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How can Transportation Sector Achieve High-quality Carbon Peaking in China?

-- Based on International Comparison

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Abstract: Promoting the peak of carbon emissions in the transportation sector as soon as possible is the key to advancing carbon peaking process in China. This article combines the KAYA model, peak quality standards based on Tapio decoupling model, and international experience to predict the future trend of carbon emissions of transportation sector, and to analyze the path for the transportation sector to achieve high-quality peak in China. Research has found that: (1) Based on China's goals (by 2030, the proportion of oil and gas will decrease to 75%), it has been found that China's transportation sector may achieve carbon peak by 2032, with lower peak quality than developed countries such as Japan. (2) Based on international experience, stable GDP growth and technological progress are key to ensuring the quality of carbon peak in the transportation sector. (3) On the basis of reducing the share of oil and gas to 75% by 2030, if China further decreases the energy intensity of its transportation sector by 27% compared to 2018 levels (a 7% greater decrease than the target scenario), it is projected that China's transportation sector may achieve a high-quality carbon peak by 2030 and potentially match the peak quality level of France. This paper can provide theoretical support for promoting carbon emissions reduction and facilitating the peak in China's transportation sector.

Keywords: China; Transportation Sector; Carbon Peak; High Quality; International Experience.

1. Introduction

To tackle climate change, reducing greenhouse gases, mainly consisting of carbon dioxide, has become a global undertaking. As one of the world's most significant emitters of greenhouse gases [1, 2], China has taken on the international responsibility of carbon emissions reduction voluntarily. In 2020, the Chinese government officially pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 [3]. Whether China can meet these commitments on time is of considerable significance for realizing the goal of the Paris Agreement to limit global warming to below 2°C [4].

However, achieving this goal is profoundly challenging. The transportation sector, one of the hardest to decarbonize [5]. The proportion of carbon emissions from the transportation sector in China's social carbon emissions is increasing, from 5% in 1990 to 10% in 2018. During the same period, the proportion of carbon emissions in the global transportation sector increased from 2% to 11%, with an average annual growth rate of about 8.3%, far higher than Japan (-0.10%) and the European Union (0.73%) [6]. As of 2018, carbon emissions from China's transportation sector had yet to peak or show signs of slowing down, and future increases in these emissions may impede China's overall progress toward peaking total carbon emissions.

Furthermore, China is currently in a transitional phase from extensive development, and the carbon emission efficiency in the transportation sector has consistently been low. As shown in Figure 1, from 2000 to 2018, China's carbon emission efficiency was about 2/5 of that of Japan and 2/3 of that of the European Union, and the improvement was relatively small. Rushing to peak emissions may not enhance emission efficiency and might even fail to effectively reduce emissions. Therefore, to promote a "fast and good" peak in carbon emissions for China's transportation sector, it is essential to conduct a thorough analysis comparing developed countries' peak levels. This will help explore the path for the transportation sector to achieve high-quality carbon peaking in China.

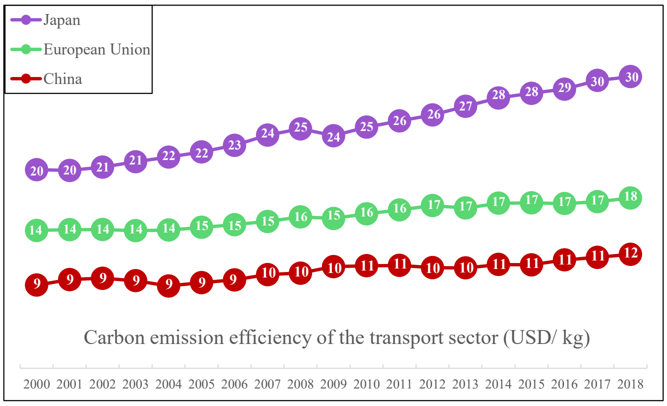

Figure 1. Carbon emission efficiency of transportation sectors in China, the European Union, and Japan

Data source: Carbon emissions of the transportation sector from the International Energy Agency [6], and GDP data at constant 2010 prices is from the World Bank [7].

Based on the above practical background, this article intends to study the following issues: Firstly, predict the carbon peak time and peak of China's transportation sector; secondly, explore the optimal scenarios for the peak quality and emission reduction of carbon emissions in China's transportation sector. Therefore, based on using the KAYA model to predict the time and peak of carbon peaking in the transportation sector, this article attempts to combine Tapio decoupling theory with international comparison to analyze the quality of carbon peaking in the transportation sector, explore the path for China's transportation sector to achieve high-quality peaking from an international perspective, and provide a visual perspective for the Chinese government to set emission reduction targets.

The main innovations of this article are as follows: Firstly, unlike previous studies that only focused on the time and peak of carbon peaking [1, 2, 8, 9], this article focuses on the quality of carbon peaking, and proposes a carbon peaking quality evaluation standard based on Tapio decoupling theory, quantifying quality indicators for comparative analysis. Secondly, unlike studying a single country or region [10-12], this article is based on a comparison of quality evaluation standards and draws on the carbon peaking experience of developed countries to guide China's transportation sector to achieve carbon peaking scientifically, reasonably, and efficiently.

2. Literature review

The transportation sector has become a key sector for carbon reduction, and its potential for emission reduction has received much attention. Some studies have shown that reducing energy intensity and improving energy structure are key factors in reducing carbon emissions in China's transportation sector [1, 13-16]. By studying carbon emissions in the transportation sectors of the United States, China, India, Canada, Russia, Brazil, and Japan, Solaymani [17] believes that optimizing energy structure and limiting the number of private cars can reduce carbon emissions. Similarly, Wang et al. [18] studied the "the Belt and Road" countries and proved that improving the efficiency of cargo transportation on the Eurasian Continental Bridge is the key to reducing emissions. Some scholars have individually analyzed the driving factors behind carbon emissions of the transport sector in Turkey [19], Pakistan [20] and Thailand [21].

The prediction model usually combines "method+scenario analysis" to predict carbon emissions. This article summarizes the carbon peak prediction methods of China's transportation sector from methods, advantages and disadvantages, representative literature, and peak times. As shown in Table 1.

Table 1. Comparison of carbon emission prediction models in China's transportation sector

Method	Advantage	Disadvantage	Literature	Peak time
Econometrics (EA)	Simple technology; Predictions can be based on any available data	Overreliance on historical trends; The influencing factors have strong subjectivity	Chen et al. [1]	2043
			Yang et al. [10]	-
			Zhang and Su [12]	2025
KAYA decomposition prediction	Fully identify internal driving forces; Easy to analyze from an economic perspective	The number of settings for intrinsic driving forces is limited	Wang and He [22]	2035
			Wang et al. [23]	-
Remote Energy Alternative Program (LEAP)	Flexible modeling structure; Less data demand; A simple and comprehensive accounting framework	Highly dependent on personal judgment; Lack of official data on technical parameters	Liu et al. [8]	2030
			Zhang et al. [11]	-
			Zhou et al. [24]	2035
			Liu et al. [25]	2026-3038
National Energy Technology Model (NET)	Can predict energy consumption and pollution emissions under the background of minimum cost	Low execution efficiency; Lack of technical parameters	Zhao et al. [2]	2024
Gray prediction	Relatively accurate predictions can be made with limited data available	Lack of transparency in methodology; Unable to identify driving factors	Ye et al. [26]	-

Note: "-" represents the conclusion of the peak time was not obtained during the research period.

Regarding the research on China's carbon peak, scholars focus on whether China can achieve its commitment to carbon peak before 2030. Zhang and Su [12] believe that the carbon emissions of the transportation sector in the Yellow River Basin will peak in 2025. Different scholars believe that carbon emissions from China's transportation sector may peak before 2030 [2, 8, 25, 27], before 2050 [1, 22, 24, 28, 29], or after 2050 [10, 11].Due to differences in research designs among different scholars, such as databases, methods, underlying assumptions, and policy objectives, there will be significant flexibility in predicting the peak and timing of carbon peaking in the transportation sector [23, 30]. In order to facilitate the analysis of the fundamental sources of carbon emissions from an economic perspective, this article intends to use the KAYA decomposition model to predict the carbon peak in China's transportation sector.

In international research on carbon peaking, scholars mainly focus on the carbon emission trends of individual countries and international comparisons of carbon emissions. For example, some scholars have studied the carbon emission trends of the transportation sector in the European Union [31], India [32], Thailand [33], Indonesia [34], and Oman [35]. Pan et al. [36] predict that China will achieve carbon peak by 2030, with a greater sense of responsibility for independent contributions than the United States and EU countries. Similarly, Fragkos and Kouvaritakis [37] predict that China will also reach its carbon peak by 2030, later than developed economies such as OCED and earlier than other developing countries such as India. Regarding the transportation sector, Zhang et al. [38] compared the decarbonization scenarios of the transportation sectors in China and the United States, and concluded that the future decarbonization efforts of the transportation sector in the United States are better than those in China. Wang and He [22] compared the carbon peak pathways in the transportation sectors of China, the United States, Japan, and EU countries, and concluded that there is significant room for improvement in China's carbon peak pathways compared to developed countries.

The above research has the following shortcomings: Firstly, there is an excessive emphasis on the time and peak of carbon peaking, without considering the quality of carbon peaking, and a lack of systematic analysis of carbon peaking. Secondly, most existing research only compares emission reduction paths and peak times, without benchmarking the carbon peak quality of developing countries such as China with that of developed countries. As a major emitter, achieving high-quality carbon peaking has global significance in China. Therefore, this article attempts to propose standards for evaluating the quality of carbon peaking, explore the peak time of China's transportation sector, and explore the path to achieving high-quality peaking.

3. Models and Data Sources

3.1. Prediction based on KAYA Model

The KAYA formula can be used to decompose CO2 emissions from the transportation sector into four influencing factors, namely GDP, energy intensity, energy structure, and carbon emission coefficient. As shown in equation (1):

$$CO_2 = GDP \times \frac{E}{GDP} \times \frac{e}{E} \times \frac{CO_2}{e} \quad (1)$$

Among them, CO2 represents the CO2 emissions of the transportation sector, GDP represents the gross domestic product, E represents the energy consumption of the transportation sector, and e represents the oil and gas consumption of the transportation sector. According to the meaning of economics, equation (1) can be rewritten as equation (2):

$$CO_2 = GDP \times EI \times ES \times EF \quad (2)$$

Among them, EI represents the energy intensity of the transportation sector, ES represents the proportion of oil and gas energy in the transportation sector to the total energy, and EF represents the transportation carbon emission coefficient. It should be noted that: (1) the transportation sector mainly consumes oil and natural gas, with oil and gas accounting for up to 91% of the total energy consumption [39].Therefore, the article mainly considers the CO2 emissions generated by oil and natural gas, that is, the proportion of oil and gas represents the energy structure.(2) On the one hand, the CO2 emission coefficients of various energy sources are relatively stable and will not experience significant fluctuations due to technological progress or an increase in energy utilization efficiency [40]; On the other hand, there is currently a lack of clear vehicle CO2 emission standards in China, and the changes in vehicle emission factors mainly come from changes in the energy structure of vehicle models, which is consistent with the adjustment effect of energy structure. Therefore, this article considers that the emission factor remains constant while the transportation carbon emission coefficient remains constant.

According to the model calculation, the change in CO2 emissions from the transportation sector from the baseline year (t) to the target year (t+n) can be decomposed into four factors, as shown in equation (3):

$$\Delta CO_2 = \Delta GDP + \Delta EI + \Delta ES + \Delta EF \quad (3)$$

Considering that the carbon emission coefficient effect is zero, the decomposition results of the other three factors are as follows:

$$\Delta GDP = \sum_i \frac{CO_{2,t+n} - CO_{2,t}}{lnCO_{2,t+n} - lnCO_{2,t}} \times ln(\frac{GDP_{t+n}}{GDP_t})$$

$$(Economic\ growth\ effect) \quad (4)$$

$$\Delta EI = \sum_i \frac{CO_{2,t+n} - CO_{2,t}}{lnCO_{2,t+n} - lnCO_{2,t}} \times ln(\frac{EI_{t+n}}{EI_t})$$

$$(energy\ intensity\ effect) \quad (5)$$

$$\Delta ES = \sum_i \frac{CO_{2,t+n} - CO_{2,t}}{lnCO_{2,t+n} - lnCO_{2,t}} \times ln(\frac{ES_{t+n}}{ES_t})$$

$$(Energy\ structure\ effect) \quad (6)$$

Based on equations (3) - (6), the contribution rate of influencing factors conforms to equation (7):

$$\frac{\Delta GDP}{\Delta CO_2} \times 100\% + \frac{\Delta EI}{\Delta CO_2} \times 100\% + \frac{\Delta ES}{\Delta CO_2} \times 100\% = 100\% \quad (7)$$

Various studies have shown that economic growth is the main factor in increasing CO2 emissions in the transportation sector, and reducing energy intensity and improving energy structure are key factors in reducing CO2 emissions in the transportation sector [1, 13-16]. Therefore, according to equation (2), the predicted CO2 emissions from the transportation sector can be described as equation (8):

$$FCO_{2_t} = (GDP_{t-1} + G) \times (EI_{t-1} - I) \times (ES_{t-1} - S) \times EF_{t-1} \quad (8)$$

Among them, FCO_2 represents the predicted CO2 value of the transportation sector, G represents the annual average growth value of GDP,I represents the annual average decline value of energy intensity in the transportation sector, S represents the annual average decline value of the proportion of oil and gas in the transportation sector. The basis for setting G, I and S are as follow: (1) Research shows that China's average annual GDP growth rate is expected to be 5%-6% in 2020-2025, 4%-5% in 2025-2030, 3%-4% in 2030-2040, and 2%-3% in 2040-2050 [41]. This paper takes into account China's positive growth trend, assuming a GDP annual growth rate of 6% for 2020-2025, 5% for 2025-2030, 4% for 2030-2035, and 3% for 2040-2050.Since the reduction target of energy intensity has not been issued in China, the decline of energy intensity in this paper is set to obey the historical law. The energy intensity of the transportation sector has decreased from 5.5kgce/USD in 1990 to 3.7kgce/USD in 2018, with an annual decrease of approximately 0.06kgce/USD in China [39].(3) In 2019, the head of State Grid of China pointed out at the 24th World Energy Conference that by 2050, the energy cleanliness rate (non fossil fuels accounting for the proportion of primary energy consumption) will exceed 50% in China [42]. In 2020, the Chinese government pledged at the Climate Ambition Summit to increase China's energy cleanliness rate to 25% by 2030 [3]. Therefore, based on national goals, this article sets the energy cleanliness rate (non oil and gas proportion) of the transportation sector to reach 25% and 50% respectively by 2030 and 2050, and changes at a constant rate.

3.2. Quality Assessment based on Tapio Decoupling Model

In order to study the relationship between carbon emissions and economic growth in the transportation sector, this paper introduces a decoupling model. Tapio [43] introduced the elasticity coefficient into the decoupling model and used the percentage of pollutant changes caused by every 1% economic change as the research result. The calculation is as follows:

$$\varepsilon = \frac{\Delta CO_2}{CO_2} \div \frac{\Delta GDP}{GDP} \quad (9)$$

Among them, ε represents the decoupling index, ΔCO_2 represents the CO2 change in the transportation sector, ΔGDP represents the change in Gross Domestic Product (GDP).

In order to measure the peak quality of carbon emissions in the transportation sector, this paper proposes quality evaluation criteria for carbon peak in the transportation sector based on the Tapio decoupling model: The research period for measuring peak quality is from reaching the highest historical value to three years after reaching the peak. If the decoupling index is smaller, it is considered that the peak quality is higher. The reason for this approach is: (1) Observing the emissions for three years after reaching the peak can reveal a clear emission trend (such as a steady or rapid decline), and the decoupling index for three years is a stable and appropriate result. (2) If the decoupling index is negative during the research period, that is, carbon emissions tend to decrease. If the decoupling index is smaller, the rate of carbon emission reduction is greater, the pollution prevention and control measures taken are more effective, and the peak quality can be considered higher.

3.3. Data sources

In order to explore the path for China's transportation sector to achieve high-quality carbon peaking, this article selects the top four developed countries in terms of transportation sector carbon emissions for comparison, including the United States, Japan, Germany, and France. The research period of this article is from 1990 to 2018, and the GDP of each country comes from the World Bank (https://data.worldbank.org.cn/); The CO2 emission data, oil consumption, natural gas consumption, and total energy consumption of transportation sectors in various countries are sourced from the International Energy Agency (IEA: https://www.iea.org/); The energy data of China's transportation department comes from the corresponding year's China Energy Statistical Yearbook. In order to eliminate the impact of inflation, this article selects GDP data measured at 2010 constant prices.

4. Carbon Peak Prediction for the Transportation Sector: Time and Peak

4.1. Target Scenario Prediction

As of 2018, carbon emissions from the transportation sector in China have not yet reached the peak. As shown in Figure 2, the carbon emissions of China's transportation sector have shown a monotonous growth trend, increasing from 99Mt in 1990 to 925Mt in 2018, with an average annual growth rate of 8.3%, closely following the GDP growth rate (9.6%), which is consistent with GDP growth. According to the KAYA decomposition results, from 1990 to 2018, both the economic growth effect and the energy structure effect promoted the growth of carbon emissions in the transportation sector, with contribution rates of 115.24% and 2.12%, respectively. Only the energy intensity effect suppressed the growth of carbon emissions in the transportation sector, with a contribution rate of -17.36%. The possible reasons are that: in the past 30 years, with the rapid development of industrialization and urbanization in China, transportation infrastructure construction has become increasingly perfect, transportation demand and energy consumption have continued to increase, and social development is highly dependent on oil and gas energy. The rapid economic growth has offset the emission reduction effect of energy efficiency improvement, leading to a gradual increase in carbon emissions in the transportation sector.

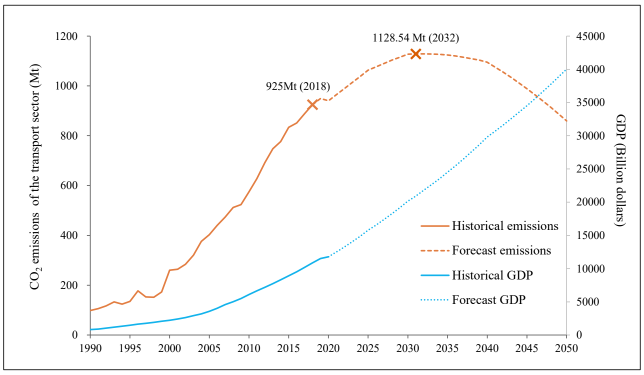

Figure 2. The CO2 emissions of the transport sector and GDP growth

Note: The number on the curve represents the peak value (peak time).

The prediction of carbon emissions from China's transportation sector shows that under the target scenario, the transportation sector will reach its peak in carbon emissions by 2032, with a peak of 1128.54 Mt (see Figure 2). At present, China's transportation sector still heavily relies on oil and gas energy (91%), and the penetration rate of new energy vehicles in 2019 was less than 5%. In 2020, China's fuel economy was about 47 miles per gallon, which still lags behind Japan's previous 59.8 miles per gallon. Therefore, under the "carbon peak and carbon neutrality" strategy, China will actively improve its transportation energy structure, develop the new energy vehicle market, and improve fuel economy in the future, which is expected to achieve effective emission reduction.

4.2. Adjusting Scenario Prediction

It is obvious that the carbon peak commitment before 2030 cannot be achieved temporarily under the target scenario. In order to ensure that the transportation sector achieves carbon peak around 2030, this article has readjusted the scenario goals, as shown in Table 2

Table 2. Adjusting Scenario Settings

Scenario	Content
Scenario 1	The energy cleanliness rate has been adjusted to reach 30% by 2030 and 65% by 2050 [44]
Scenario 2	Energy intensity adjusted to a decrease of 0.08 per year
Scenario 3	Combining Scenario 1 and Scenario 2

As shown in Figure 3, by increasing the energy cleanliness rate, the Chinese transportation sector expects the carbon peak time to be 2030, 2 years ahead of the baseline scenario, with a peak of 1052.31 Mt, a decrease of 6.8% compared to the baseline scenario. By increasing the reduction in energy intensity, it is expected to reach its peak in 2030, with a peak of 1036.23Mt, a decrease of 8.2% compared to the baseline scenario. Combining two emission reduction measures, it is predicted that the peak time will be 2025, with a peak of 981.1 Mt, a decrease of 13.1% compared to the baseline scenario.

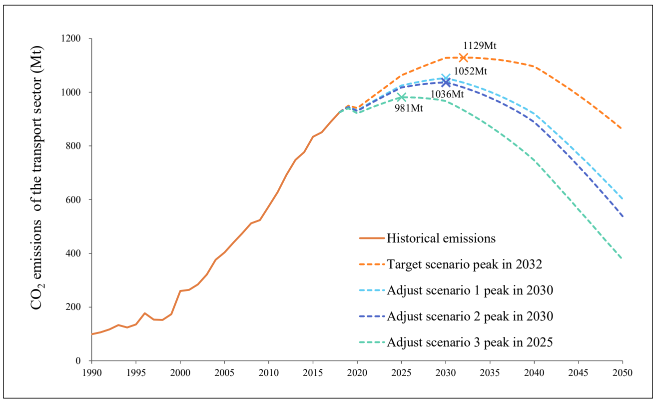

Figure 3. The CO2 emissions of the transport sector

5. Peak Quality Assessment

5.1. International Comparison and Experience

Unlike China, the four major developed countries have achieved carbon peak in their transportation sector before 2018, despite having sound transportation infrastructure and slow growth. As shown in Figure 4, Germany, Japan, France, and the United States achieved carbon peaking in 1999, 2001, 2002, and 2005, with peaks of 178Mt, 263Mt, 134Mt, and 1808Mt, respectively. At its peak, the GDP growth rate was all less than 3%.

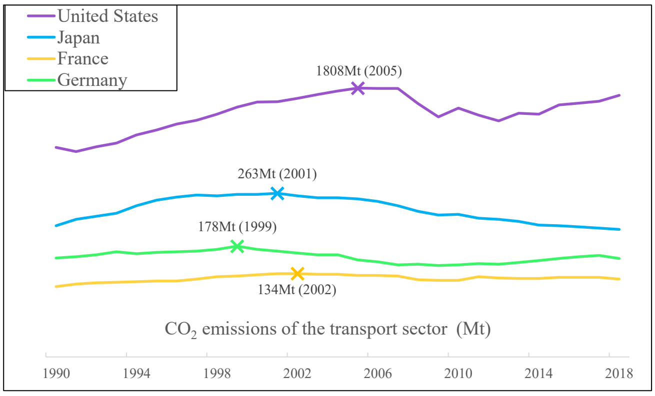

Figure 4. The CO2 emissions of the transportation sector

This article uses the decoupling index of carbon emissions and economic growth during the peak period for three years to reflect the quality of carbon peaking, as shown in Table 3. The smaller the decoupling value, the smaller the correlation between carbon emissions in the transportation sector and economic growth, indicating a higher quality of carbon peaking. The decoupling indices of Japan, Germany, France, and the United States were -1.615, -0.968, -0.203, and -0.023, respectively, with a decrease in peak mass.

Based on the KAYA decomposition conducted three years after reaching the peak in various countries, it was found that economic growth is the most important factor promoting the growth of carbon emissions in the transportation sector of each country, and the contribution rate of economic growth effect is inversely related to the peak quality, that is, the smaller the contribution rate, the higher the peak quality. Improving energy structure and reducing energy intensity are key factors in suppressing the growth of carbon emissions in the transportation sector, among which the contribution rate of energy intensity effect is far greater than that of energy structure effect. The main reason is that during peak periods, the transportation sector still relies excessively on oil and natural gas, with a relatively small improvement, and oil and gas account for about 98% of the total energy. The decrease in energy intensity is mainly due to the informatization of transportation systems in various countries, the improvement of laws and regulations, and the emphasis on railway transportation [45].For example, Japan has launched a modern logistics system and developed an EDI information system; Against the backdrop of expanding freight demand, France has adopted measures such as line speed increase and intermodal transportation by road and rail; Germany has established and developed "freight centers" and "logistics centers"; The United States has established a "lean supply chain" and opened up "third-party logistics". These measures have greatly improved transportation efficiency, reduced transportation unit energy consumption and environmental burden.

Table 3. Decoupling Index and KAYA Decomposition of Carbon Peaking in Transportation Sectors of Various Countries

Country	Peak time	Decoupling index	Energy structure effect	Energy intensity effect	Economic growth effect
United States	2005	-0.023	-928%	-3395%	4223%
Japan	2001	-1.615	-11%	-150%	61%
France	2002	-0.203	24%	-606%	482%
Germany	1999	-0.968	-8%	-191%	99%

According to international experience, reducing energy intensity and improving energy structure are key to ensuring peak quality. When the economic growth effect is small and the energy intensity effect is greater than the energy structure effect, it can lead to higher peak quality. As shown in Table 4, in the benchmark scenario, the expected decoupling index of China's transportation sector is -0.025, which is basically the same as the decoupling index of the United States, but the decoupling index is still relatively small. The decoupling indices in adjustment scenarios 1, 2, and 3 are -0.198, -0.222, and -0.017, respectively. At this point, adjusting Scenario 1 and Scenario 2 are close to France's decoupling index, and the peak time is earlier, with a lower peak compared to the baseline scenario, indicating significantly better peak quality. Among them, adjustment scenario 2 conforms to the law of peak quality in developed countries, showing higher peak quality. However, although the peak time was advanced in scenario 3, the decoupling index was smaller than the baseline scenario, and the peak quality was not as good as the other three scenarios. Therefore, this article believes that adjusting scenario 2 is the optimal scenario for China's transportation sector to achieve high-quality peak traffic.

Table 4. Decoupling Index and KAYA Decomposition of Carbon Peaking in China's Transportation Sector

Country	Peak time	Peak value	Decoupling index	Energy structure effect	Energy intensity effect	Economic growth effect
China	2032	1129Mt	-0.025	-1726%	-2233%	3859%
China (Adjust 1)	2030	1052Mt	-0.198	-315%	-267%	482%
China (Adjust 2)	2030	1036Mt	-0.222	-185%	-343%	429%
China (Adjust 3)	2025	989Mt	-0.017	-2605%	-3143%	5647%

5.2. Comparison of Indicators between China and Developed Countries

There are significant differences in the indicators for carbon peaking of the transportation sector in the United States, Japan, and EU countries (France and Germany), as shown in Table 5. According to the decoupling index, the carbon peak quality of the transportation sector in the United States is lower than that of Japan and EU countries. From the analysis of development indicators, the GDP growth rate of the United States is about 2.4%, with a per capita GDP of about 49000 US dollars per person, higher than Japan and EU countries. The energy efficiency and emission efficiency are relatively low, about one-third of those of other developed countries. However, per capita energy consumption and emissions are relatively high, about three times that of other developed countries. Therefore, in order to achieve high-quality peak production, it is necessary to have stable GDP growth rate, high energy efficiency, high emission efficiency, low per capita emissions, and per capita energy consumption.

Table 5. Comparison of carbon peak indicators in transportation sectors of developed countries

Indicator	United States	Japan	France	Germany
Peak year	2005	2001	2002	1999
Peak value (Mt)	1808	263	134	178
Decoupling index	-0.023	-1.615	-0.203	-0.968
Energy structure (proportion of oil and gas)	99%	98%	97%	98%
Energy efficiency (ten thousand USD/toe)	2.3	6.0	5.3	5.0
Emission efficiency (USD/kg)	7.9	20.4	17.9	17.0
Peak GDP growth rate	2.4%	0.8%	1.8%	2.3%
Population size (100 million people)	3.0	1.3	0.6	0.8
Per capita GDP (ten thousand USD/person)	4.9	4.2	3.9	3.7
Per capita CO2 emissions from the transportation sector (t/person)	6.1	2.1	2.2	2.2
Per capita transportation energy consumption (toe/person)	2.1	0.7	0.7	0.7

Table 6. Comparison of predicted CO2 peak indicators by China's transportation sector

Indicator	China	China (Adjust 1)	China (Adjust 2)	China (Adjust 3)
Peak year	2032	2030	2030	2025
Peak value	1129Mt	1052Mt	1036Mt	989Mt
Decoupling index	-0.025	-0.198	-0.222	-0.017
Energy structure (proportion of oil and gas)	73%	70%	75%	76.9%
Energy efficiency (ten thousand USD/toe)	5.03	4.82	5.24	4.55
Emission efficiency (USD/kg)	19.3	19.1	19.4	16.3
Peak GDP growth rate	4.0%	4.0%	4.0%	5.0%
Population size (100 million people)	14.4	14.5	14.5	14.3
Per capita GDP (ten thousand USD/person)	1.5	1.4	1.4	1.1
Per capita CO2 emissions from the transportation sector (t/person)	0.78	0.73	0.71	0.68
Per capita transportation energy consumption (toe/person)	0.30	0.29	0.26	0.24

Note: In 2020, the population of China was approximately 1.41 billion people [46]; the estimated population size by 2030 is approximately 1.45 billion people [47]; after the population reaches its peak, it is expected that the population will decrease to 1.43 billion by 2035 [48].

Based on international experience, China's adjustment scenario 2 shows a high quality peak performance, further supporting the decoupling quality conclusion. As shown in Table 6, the energy efficiency and emission efficiency in "Adjustment Scenario 2" are the highest among the four scenarios, and basically reach the peak level of Japan and EU countries. At the same time, per capita emissions and energy consumption are relatively low, even lower than developed countries. Although "Adjusting Scenario 3" has advanced the peak time, energy efficiency and emission efficiency are significantly low. Therefore, "peaking early" does not necessarily mean "high quality". If the transportation department wants to achieve high-quality peak in "Adjustment Scenario 2", the proportion of oil and gas needs to decrease to 75% by 2030 and 50% by 2050 (the baseline scenario); the energy intensity of the transportation sector will decrease by 27% in 2030 compared to 2018 (a 7% decrease compared to the baseline scenario), and by 71% in 2050 compared to 2018 (a 17% decrease compared to the baseline scenario).

6. Conclusion and Policy Recommendations

This article proposes a quality evaluation standard for carbon peaking in the transportation sector based on the Tapio decoupling model, and combines the KAYA model to predict the time, the value, and the quality of carbon peaking in China's transportation sector, and compares it with developed countries. The main conclusions are as follows:

(1)If the proportion of non oil and gas in the transportation sector is set to reach 25% and 50% respectively by 2030 and 2050, China's transportation sector may achieve carbon peak by 2032, with a peak of 1128.54 million tons, and the peak quality will be lower than that of developed countries such as Japan.

(2)According to international experience, reducing energy intensity and improving energy structure are key to ensuring peak quality. When the economic growth effect is small and the energy intensity effect is greater than the energy structure effect, it can lead to higher peak quality.

(3)In the scenario where the proportion of oil and gas remains unchanged, if the energy intensity of the transportation sector is reduced by 27% compared to 2018 in 2030 and 71% compared to 2018 in 2050, it is expected that China's transportation sector may achieve high-quality carbon peaking by 2030, with a peak of 1036.23 Mt. At that time, the quality of carbon peaking will basically reach the peak quality level of France.

In order to achieve high-quality carbon peaking, it is imperative to reduce the proportion of oil and gas and improve energy efficiency. Based on this, this article proposes two policy recommendations:

(1) Adjust the energy structure. On the one hand, we will shift the oil and gas energy of the transportation sector towards clean energy as much as possible, such as wind energy, solar energy, and so on. On the other hand, through tax cuts, subsidies and policy support to increase support for new energy vehicles, accelerate the promotion of new energy vehicles to replace traditional fuel vehicles.

(2)Promote technological progress. The Chinese government should learn from Japan and EU countries to establish and improve transportation management systems based on information systems, improve railway transportation speed and motor vehicle fuel economy, and strengthen road rail intermodal transportation. In addition, considering the low peak quality in the United States, it has been found that carbon emissions in the transportation sector have shown an increasing trend in the past decade, with a growth rate of about 1%, mainly due to supply chain transportation issues in American e-commerce [45]. The Chinese government should reasonably avoid this supply chain issue. The Chinese government can establish a supply chain management system that directly targets end consumers, establish automated storage warehouses, and develop cloud robots for distribution, shortening the supply chain and avoiding excessive transportation.

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