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Research on the Green and Low-carbon Transformation Path of China's Transportation Industry under the Goal of "Double Carbon"

Zhenyi Zhang, Xuyang Huang, Shengxin Ling, Xiaomeng Long

Guangxi Normal University, Guilin, Guangxi, China

Abstract: ***The transportation industry is one of the main sectors of China's carbon emission sources. Accelerating the green and low-carbon transformation of the transportation industry will help China achieve the "double carbon" strategic goal and the construction of a beautiful China on schedule. This paper first measures the carbon emissions of China's transportation industry from 2001 to 2022, then uses the logarithmic mean Divisia index (LMDI) method to decompose the driving factors of carbon emissions, and finally uses Monte Carlo simulation to set three different scenarios: benchmark scenario, technological progress scenario and low-carbon target scenario. The dynamic impact of different policy paths on the carbon emissions of the transportation industry from 2023 to 2030 and its peak potential are studied, and the strategies and paths of green and low-carbon transformation of transportation are proposed. First, the most important driving factor for carbon emissions in China 's transportation industry is economic scale. Second, the promoting factors are fuel energy-oil ratio and traffic energy intensity. The fuel energy-oil ratio has the greatest emission reduction effect, while the effect of traffic energy intensity on carbon emissions is not stable, and there are stage differences. Third, the results of Monte Carlo simulation show that compared with the benchmark scenario, the emission reduction intensity of the technological progress scenario can reach up to 40.00 %, and the emission reduction intensity of the low-carbon target scenario can reach up to 57.29 %. In addition, among the three scenarios, only under the low-carbon target scenario, it is possible to achieve the carbon peak target of the transportation industry in 2030, and the other two scenarios have not yet reached the peak inflection point. Fourthly, it is found that the low-carbon target scenario is the most feasible way to achieve the overall carbon peak goal of China 's transportation industry, and the emission reduction path with the core idea of "transportation energy transformation as the focus and carbon emission double control as the basis" is proposed. Finally, according to the research conclusions, this paper provides relevant policy recommendations for the transportation industry to achieve the 2030 carbon peak goal.***

Keywords: Transportation carbon emissions; Monte Carlo simulation; Emission reduction path.

1. INTRODUCTION

In the process of continuous development and evolution of human society, global climate change has gradually become one of the most complex challenges facing mankind. China is deeply affected by extreme weather, but at the same time, China's total carbon dioxide emissions rank first in the world, accounting for 30% of the world's total. Carbon emissions from transportation account for about 10% of the country's total carbon emissions [1], and carbon emissions from urban transport are expected to grow at an annual rate of 1.7%, especially in developing countries [2]. Transportation is a basic, leading and strategic industry in the national economy, which plays an important role in the development of the national economy. However, the large amount of carbon emissions brought about by the promotion of economic development cannot be ignored. The "Opinions of the Central Committee of the Communist Party of China and the State Council on Accelerating the Comprehensive Green Transformation of Economic and Social Development" clearly put forward "improving the green and low-carbon development mechanism" and "by 2030, green transformation in key areas will make positive progress." Therefore, it is necessary to accelerate the green and low-carbon transformation of transportation and promote the realization of the "double carbon" goal and the construction of a beautiful China.

In recent years, more and more studies have begun to pay attention to carbon emissions, mainly focusing on carbon emissions accounting, influencing factors analysis and emission forecasting, and the research perspective has gradually shifted from manufacturing to transportation. As one of China's major carbon emission sectors, how to transform the transportation industry to green and low-carbon transportation has become a major challenge for its future development. Most of the existing studies stop at the analysis of the influencing factors of carbon emissions in the transportation industry, and few can further simulate and predict the peak potential of the transportation industry in 2030. For example, Zhang Guoxing et al. [3] only predicted the carbon emissions of transportation in the Yellow River Basin; wang Jingtian et al. [4] analyzed the emission reduction potential of different modes of transportation. However, the above scholars only predicted future emission trends, and did not further analyze the realization of carbon peak in the transportation industry. The report of the 20th National Congress of the Communist Party of China pointed out that "carbon peak carbon neutrality is an extensive and profound economic and social systematic change," and it is necessary to formulate action steps in stages based on goals. Under the deployment of the "carbon peak action plan by 2030," the transportation industry is accelerating the formation of green and low-carbon transportation modes to help achieve the peak goal. Therefore, the possible contributions of this paper are as follows: According to the five-year plan of China's transportation industry, taking the "Tenth Five-Year Plan" as the starting point, the driving factors of carbon emissions in the transportation industry in the past are decomposed, and the staged changes of different driving factors are innovatively considered; under the guidance of the "Carbon Peak Action Plan by 2030," this paper conducts a simulation study on the peak path of the transportation industry in 2030; in the simulation method, Monte Carlo simulation is used to avoid the past scholars' practice of using discrete values as simulation parameters, which can make the results more reliable.

This paper first calculates the carbon emissions of China's transportation industry from 2001 to 2022 based on the carbon emissions accounting method published by the IPCC in 2006. Then, the LMDI method is used to decompose the driving factors of carbon emissions in the transportation industry. The main driving factors include transportation energy intensity, transportation fuel energy oil ratio, average transportation oil price, per capita output value, and population size. Finally, the benchmark scenario, technological progress scenario and low-carbon target scenario are set up, and Monte Carlo simulation is used to dynamically analyze the peak situation of the transportation industry from 2023 to 2030.

2. LITERATURE REVIEW

The key path to deal with global ecological challenges and energy crisis is to promote the transformation of green economy. This strategic concept has formed a broad consensus in the international governance system. As the circulation of the modern economic system, the transportation industry plays a pillar role in supporting the coordinated development of the region. However, due to its huge energy consumption, the transportation industry is facing more severe challenges in the process of 'decarbonization'. It has become the most difficult field in the process of achieving the goal of carbon peak, which has attracted the attention of scholars at home and abroad.

2.1 Research on the Influencing Factors of Carbon Emissions in the Transportation Industry

Economic scale, population size and energy consumption are the main factors to promote the growth of carbon emissions in the transportation industry, and energy intensity is the main factor to curb carbon emissions. For example, Darido's research shows that economic development and population growth are the key factors leading to the increase of carbon emissions in the transportation industry [5]; through linear and non-linear Granger causality tests, Wen and Li [6] found that there is a linear causal relationship between carbon dioxide emissions and GDP, gross national income and cargo turnover, which further confirms the significant impact of economic factors on carbon emissions. With the improvement of economic development level, people's pursuit of quality of life is increasing day by day, and the demand level and quality requirements for transportation services are also increasing accordingly. At the same time, as the world's most populous country, the transportation industry as a service industry, the expansion of population size has directly promoted the rise of transportation demand, and the economic scale and population size have shown a significant role in promoting transportation demand. The promoting effect of energy consumption is more obvious, because carbon emissions mainly come from the consumption of fossil energy. The development of China's transportation industry relies on fossil energy. If the current energy structure remains unchanged, the industry will still maintain the status quo of high energy consumption and high emissions. In developed countries, the transport intensity effect is the main force to promote transport carbon emission reduction; in developing countries, the energy intensity effect has become an important factor in reducing carbon emissions in the transportation sector. [7] Chen et al. [8] further found that environmental technology innovation can improve the carbon emissions of China's transportation sector. The energy efficiency of the production sector [9], the optimization of energy structure and the progress of science and technology [10] are all conducive to reducing the growth of transportation carbon emissions.

2.2 Research on the Research Methods of Carbon Emission in Transportation Industry

Different scholars have adopted different methods to study the influencing factors of carbon emissions in the transportation industry. At present, the most important research methods are LogarithmicMeanDivisiaIndex, (LMDI), Stochastic Impacts by Regression on Population, Affluence and Technology, (STIRPAT), spatial Durbin model and spatial econometric model based on panel data. These methods can effectively identify the influencing factors of transportation carbon emissions and are widely used in various studies. Liu et al. [11] used the LMDI model to decompose the influencing factors of carbon emissions in the transportation industry from 2001 to 2018, and pointed out that capital investment and technical level are the key factors to promote and inhibit the change of carbon emissions respectively. Sun et al. [12] used the STIRPAT model to quantify the contribution of different influencing factors to carbon emissions in the Yangtze River Delta region of China; [13] constructed a panel data model with China, the United States, the European Union and Japan as cross-sectional individuals. The results show that factors such as economic, social, transportation infrastructure investment, transportation intensity, transportation structure, and transportation energy intensity have a greater impact on carbon emissions in the transportation industry. Sporkmann et al. [14] used the spatial Dubin model combined with the extended STIRPAT model to examine the impact of transportation intensity, modal segmentation between roads and railways, and infrastructure density on carbon emissions from European land transportation. The results clearly show that the spatial autocorrelation model in transportation emissions can reduce industry carbon emissions by reducing transportation intensity and encouraging the shift from roads to railways. Summing up the above research findings, it is found that there is no best method at present, but the LMDI method in the factor decomposition method is favored because of its wide applicability, flexible operation and easy interpretation of the results. Therefore, this paper chooses the LMDI method to decompose the driving factors of carbon emissions in China’s transportation industry.

2.3 Research on the Future Prediction of Carbon Emissions in the Transportation Industry

In the study of future prediction of carbon emissions, the scenario analysis method is used to predict the future development trend of specific research objects by constructing a variety of different scenarios under certain assumed trends. Although it cannot fully restore the reality and has certain deviations, its value lies in being able to outline possible future scenarios. Through the analysis of the results of multiple scenarios, the emission reduction path can be identified and the system can be optimized. The commonly used simulation methods include Monte Carlo simulation, STIRPAT model, LEAP model and econometric regression model. Wang et al. [15] pointed out that China’s CO2 emissions from transportation will reach a peak of 1129 million tons in 2040-2045 in the comprehensive scheme of scenario prediction. Huang Zhihui et al. [16] focused on China’s road traffic carbon emissions, which is expected to reach a peak of 1.22 billion tons ~ 1.39 billion tons at the end of the ‘15th Five-Year Plan’, and will experience a platform period of 2 ~ 3 years. Yuan Zhiyi et al. [17] pointed out that the carbon emissions of China’s transportation sector will show a trend of rapid growth in the near and medium term and slow growth in the long term.

At present, the academic community has rich research results on the influencing factors and research methods of carbon emissions in the transportation industry. However, in the research of the transportation industry, only carbon emissions under a single scenario are often simulated, and few scholars use Monte Carlo simulation for multi-scenario simulation. Therefore, this paper attempts to carry out multi-scenario simulation of carbon emissions in China’s transportation industry under the background of carbon peak, and dynamically analyze the emission reduction potential and peak situation of the transportation industry, so as to provide reference for subsequent policy formulation.

3. RESEARCH METHODOLOGY AND DATA SOURCES

3.1 Carbon Emission Accounting Method of Transportation Industry

According to China’s “National Economic Industry Classification” standard (GB/T4754-2017), the transportation industry referred to in this paper combines transportation, warehousing and postal services, and uses seven commonly used energy sources, including raw coal, gasoline, kerosene, diesel, fuel oil, electricity and natural gas to calculate the carbon emissions of transportation. This paper refers to the “top-down” macro measurement method of carbon emissions from energy consumption published by the IPCC in 2006 to calculate the carbon emissions of China’s transportation industry. The specific calculation formula is as follows:

$$CE = \sum_{i=7} E_i \times K_i \times F_i,$$

CE indicates the carbon dioxide emissions of China’s transportation industry, and E_i is the type i energy consumption; K_i is the reference coefficient of class i energy conversion standard coal; F_i is the carbon emission coefficient of type i energy.

3.2 Decomposition Model of Driving Factors of Carbon Emission in Transportation Industry

The IPAT model decomposes carbon emissions into four factors, which are expressed in the form of chain product. The specific formulas are as follows:

$$CE = \frac{CE}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P,$$

CE is carbon emissions, E is energy consumption, GDP is gross domestic product, and P is population.

Based on the IPAT model, the LMDI decomposition model further decomposes the carbon emissions of China's transportation industry into five factors. The specific formulas are as follows:

$$CE = \frac{CE}{E} \times \frac{E}{Q} \times \frac{Q}{GDP} \times \frac{GDP}{P} \times P = D \times H \times M \times J \times P,$$

Introduce the amount of fuel consumed by the transportation industry Q, GDP is the output value of the transportation industry; $D = \frac{CE}{E}$ is the transportation energy intensity, which represents the carbon emissions released by unit transportation energy, reflecting the impact of energy structure on carbon emissions. $H = \frac{E}{Q}$ is the energy-to-oil ratio of transportation fuel, which represents the actual released energy per unit of fuel used in transportation, reflecting the impact of different fuel types on carbon emissions; $M = \frac{Q}{GDP}$ is the average oil price of transportation, which represents the average price of unit fuel used in transportation, reflecting the impact of transportation costs on carbon emissions; $J = \frac{GDP}{P}$ is the per capita output value of transportation, which represents the per capita GDP output value in transportation, reflecting the impact of economic scale on carbon emissions; P is population size, reflecting the impact of population size on carbon emissions.

In this paper, the additive effect in the LMDI method is used to decompose these five factors, and the contribution values of different factors to the carbon emissions of the transportation industry are obtained. The variation of carbon emissions from year to year can be expressed as:

$$\Delta CE = CE^t - CE^s = \Delta D + \Delta H + \Delta M + \Delta J + \Delta P$$

ΔCE is the variation of carbon emissions;CE^t, CE^s is the carbon emissions of t, $s$year ($t > s$);

ΔD、ΔH、ΔM、ΔJ、ΔP are the impact of changes in transportation energy intensity, transportation fuel oil ratio, average transportation oil price, per capita output value, and population size on carbon emissions.

Of which:

$$\Delta D = \omega(D,t)(\ln D^t - \ln D^0),$$
$$\Delta H = \omega(H,t)(\ln H^t - \ln H^0),$$
$$\Delta M = \omega(M,t)(\ln M^t - \ln M^0),$$
$$\Delta J = \omega(J,t)(\ln J^t - \ln J^0),$$
$$\Delta P = \omega(P,t)(\ln P^t - \ln P^0),$$

Where, the superscript t of $\chi \in \{D,H,M,J,P\}$ is the target year, the superscript 0 is the starting year, and $\omega_i(t*)$ is the function value at time $t*$.

$$\omega(\chi,t) = L(\chi^t,\chi^0),$$
$$L(x,y) = \frac{x-y}{\ln x - \ln y}, x \neq y.$$

3.3 Carbon Emission Prediction Model of Transportation Industry

Monte Carlo simulation has its unique advantages in prediction. In Monte Carlo simulation, the random values of different variables can be generated according to the probability distribution, and then the random values of these variables are combined to generate a variety of scenarios. Its advantage is that it can give each variable a different probability distribution. Therefore, this paper chooses Monte Carlo simulation to predict the carbon emissions of China's transportation industry from 2023 to 2030 with the change rate of each variable. The change rate of carbon emissions can be expressed as:

$$
\begin{aligned}
r &= \frac{CE_{t+1}-CE_t}{CE_t} \\
&= \frac{CE_{t+1}}{CE_t} - 1 \\
&= \frac{D_{t+1}\times H_{t+1}\times M_{t+1}\times J_{t+1}\times P_{t+1}}{D_t\times H_t\times M_t\times J_t\times P_t} - 1 \\
&= \frac{(1+a)D_t\times(1+b)H_t\times(1+c)M_t\times(1+d)J_t\times(1+e)P_t}{D_t\times H_t\times M_t\times J_t\times P_t} - 1 \\
&= (1+a)(1+b)(1+c)(1+d)(1+e) - 1
\end{aligned}
$$

t represents the year t, $t+1$ represents the year $t+1$, r represents the change rate of carbon emissions in China's transportation industry, and a、b、c、d、e is the change rate of D、H、M、J、P respectively. Finally, the change rate of carbon emissions in China's transportation industry can be converted into the product of the change rate of D、H、M、J、P minus 1.

Therefore, the carbon emissions in the $t+1$ year can be calculated based on the carbon emissions in the t year and the rate of change of carbon emissions. The calculation formula is as follows:

$$CE_{t+1} = (1+r) \times CE_t.$$

3.4 Data Sources

The main variables in this paper are carbon emissions, energy consumption, industry added value, national GDP and population in the transportation industry. Among them, energy consumption comes from the '*China Energy Statistical Yearbook*', and industry added value, GDP and population all come from the '*China Statistical Yearbook*'. In addition, in order to ensure the comparability of data and exclude the influence of price factors, the added value of the industry and GDP are adjusted by the base period of 2001 constant price.

4. CARBON EMISSIONS DECOMPOSITION RESULTS AND ANALYSIS YEAR BY YEAR

According to the results of China's transportation carbon emissions accounting (Figure 1), the transportation carbon emissions from 2002 to 2022 showed a trend of 'continuous rise-rapid decline-continuous rise'. Carbon emissions continued to rise from 2002 to 2019, and carbon emissions declined rapidly from 2019 to 2020.Although carbon emissions continued to rise from 2020 to 2022, the growth rate generally showed a trend of continuous growth.

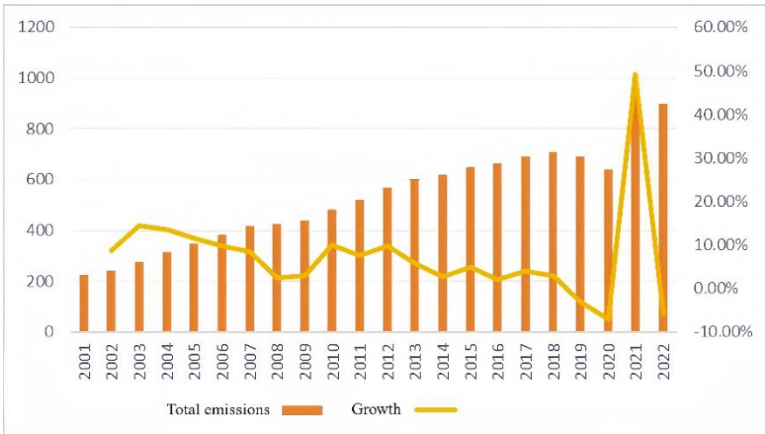

Figure 1: Carbon emissions of transportation industry from 2001 to 2022

There are obvious differences in the effects of different influencing factors on the change of energy carbon emissions in China's transportation industry (Table 1). Comparing the cumulative effects of various influencing factors during the study period (the absolute value of the cumulative effect), the order from large to small is per capita output value, fuel energy oil ratio, average oil price, population size and transportation energy intensity.

Specifically, during the study period, the transportation energy intensity showed an overall inhibitory effect on carbon emissions, but it also showed a promoting effect in individual years. The improvement of energy intensity is closely related to the improvement of technical level. By introducing energy-saving innovative products and advanced processes, the proportion of fossil energy used in transportation can be effectively reduced, and the overall utilization efficiency of energy can be improved, thus achieving the reduction of carbon emissions. However, there is still some volatility in the emission reduction effect brought by the current technological progress, which indicates that the green innovation ability of China's transportation industry needs to be further strengthened. The cumulative negative fuel-to-oil ratio means that the transportation industry's dependence on oil is on a downward trend. Transportation modes or freight volumes with high energy consumption and high oil consumption may be suppressed, while transportation modes or passenger demand with relatively low energy consumption and low oil consumption may be relatively stable or increasing. When the average oil price decreases, the cost of fuel use decreases. In order to obtain more profits at lower oil prices, transportation companies may increase the amount of transportation tasks, extend the transportation distance, or increase the frequency of vehicle use, resulting in an increase in total fuel consumption. In the process of rising oil prices, transportation companies may look for alternative energy sources in the short term to reduce fuel costs. However, alternative energy sources are not necessarily low-carbon energy sources. Alternative measures have alleviated the cost pressure caused by rising oil prices to a certain extent, but their carbon emission intensity is often higher than traditional fuel, resulting in an increase in carbon emissions in the transportation industry. The average oil price is mainly positive, indicating that oil price fluctuations will promote the increase of carbon emissions in the transportation industry. When the per capita GDP effect and the population size effect are both positive, it indicates that economic growth and population size expansion will promote the increase of carbon emissions in the transportation industry.

Table 1: Decomposition results of LMDI from 2001 to 2022

year	Total effect	transportation energy intensity	fuel oil ratio	average oil price	per capita output value	population size
2001	0	0	0	0	0	0
2002	19.58	-8.41	-113.93	118.40	22.02	1.50
2003	34.69	24.31	-81.77	63.85	26.75	1.55
2004	37.45	12.05	-47.06	35.53	35.20	1.73
2005	36.01	-6.25	-55.19	54.89	40.61	1.95
2006	33.97	-7.34	-76.48	65.27	50.59	1.93
2007	32.26	-21.93	-29.26	19.16	62.22	2.07
2008	10.45	-5.87	-37.80	7.82	44.16	2.14
2009	12.07	21.03	-137.51	87.52	38.92	2.11
2010	44.10	3.09	-55.20	33.96	60.03	2.21
2011	36.21	-3.51	-49.68	31.14	55.19	3.07
2012	50.95	18.25	-54.79	47.75	35.70	4.04
2013	33.26	0.68	11.30	-20.05	37.87	3.46
2014	15.80	-17.55	0.76	-5.34	33.83	4.10
2015	30.89	2.90	107.40	-113.73	31.19	3.13
2016	13.24	-15.87	7.40	-17.96	35.38	4.29
2017	27.48	-31.11	-33.80	29.58	59.03	3.78
2018	19.78	-19.48	-81.07	65.06	52.62	2.65
2019	-20.87	-11.29	41.72	-80.67	27.05	2.32
2020	-49.11	5.95	-15.84	-42.42	2.24	0.96
2021	-52.16	5.46	-16.93	-43.86	2.33	0.84
2022	-54.77	5.01	-18.07	-45.35	2.43	0.74
accumulate	311.28	-49.88	-735.8	290.55	755.36	50.57

Note: 2001 is the starting year, with a total effect of 0. The 2002 row indicates the change in carbon emissions from 2001 to 2002 and the impact of changes in driving factors on carbon emissions, and so on. The same below.

5. CARBON PEAK SCENARIO SIMULATION

5.1 Scenario Setting

Monte Carlo simulation is a prediction method based on random number generation and probability distribution. Through multiple random sampling and repeated calculation of key variables, it is possible to simulate future carbon emission results and provide uncertainty range and statistical characteristics. The selection of parameter distribution type directly affects the robustness of the simulation results. At present, scholars have not reached a consensus on the selection of distribution. Lin et al. [18] used discrete probability model to realize parameter characterization; lin et al. [19] chose normal distribution to generate random numbers; shao Shuai [20] innovatively used the triangular probability function to construct the uncertainty analysis framework. At present, the discrete and normal distribution models have theoretical limitations in parameter estimation. The former is difficult to capture the dynamic characteristics of continuous variables, while the latter is susceptible to extreme value interference and leads to deviation accumulation. In contrast, the triangular probability model can effectively balance the computational complexity and the credibility of the results by setting the three-point estimation of the minimum, maximum and most likely values, so it shows stronger applicability in the variable sampling process. Based on this, this study chooses triangular distribution as the core parameter generation mechanism to improve the theoretical rationality and practical feasibility of the simulation process.

5.1.1 Baseline Scenario

The benchmark scenario is based on the historical development characteristics of China's transportation industry. It is assumed that the current economic environment and technical level remain unchanged without any policy intervention, so the rate of change of all variables continues the previous trend. Referring to Shao Shuai [20], this paper calculates the annual average rate of change of China's transportation energy intensity, fuel oil ratio, average oil price, per capita output value and population size, and then selects the minimum value, maximum value and mode as the parameters of triangular distribution. The specific parameter settings are shown in Table 2.

5.1.2 Technological Progress Scenario

The technical scenario assumes that China will further improve the efficiency of resource utilization, accelerate the modernization of the transportation industry and clean energy substitution, and promote the optimization of industrial structure and the promotion of green technology in the future economic and transportation industry development. Therefore, in this scenario, only the results brought about by technological innovation are considered, and there are no other effects. This paper assumes that under this scenario, during the period of 2023-2030, the mode of transportation energy intensity, fuel-to-oil ratio, average oil price, per capita output value and population size will decrease compared with the baseline scenario, and refers to the research of Lim Boqiang [18]. The maximum and minimum values of the average annual rate of change are adjusted by 0.4%, and their maximum and minimum values are obtained respectively. Other variables are consistent with the baseline scenario. The specific parameter settings are shown in Table 2.

5.1.3 Low-carbon Target Scenario

Under the low-carbon target scenario, the Chinese government will adopt more stringent policy guidance, stronger technical support and more efficient means of resource allocation, in-depth implementation of the 'CPC Central Committee and State Council on the complete and accurate full implementation of the new development concept to do a good job in carbon peak carbon neutralization work' and 'green transportation '14th Five-Year' development plan' and other relevant policy requirements, to promote the green low-carbon transformation of the transportation industry. If the transportation industry wants to successfully achieve carbon peaks, the key is to optimize the energy structure, turn to a cleaner energy type, and focus on improving energy efficiency. The guiding role of innovation is also very important. It is necessary to accelerate the process of green low-carbon science and technology revolution, enhance the ability of industrial technology innovation, accelerate the transformation to green low-carbon transportation mode, vigorously promote the construction of green transportation infrastructure, and actively advocate the concept of green travel. Therefore, under the low-carbon scenario, this paper assumes that all variables will be affected. During the period of 2023-2030, the transportation energy intensity, fuel-to-oil ratio, average oil price, per capita output value, and the mode of population size have changed to a greater extent than the technical scenario. The maximum and minimum values were adjusted by 0.2%, 0.5%, 0.4% and 0.2%, respectively. The parameters of transportation energy intensity, fuel-to-oil ratio, average oil price, per capita output value, and population growth rate under the low-carbon scenario are set as shown in table 2 below.

Table 2: The parameter setting of the change rate of each driving factor under different scenarios (%)

	Baseline scenario			**Technological progress scenario**			**Low-carbon target scenario**		
	maximum	minimum	mode	maximum	minimum	mode	maximum	minimum	mode
D	0.015	-0.020	-0.003	-0.019	-0.027	-0.023	-0.039	-0.047	-0.043
H	0.076	-0.051	-0.010	-0.026	-0.034	-0.030	-0.046	-0.054	-0.050
P	0.041	-0.075	-0.004	-0.020	-0.028	-0.024	-0.040	-0.048	-0.044

J	0.058	0.002	0.028	0.032	0.024	0.028	0.012	0.004	0.008
G	0.003	0.001	0.002	0.006	0.002	0.002	0.014	0.022	0.018

5.2 Analysis of Carbon Peak Simulation Prediction Results

5.2.1 Baseline scenario

The simulation results of carbon emissions in China's transportation industry from 2023 to 2030 under the benchmark scenario are shown in Figure 2. Since all variables maintain the previous trend, the economic scale is still the biggest driving factor, and the carbon emissions of the transportation industry show an annual growth trend from 2023 to 2030.

In 2023, the carbon emissions of the transportation industry ranged from 8.7965 million tons to 1055.67 million tons, with an average of 9.5149 million tons. The carbon emissions of the transportation industry in 2025 range from 8.9554 million tons to 13.2459 million tons, with an average of 10.6117 million tons. In 2030, the carbon emissions of the transportation industry will range from 10.4997 million tons to 19.3074 million tons, with an average of 13.8961 million tons. Compared with 2021, the average annual growth rate of carbon emissions in the transportation industry in 2025 is about 3.43% to 10.97%, and the average annual growth rate of carbon emissions in the transportation industry in 2030 is about 6.55% to 11.79%. However, under the baseline scenario analysis, it can be found that the current emission reduction effect is not sustainable in the absence of corresponding policy interventions. With the deepening of China's opening up and the continuous advancement of economic globalization, carbon emissions in the field of transportation may even rebound sharply. In view of this, the government's implementation of effective policy intervention plays an indispensable role in ensuring the smooth realization of the goal of peaking carbon emissions.

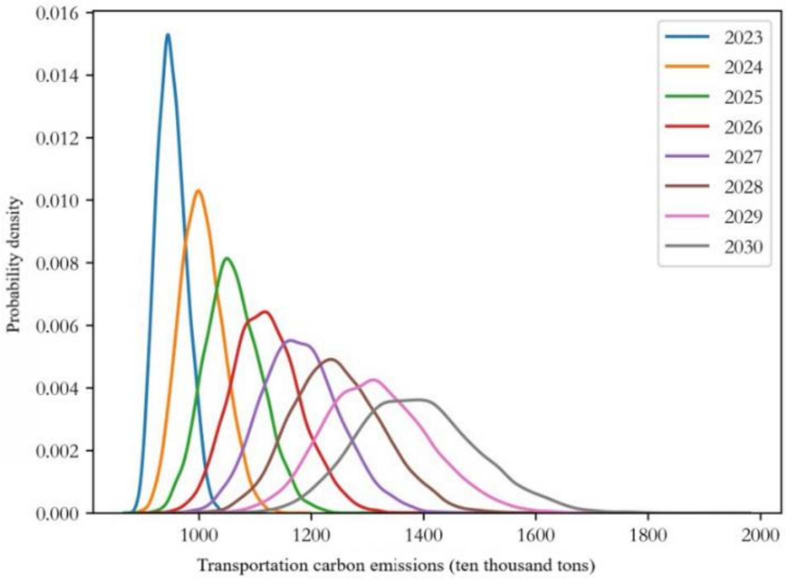

Figure 2: Carbon emission simulation results of China's transportation industry under the baseline scenario

5.2.2 Technological Progress Scenario

Compared with the baseline scenario, the total carbon emissions of China's transportation industry will slow down year by year from 2023 to 2030 under the technology scenario (Figure.3), reflecting the positive effect of technological progress on emission reduction. In 2023, the carbon emissions of the transportation industry ranged from 8.6054 million tons to 9.8919 million tons, with an average of 9.2081 million tons. The carbon emissions of the transportation industry in 2025 range from 8.5855 million tons to 110.45 million tons, with an average of 9.638 million tons. The carbon emissions of the transportation industry in 2030 range from 8.610 3 million tons to 13.721 8 million tons, with an average of 10.666 9 million tons. Compared with 2021, the average annual growth rate of carbon emissions in the transportation industry in 2030 is about 1.50% to 8.00%.

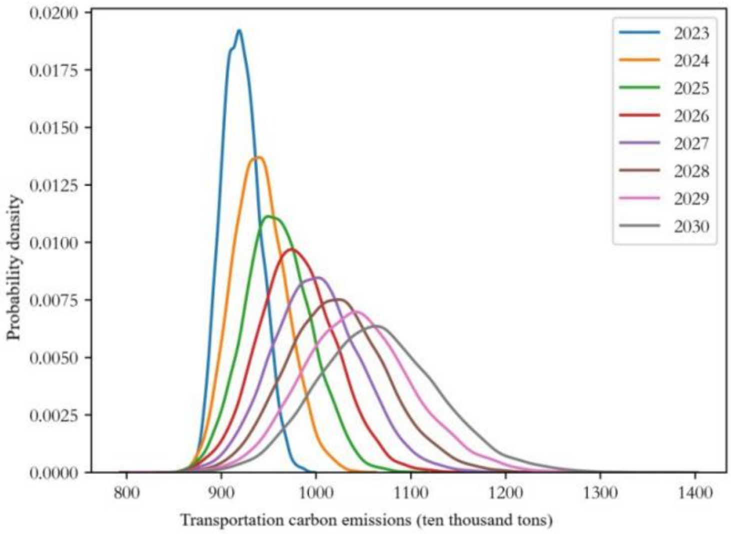

Figure 3: Simulation results of carbon emissions in China's transportation industry under the technical scenario

5.2.3 Low-carbon Scenario

Under the low-carbon scenario, China's transportation industry has achieved a greater reduction in carbon emissions than the baseline scenario and the technology scenario (Figure 4). In 2023, the carbon emissions of the transportation industry ranged from 8.7605 million tons to 9.4515 million tons, with an average of 9.0587 million tons. The range of carbon emissions from the transportation industry in 2025 is 8.4969 million tons to 1002.75 million tons, with an average of 9.1464 million tons. The carbon emissions of the transportation industry in 2030 range from 8.2462 million tons to 10.7978 million tons, with an average of 9.3771 million tons. Compared with 2021, the average annual growth rate of carbon emissions in the transportation industry in 2025 is about 1.99% to 8.99%, and the average annual growth rate of carbon emissions in the transportation industry in 2030 is about 0.99% to 5.00%.

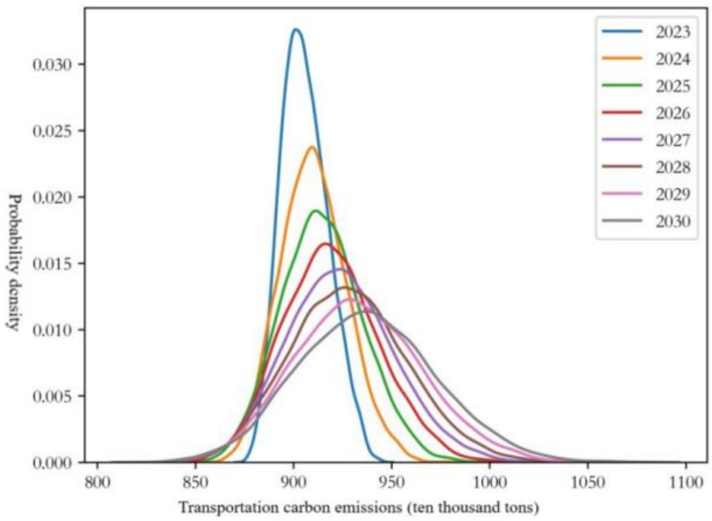

Figure 4: Carbon emission simulation results of China's transportation industry under low-carbon scenario

Comparing the carbon emission values of the transportation industry in 2030 under various scenarios, the carbon emission value under the low-carbon target scenario is the smallest, about 937.71 million tons. Compared with the baseline scenario, the emission reduction under the low-carbon target scenario is about 29.81 million tons to 1106.61 million tons, and the emission reduction intensity is about 2.84% to 57.29%. Compared with the technological progress scenario, the emission reduction under the low-carbon target scenario is about 218.75 million tons to 547.56 million tons, and the emission reduction intensity is about 25.40% to 40.00%. Moreover, under the baseline scenario and the technological progress scenario, there is no inflection point to achieve the carbon peak; in the low-carbon target scenario, the transportation industry is likely to achieve the goal of carbon peak. Therefore, more stringent policy interventions and the application of efficient and low-carbon technologies have a profound impact on the reduction of carbon emissions in the transportation industry. In addition to increasing the use of renewable energy and promoting energy-saving technologies in the transportation industry, it also includes the introduction of more stringent carbon emission standards and incentive mechanisms in the production process of the transportation industry. The carbon emissions of the transportation industry in the low-carbon scenario not only reduce carbon emissions, but also provide successful experience and policy support for the green transformation of the transportation industry in other regions.

6. PATH PLANNING

By comparing the carbon emission prediction results under different scenarios, the low-carbon scenario is the most likely path to achieve the overall carbon peak target of China's transportation industry. Through the synergistic mechanism of technological innovation carbon emission reduction and policy-driven, the transportation structure and efficiency have been greatly adjusted, which has led to a significant reduction in carbon emissions in the transportation industry. According to the criteria of "implementing policies according to categories, combining long and short, step by step, seeking progress in stability, and orderly carbon peaking in turn," on the basis of meeting the overall strategic arrangement of the country and the diversified needs of the people, this study puts forward the emission reduction path with the core idea of "transforming transportation energy into heavy and carbon emission double control as the basis," so as to promote the realization of carbon peaking in the field of transportation as scheduled.

6.1 During the "14th Five-Year Plan" Period

transportation carbon emissions will gradually transition from a high-speed growth stage to a medium-low-speed growth stage. However, there are still many difficulties and challenges to achieve the goal of traffic carbon peak on schedule. Therefore, the main direction of traffic emission reduction in the '14th Five-Year Plan' is to 'control traffic energy consumption and accelerate the adjustment of transportation structure'. Specifically, the construction of multimodal transport system, in the original transport organization model innovation to enhance the proportion of railway, water transport in the integrated transport. Vigorously promote new energy vehicles, gradually reduce the proportion of traditional fuel vehicles in new car production and sales and car ownership, and establish a three-dimensional guarantee mechanism of "policy-technology-facilities" for the penetration of new energy vehicle market. Promote the reconstruction of urban transportation infrastructure network, develop multi-level bus service modes such as customized buses, peak commuter shuttles, and tidal lanes, build a diversified public transportation service system, and form a green travel ecology of "trunk rail + branch bus + terminal slow travel." In this stage, efforts are made to break through the path dependence of traditional fuel transportation equipment and realize the simultaneous optimization of energy consumption elasticity coefficient and low-carbon index of transportation structure.

6.2 During the " 15th Five-Year Plan " Period

on the basis of the "14th Five-Year Plan" development, the adjustment and optimization of transportation structure have made significant progress, the growth of transportation energy consumption has been strictly controlled, and the proportion of non-fossil energy consumption has been further improved. On this basis, the main direction of traffic emission reduction in the '15th Five-Year Plan' is to 'greatly improve energy efficiency and improve the dual control system of transportation carbon emissions'. Specifically, it is necessary to vigorously promote the innovation and application of green transportation technology, and promote the intelligent and green integrated development of comprehensive transportation system. Research and introduction of important measures around the large-scale promotion of new energy, carbon finance, inter-departmental policy coordination and other issues. Explore the establishment of carbon emissions double control work reward and punishment mechanism. The phased implementation path not only follows the transformation law of "easy first, difficult later, echelon advancement," but also conforms to the characteristics of the times of my transportation development. Through the dynamic matching of the diffusion effect of technological innovation and the incentive effect of institutional innovation, it can provide continuous impetus for the realization of the goal of traffic carbon peak.

7. CONCLUSIONS AND POLICY RECOMMENDATIONS

7.1 Conclusion

As one of the main sectors of carbon emissions, the transportation industry has an important impact on the realization of China's carbon peak target. This paper first calculates the carbon emission value of China's transportation industry from 2001 to 2022, then uses the LMDI method to decompose the driving factors of carbon emission, and finally uses Monte Carlo simulation to predict the peak of transportation industry under different scenarios from 2023 to 2030. The main conclusions are:

First, The driving factors of carbon emissions in the transportation industry are per capita output value, average oil price and population size, among which the average oil price contributes more. The promotion factors include fuel energy-oil ratio and traffic energy intensity. Among them, the fuel energy-oil ratio has the greatest emission reduction effect, indicating that China's transportation system planning and green low-carbon transformation have achieved more effective results since the '11th Five-Year Plan'. The effect of traffic energy intensity on carbon emissions is not stable, and there are stage differences.

Second, According to the Monte Carlo simulation results, the carbon emissions of the transportation industry under the baseline scenario, the technological progress scenario and the low-carbon target scenario in 2030 are 10.4997 million tons to 19.3074 million tons, 8.6054 million tons to 9.8919 million tons and 8.2462 million tons to 10.7978 million tons, respectively. The technological progress scenario and the low-carbon target scenario have obvious emission reduction effects, and the low-carbon target scenario under policy intervention can achieve the maximum emission reduction. Compared with the baseline scenario, the emission reduction under the low-carbon target scenario is about 29.81 million tons to 1106.61 million tons, and the emission reduction intensity is about 2.84% to 57.29%; compared with the technological progress scenario, the emission reduction under the low-carbon target scenario is about 218.75 million tons to 547.56 million tons, and the emission reduction intensity is about 25.40% to 40.00%.

Third, Only under the low-carbon target scenario, the transportation industry is likely to achieve the carbon peak goal by 2030, while the carbon emissions of the transportation industry under the other two scenarios still show an upward trend, and there is no peak inflection point. Therefore, the dual role of innovation-driven and policy support should be fully utilized in the future.

Fourth, Based on the analysis of the prediction results of carbon emissions in the future transportation industry, it is found that the low-carbon target scenario is the most feasible way to achieve the overall carbon peak target of China's transportation industry. Therefore, an emission reduction path based on the core idea of "transportation energy transformation and carbon emission double control" is proposed to promote the transportation sector to achieve carbon peaks on schedule.

7.2 Policy Recommendations

7.2.1 Build a green low-carbon transportation system and guide people to adopt green transportation.

Economic scale and population growth are still the core variables driving the growth of carbon emissions. At the macro level, it is necessary to fully implement the concept of sustainable development and accelerate the construction of a green low-carbon circular transportation system; at the micro level, we should build a low-carbon lifestyle through policy guidance, focus on promoting the priority development strategy of urban public transport, and advocate people to adopt environmentally friendly transportation methods such as new energy vehicles and shared travel.

7.2.2 Optimize the energy structure of the transportation industry and improve energy efficiency.

We should increase the development and utilization of clean energy such as solar energy, wind energy, water energy, hydrogen energy and biomass energy, increase the proportion of clean energy, reduce the dependence on traditional fossil energy, promote the complementary and coordinated development of various clean energy sources, and build a multi-energy complementary integrated energy supply system. According to the demand characteristics of different regions and different modes of transportation, we should rationally allocate different energy types and realize the optimal allocation of energy.

In addition, improving the energy efficiency of the transportation industry is also the key to reducing carbon emissions. Enterprises should strengthen technology research and development, promote the intelligentization and greening of transportation tools, and accelerate the transformation of green technology achievements. The government should improve innovation incentives, encourage and guide enterprises to actively develop new energy application transportation technologies, pay attention to enhancing the public's awareness of environmental protection and green travel, and advocate people to adopt environmentally friendly transportation methods such as new energy vehicles and shared travel.

7.2.3 Construct innovation policy coordination mechanism.

The research results show that it is difficult for a single technological innovation to achieve the expected emission reduction targets. It is necessary to establish a "technology-system" two-wheel drive system. Under the framework of the national strategic deployment, we should focus on promoting the new infrastructure construction proposed by the "Outline of Building a Strong Transportation Country." Through the intelligent transformation of the transportation system enabled by the Internet of Things and cloud computing technology, a policy closed-loop of benign interaction between scientific and technological innovation and institutional innovation is formed.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest relevant to this study.

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