transport $CO_2$ emissions |
| $\Delta C_E$ | contribution of fuel $CO_2$ emission factors to road transport $CO_2$ emissions |
| $i$ | type of passenger vehicles |
| $j$ | type of freight vehicles |
| $k$ | type of fuel used by passenger vehicles |
| $h$ | type of fuel used by freight vehicles |
| BAU | business-as-usual scenario |
| CE | clean electricity scenario |
| FEI | fuel economy improvement scenario |
| SAV | shared autonomous vehicles Scenario |
| CET-LCP | $CO_2$ emissions trading scenario with low carbon prices |
| CET-MCP | $CO_2$ emissions trading scenario with mid carbon prices |
| CET-HCP | $CO_2$ emissions trading scenario with high carbon prices |
| CS | comprehensive scenario |

## References

1. European Automobile Manufacturers Association (ACEA). *Paving the Way to Carbon-Neutral Transport: 10-Point Plan to Help Implement the European Green Deal*; ACEA: Brussels, Belgium, 2020.
2. Li, W.; Bao, L.; Wang, L.; Li, Y.; Mai, X. Comparative evaluation of global low-carbon urban transport. *Technol. Forecast. Soc. Chang.* **2019**, *143*, 14–26. [CrossRef]
3. Li, W.; Bao, L.; Li, Y.; Si, H.; Li, Y.M. Assessing the transition to low-carbon urban transport: A global comparison. *Resour. Conserv. Recycl.* **2022**, *180*, 106179. [CrossRef]
4. Paustian, K.; Ravindranath, N.H.; Amstel, A.V. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; International Panel on Climate Change: Geneva, Switzerland, 2006.
5. Vuuren, D.; Hoogwijk, M.; Barker, T.; Riahi, K.; Boeters, S.; Chateau, J.; Scrieciu, S.; Vliet, J.; Masui, T.; Blok, K.; et al. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. *Energy Policy* **2009**, *37*, 5125–5139. [CrossRef]
6. Li, Y.; Bao, L.; Li, W.; Deng, H. Inventory and policy reduction potential of greenhouse gas and pollutant emissions of road transportation industry in China. *Sustainability* **2016**, *8*, 1218. [CrossRef]
7. Shan, Y.; Guan, D.; Liu, J.; Mi, Z.; Liu, Z.; Liu, J.; Schroeder, H.; Cai, B.; Chen, Y.; Shao, S.; et al. Methodology and applications of city level $CO_2$ emission accounts in China. *J. Clean. Prod.* **2017**, *161*, 1215–1225. [CrossRef]
8. Brand, C.; Tran, M.; Anable, J. The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. *Energy Policy* **2012**, *41*, 107–124. [CrossRef]
9. Zhang, L.; Long, R.; Chen, H.; Geng, J. A review of China's road traffic carbon emissions. *J. Clean. Prod.* **2019**, *207*, 569–581. [CrossRef]
10. Liu, M.; Zhang, X.; Zhang, M.; Feng, Y.; Liu, Y.; Wen, J.; Liu, L. Influencing factors of carbon emissions in transportation industry based on CD function and LMDI decomposition model: China as an example. *Environ. Impact Assess. Rev.* **2021**, *90*, 106623. [CrossRef]
11. Quan, C.; Cheng, X.; Yu, S.; Ye, X. Analysis on the influencing factors of carbon emission in China's logistics industry based on LMDI method. *Sci. Total Environ.* **2020**, *734*, 138473. [CrossRef]
12. Brand, C.; Anable, J.; Tran, M. Accelerating the transformation to a low carbon passenger transport system: The role of car purchase taxes, feebates, road taxes and scrappage incentives in the UK. *Transp. Res. Part A Policy Pract.* **2013**, *49*, 132–148. [CrossRef]

13. Dineen, D.; Ryan, L.; Gallachóir, B.Ó. Vehicle tax policies and new passenger car $CO_2$ performance in EU member states. *Clim. Policy* **2018**, *18*, 396–412. [CrossRef]
14. Nayum, A.; Klöckner, C.A.; Prugsamatz, S. Influences of car type class and carbon dioxide emission levels on purchases of new cars: A retrospective analysis of car purchases in Norway. *Transp. Res. Part A Policy Pract.* **2013**, *48*, 96–108. [CrossRef]
15. Patil, G.R. Emission-based static traffic assignment models. *Environ. Model. Assess.* **2016**, *21*, 629–642. [CrossRef]
16. Roman, R.D.; Ritchie, S.G. Accounting for population exposure to vehicle-generated pollutants and environmental equity in the toll design problem. *Int. J. Sustain. Transp.* **2017**, *11*, 406–421. [CrossRef]
17. Yan, S.; Eskeland, G.S. Greening the vehicle fleet: Norway's $CO_2$-Differentiated registration tax. *J. Environ. Econ. Manag.* **2018**, *91*, 247–262. [CrossRef]
18. Hörcher, D.; Borger, B.D.; Seifu, W.; Graham, D.J. Public transport provision under agglomeration economies. *Reg. Sci. Urban Econ.* **2020**, *81*, 103503. [CrossRef]
19. Timilsina, G.R.; Dulal, H.B. *Fiscal Policy Instruments for Reducing Congestion and Atmospheric Emissions in the Transport Sector: A Review*; World Bank Policy Research Working Paper No. 4652; World Bank: Washington, DC, USA, 2010; Available online: https://ssrn.com/abstract=1149604 (accessed on 30 April 2022).
20. Chen, S.; Zheng, X.; Yin, H.; Liu, Y. Did Chinese cities that implemented driving restrictions see reductions in PM10? *Transp. Res. Part D Transp. Environ.* **2020**, *79*, 102208. [CrossRef]
21. Burniaux, J.M.; Chateau, J. *Mitigation Potential of Removing Fossil Fuel Subsidies: A General Equilibrium Assessment*; OECD Economics Department Working Papers; OECD: Paris, France, 2011.
22. Jia, S.; Mao, B.; Liu, S.; Sun, Q. Calculation and analysis of transportation energy consumption level in China. *J. Transp. Syst. Eng. Inf. Technol.* **2010**, *10*, 22–27. [CrossRef]
23. Li, Y.; Bao, L.; Bao, J. Evaluating Emission Mitigation Potential of Shanghai Transportation Policies Using LEAP. In Proceedings of the 93rd Transportation Research Board, Washington, DC, USA, 12–16 January 2014.
24. Liu, H.; Wang, Y.; Chen, X.; Han, S. Vehicle emission and near-road air quality modeling in Shanghai, China, based on taxi GPS data and MOVES revised emission inventory. *Transp. Res. Rec.* **2013**, *2340*, 38–48. [CrossRef]
25. Feng, X.; Zhao, M.; Wang, M.; Du, X.; Tian, C.; Gao, J. Simulation research on co-controlling pollutants and greenhouse gases emission in China's transportation sector. *Clim. Change Res.* **2021**, *17*, 279–288.
26. Pang, K.; Zhang, Q.; Ma, C.; Zhu, L.; Chen, H.; Kong, X.; Pan, F.; Yang, H. Forecasting of Emission Co-reduction of Greenhouse Gases and Pollutants for the Road Transport Sector in Lanzhou Based on the LEAP Model. *Environ. Sci.* **2021**. (In Chinese) [CrossRef]
27. Duan, L.; Hu, W.; Deng, D.; Fang, W.; Xiong, M.; Lu, P.; Li, Z.; Zhai, C. Impacts of reducing air pollutants and $CO_2$ emissions in urban road transport through 2035 in Chongqing, China. *Environ. Sci. Ecotechnol.* **2021**, *8*, 100125. [CrossRef]
28. Chi, L. The Prediction of Beijing Passenger Transport Energy Demand and Pollutants Emission in Future Based on LEAP Mode. Ph.D. Thesis, Beijing Jiaotong University, Beijing, China, 2014. (In Chinese).
29. Hu, X.L.; Jiang, K.J. $CO_2$ emission reduction strategies analysis: AIM/energy-emission model. *Energy China* **1998**, *11*, 17–22.
30. Zhang, C.X. Research on the Development of Electric Vehicle Impact on Energy and Environment in Guangzhou Based on LEAP. Master's Thesis, North China Electric Power University, Beijing, China, 2013. (In Chinese).
31. Zhang, M.; Miu, H. Research on the Change of Motorized Passenger Transport Energy Consumption in Selected Chinese Cities Based on LMDI Method. *Acta Sci. Nat. Univ. Pekin.* **2010**, *46*, 483–486. [CrossRef]
32. International Energy Agency (IEA). *The Future of Trucks: Implications for Energy and the Environment*; IEA: Paris, France, 2017.
33. Pierpaolo, C.; Marine, G.; Jacopo, T. *Global EV Outlook 2019—Scaling Up the Transition to Electric Mobility*; IEA: Paris, France, 2019.
34. International Energy Agency (IEA). *Global Energy and $CO_2$ Status Report 2018: The Latest Trends in Energy and Emissions in 2018*; IEA: Paris, France, 2019.
35. Li, R.; He, Q.; Li, S. Analyses of Automobile Ownership Development Trend in China. *Urban Transp. China* **2013**, *11*, 69–75. [CrossRef]
36. China International Capital Corporation Limited. Passenger Car Ownership is Expected to Rise and then Fall to 530 Million in 2060. Available online: http://stock.jrj.com.cn/2020/12/04081131405001.shtml (accessed on 29 January 2022).
37. An, F.; Kang, L.; Qin, Z.; Mao, S.; Wang, W.; Dror, M.B. Study on the phasing-out timetable of China's traditional ICE-vehicles. *Int. Pet. Econ.* **2019**, *27*, 1–8.
38. Updated Timetable for Phasing Out China's Traditional Ice Vehicles and Its Environmental Benefits Assessment. Available online: http://www.nrdc.cn/Public/uploads/2020-06-30/5efac9b5b0832.pdf (accessed on 29 January 2022).
39. Ministry of Industry and Information Technology of the People's Republic of China. *Fuel Consumption Limits for Passenger Cars GB19578-2021*; Ministry of Industry and Information Technology: Beijing, China, 2021.
40. Toward "Net Zero" Emissions in the Road Transport Sector in China. Available online: https://wri.org.cn/research/toward-net-zero-emissions-road-transport-sector-china (accessed on 29 January 2022).
41. Jia, S.; Song, Y.; Yang, Z. Process of Peak carbon emissions of trucks during operating activities based on growth curve function. *J. Transp. Syst. Eng. Inf. Technol.* **2021**, *21*, 310. [CrossRef]
42. Li, W.; Pu, Z.; Li, Y.; Ban, X. Characterization of ridesplitting based on observed data: A case study of Chengdu, China. *Transp. Res. Part C Emerg. Technol.* **2019**, *100*, 330–353. [CrossRef]

43. Li, W.; Pu, Z.; Li, Y.; Tu, M. How does ridesplitting reduce emissions from ridesourcing? A spatiotemporal analysis in Chengdu, China. *Transp. Res. Part D Transp. Environ.* **2021**, *96*, 102885. [CrossRef]
44. Li, W.; Chen, S.; Dong, J.; Wu, J. Exploring the spatial variations of transfer distances between dockless bike-sharing systems and metros. *J. Transp. Geogr.* **2021**, *92*, 103032. [CrossRef]
45. Li, W.; Wang, L.; Li, Y.; Liu, B. A Blockchain-based emissions trading system for the road transport sector: Policy design and evaluation. *Clim. Policy* **2021**, *21*, 337–352. [CrossRef]
46. Song, L.; Cao, Z.; Dai, M. Material metabolism and carbon emission reduction strategies of passenger cars in China's mainland. *Resour. Sci.* **2021**, *43*, 501–512. [CrossRef]
47. Peng, T.; Ou, X.; Yuan, Z.; Yan, X.; Zhang, X. Development and application of China provincial road transport energy demand and GHG emissions analysis model. *Appl. Energy* **2018**, *222*, 313–328. [CrossRef]
48. Gambhir, A.; Tse, L.; Tong, D.; Martinez-Botas, R. Reducing China's road transport sector $CO_2$ emissions to 2050: Technologies, costs and decomposition analysis. *Appl. Energy* **2015**, *157*, 905–917. [CrossRef]
49. Yan, X.; Crookes, R.J. Reduction potentials of energy demand and GHG emissions in China's road transport sector. *Energy Policy* **2019**, *37*, 658–668. [CrossRef]